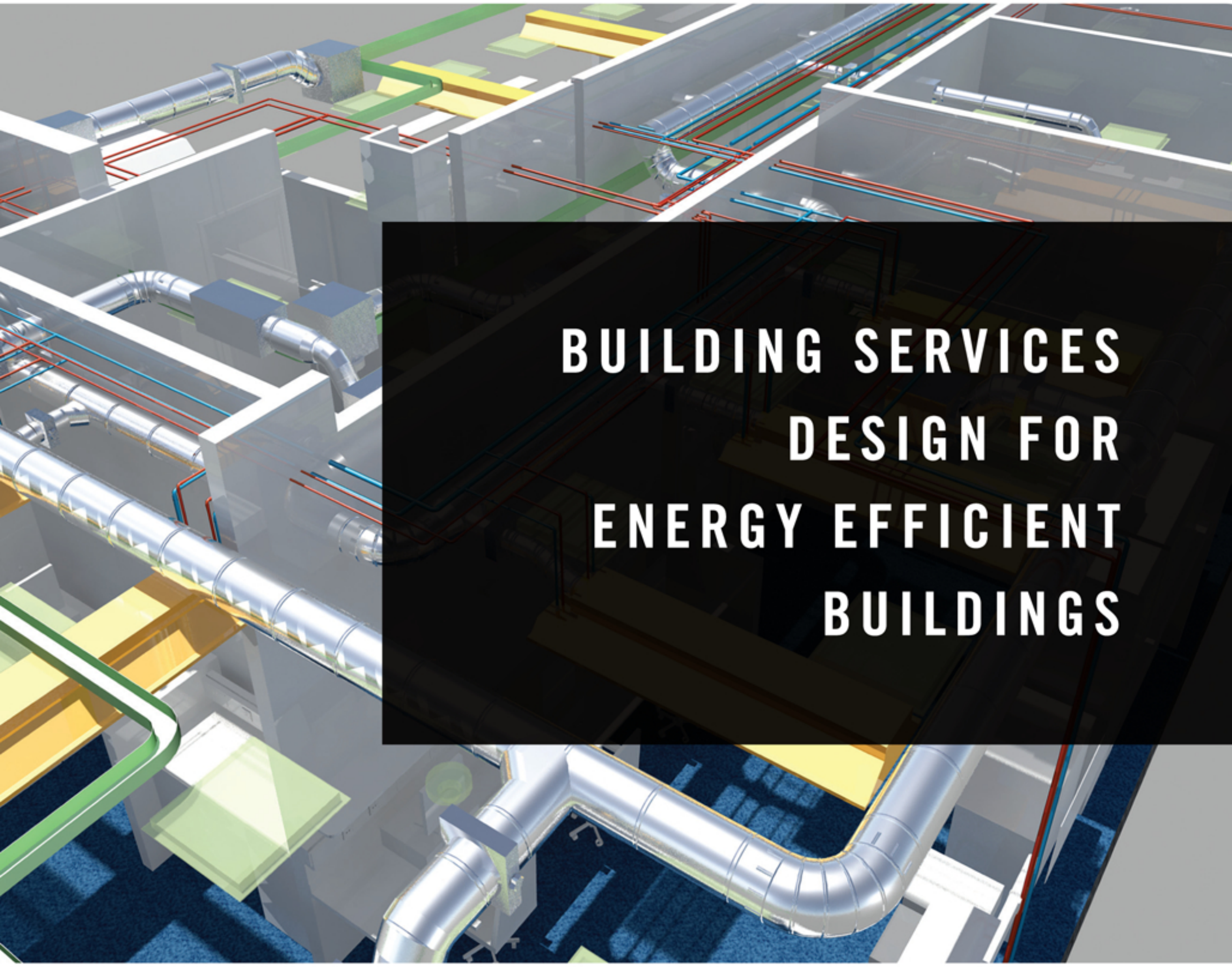

BUILDING SERVICES DESIGN FOR ENERGY EFFICIENT BUILDINGS

PAUL TYMKOW, SAVVAS TASSOU,
MARIA KOLOKOTRONI
AND HUSSAM JOUHARA

ROUTLEDGE

Building Services Design for Energy Efficient Buildings

The role and influence of building services engineers are undergoing rapid change and are pivotal to achieving low-carbon buildings. However, textbooks in the field have remained fairly traditional with a detailed focus on the technicalities of heating, ventilation and air-conditioning (HVAC) systems, often with little wider context. This book addresses that need by embracing a contemporary understanding of sustainability imperatives, together with a practical approach to the key issues impacting upon energy efficiency, in a concise manner.

The essential conceptual design issues for planning the principal building services systems that influence energy efficiency are examined in detail. These are HVAC and electrical systems. In addition, the following issues are addressed:

- background issues for sustainability and the design process
- generic strategies for energy efficient design
- post occupancy evaluation
- building ventilation
- air-conditioning and HVAC system selection
- thermal energy generation and distribution systems
- low energy approaches for thermal control
- energy efficient electrical systems, controls and metering
- building thermal load calculations
- electrical load assessment
- space planning and design integration with other disciplines.

In order to deliver sustainable buildings, a new perspective is required for building services engineers, from the outset of the conceptual design stage and throughout the whole design process. In this book, students and practitioners alike will find the ideal introduction and guide to this new approach.

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Contents

Figures

Tables

Abbreviations and acronyms

a.c.	Alternating current
ACE	Association of Consultancy and Engineering
AHU	Air-handling unit
AMD	Assessed maximum demand
ASHRAE	American Society of Heating, Refrigerating and Air-conditioning Engineers
BEMS	Building energy management system
BER	Building emission rate
BIM	Building information modelling
BMS	Building management system
BRE	Building Research Establishment
BREEAM	Building Research Establishment Environmental Assessment Method
BSJ	*Building Services Journal*
BSRIA	Building Services Research and Information Association (UK)
CASBEE	Comprehensive Assessment System for Building Environmental Efficiency
CAV	Constant air volume
CDM	Construction (design and management)
CFD	Computational fluid dynamics
CHP	Combined heat and power
CIBSE	Chartered Institution of Building Services Engineers
COP	Coefficient of performance
d.c.	Direct current
DCLG	Department of Communities and Local Government
DDC	Direct digital control
DEC	Display Energy Certificates
DECC	Department of Energy and Climate Change
DX	Direct expansion refrigerant
EC	Electronically-commutated
EER	Energy efficiency ratio
EMC	Electromagnetic compatibility
EMD	Estimated maximum demand
EMI	Electromagnetic interference
EMS	Energy monitoring system
EPBD	Energy Performance of Buildings Directive
EPC	Energy Performance Certificate

ETAHE	Earth-to-air heat exchangers
FCU	Fan coil units
FES	Fabric energy storage
GA	General arrangement (drawings)
GDP	Gross domestic product
GHG	Greenhouse gases
H&S	Health and safety
HCFC	Hydrochlorofluorocarbon
HFC	Hydrofluorocarbon
HMI	Human–machine interface
HV	High voltage
HVAC	Heating, ventilation and air-conditioning
HVCA	Heating and Ventilating Contractors Association
IAQ	Indoor air quality
IARC	International Agency for Research on Cancer
ICT	Information and communication technology
IET	Institution of Engineering and Technology
IPCC	Intergovernmental Panel on Climate Change
LAN	Local area network
LCM	Lighting control modules
LED	Light emitting diode
LEED	Leadership in Energy and Environmental Design
LENI	Lighting energy numeric indicator
LLMF	Lamp lumen maintenance factor
LOR	Light output ratio
LPHW	Low pressure hot water
LTHW	Low temperature hot water
LV	Low voltage
LZC	Low and zero carbon
M&E	Mechanical & Electrical
MCC	Motor control centres
MEP	Mechanical, electrical and public health
MF	Maintenance factor
MLIT	Ministry of Land, Infrastructure, Transport and Tourism
MPP	Maximum power point
MV	Medium voltage
NABERS	National Australian Building Environmental Rating Scheme
NR	Noise rating
PCC	Point of common coupling
PCM	Phase change materials
PCs	Personal computers
PDEC	Passive downdraught evaporative cooling
PFC	Power factor correction
PID	Proportional, integral and derivative
PIR	Passive infrared
POE	Post occupancy evaluation
PPM	Planned preventative maintenance
PV	Photovoltaics

QM	Quality management
QS	Quantity surveyor
REHVA	Federation of European Heating and Air-conditioning Associations
RFI	Radio frequency interference
RIBA	Royal Institute of British Architects
RMU	Ring main unit
SCOP	Seasonal coefficients of performance
SEER	Seasonal energy efficiency ratio
SFP	Specific fan power
SSEER	System seasonal energy efficiency ratio
SSEES	School of Slavonic and East European Studies
TER	Target emission rate
TVOC	Total volatile organic compounds
UDP	Unitary development plan
UPS	Uninterruptible power supply
USGBC	US Green Building Council
VAV	Variable air volume
VRV	Variable refrigerant volume
VSD	Variable speed drives
VVVF	Variable voltage, variable frequency
WAN	Wide area networks

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Introduction

In recent decades there has been growing awareness of the environmental impact of man's activities, and concerted efforts to identify and address the key factors that give rise to the most damaging impacts. It has become clear that buildings are one of the principal sources of environmental degradation. This is primarily due to the carbon impact of the fossil fuels used to operate buildings, which is a major contributor to climate change. There is an imperative for those practising as building services designers to influence the design of buildings, and to plan their active engineering systems, so that carbon emissions are minimised. This requires an awareness of all the factors that give rise to carbon emissions throughout the life cycle of a building.

The design of buildings is a complicated process of synthesis and iteration involving a range of disciplines. Building services engineering is one of the principal design disciplines, alongside architecture and civil/structural engineering. Building services engineering is itself made up of a range of sub-disciplines, primarily mechanical and electrical engineering. Many of those entering the building services engineering profession are from traditional mechanical and electrical engineering undergraduate courses, and have usually had only limited exposure to the wider issues involved in building design more generally, and energy efficient buildings in particular. Many undertake master's degrees in building services engineering, or similar courses, which often provide an element of conversion into their new field. For buildings to be successful, it is essential for all design professionals to work in a collaborative way with mutual respect and a clear understanding of the wider context and common imperatives. An essential feature of courses in building services engineering should, therefore, be to impart sufficient awareness of the sustainability imperative, and the nature of the design process, together with the range of interdisciplinary influences that need to be resolved and developed into a satisfactory design resolution.

This book has largely arisen from a module in Brunel University's full-time and distance-learning MSc course in Building Services Engineering that covers the general issues related to building services design. In common with many undergraduate and post-graduate courses in the subject, individual mechanical and electrical building services systems are taught as separate modules. The building services design module brings together the necessary background on sustainability with an understanding of the design process and synthesis required to achieve integrated design for low-carbon buildings and engineering systems.

The book focuses on energy efficiency as a central and fundamental strand of a wider sustainable objective for the built environment. It can be considered as a general introduction to the subject, primarily aimed at students who have not previously studied built environment subjects. It does not cover the many other aspects of sustainability that are necessary considerations in building design; aspects such as materials, waste management, water management, transport policy, biodiversity, self-sufficiency as well as the more general environmental and societal aspects. It only covers sustainability issues related to designing for low-carbon performance throughout the life of the building. It assumes a basic understanding of the main mechanical and electrical engineering systems in buildings.

Building Services Design for Energy Efficient Buildings is primarily concerned with the strategies required when planning and designing low-carbon solutions for buildings. It only refers to those building services systems that are energy consuming; so it does not cover other non-energy systems that form part of the wide spectrum of building services engineering. For example, lifts are only covered in relation to energy and load assessment aspects. It only partially covers the background principles or detailed design processes for engineering systems, sufficient to convey the key energy efficiency aspects. There are numerous academic textbooks and institutions' guides that provide comprehensive coverage of these design aspects for individual systems (or groups of related systems), including heating, ventilation, air-conditioning, hot water systems, electric power, lighting, lift engineering and automatic control systems. Such books cover in considerable depth aspects such as comfort criteria, indoor climate systems, system concepts and analysis, plant and equipment sizing, health and safety aspects, ductwork sizing, pipework sizing, cable sizing, lighting design and so on. This book does not cover these detailed design aspects but is, instead, primarily concerned with the wider concepts of systems and the design approach that should be adopted. This is necessary so that a building and its systems can be developed as an integrated whole that minimises environmental impact; minimises usage of dwindling fossil fuel supplies; and is adaptable to the predicted changes in climate.

Chapter 1 provides a brief introduction to the background issues on the environmental impact of human activities, global warming and climate change; together with the need to maintain security of energy supply. The context is provided for energy and materials usage in the built environment, including the need for designs to adapt to address climate change impacts. This chapter outlines the imperatives for designing energy efficient buildings as a key strand of creating a sustainably built environment, and introduces key design concepts for sustainability.

Chapter 2 describes the design process, including a brief outline of the principal roles in a design team and how they should work together to create integrated solutions. Development of the design brief is a key activity and is described in some detail. The essential activities of the building services designer are described, together with key design considerations at each stage that can help in achieving low-carbon performance. A brief outline is provided for legislation and codes for designers, including health and safety management, together with quality management of the design process.

Chapter 3 describes a generic strategy for achieving energy efficient buildings, based on an energy hierarchy approach. This includes an initial focus on elements of passive design for the building envelope. A range of generic measures are described for active engineering systems and renewable technologies, which are explored in more detail in Chapters 5–9; together with combined heat and power and management regimes.

The Building Regulations in England and Wales Approved Document Part L is briefly introduced as an example of national regulations for conservation of energy.

A key requirement for undertaking design is an understanding of how existing buildings perform in practice, so that relevant operational feedback can inform the design for future buildings. Chapter 4 describes how a formal post occupancy evaluation (POE) can play a key part in optimising the energy and environmental performance of buildings. This includes case studies, methodologies for environmental assessment and European directives on building energy performance.

Chapters 5–9 describe design strategies for the main energy using engineering systems. Chapter 5 explains energy efficient methods of ventilation. This includes requirements and strategies, together with natural ventilation, ventilation for cooling and traditional methods of ventilation. Chapter 6 gives details on air-conditioning systems, including system classifications and types for different applications. A method is presented for system selection and evaluation. Chapter 7 describes the principal components of HVAC equipment, including plant for generating heating and cooling, heat pumps and solar thermal systems. Chapter 8 covers distribution of thermal energy, and measures for improving energy efficiency. This includes hydraulic systems, ductwork systems and variable volume circuits for optimal energy performance. Chapter 9 describes energy efficiency considerations for designing electrical systems, together with controls, metering and monitoring for all the energy using systems. This includes renewable technologies for electricity generation.

An essential part of engineering systems design, and a key component in the decision making process for designing and selecting appropriate engineering systems, is load assessment. Chapters 10 and 11 cover the key aspects of load assessment for thermal systems (heating and cooling), and electric power systems, respectively.

The active engineering systems must be integrated with the architectural and structural designs in such a way that promotes good energy performance over the life of the building. Chapter 12 outlines the key principles of space planning and coordination for services. This includes planning plant spaces together with vertical and horizontal distribution zones.

It is hoped that *Building Services Design for Energy Efficient Buildings* will be of use to those studying at master's level in building services engineering and related built environment, architectural engineering, sustainability and energy subjects. It should also be of use to those studying on the final year of BSc, BEng and MEng courses in these subjects. It is hoped that the subject matter will also be of more general use to practitioners in the field, together with architects and other building design professionals, as a useful text bringing together a broad coverage of building services design and energy efficiency matters in a single volume.

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Chapter 1

The imperatives for an energy efficient built environment

1.1 Introduction

This chapter provides a brief introduction to the key background issues related to sustainability in the built environment, primarily those arising from carbon emissions due to the use of fossil fuels. It starts by looking at the principal threats to the global environment and the need to undertake development in a sustainable way. The background issues of global warming and climate change are summarised, together with an outline of the predicted impacts which indicate the scale and urgency of the challenge. The UK targets for limiting carbon emissions are described, together with an indication of recent performance against the targets. In order to show the relevance of these issues for building services design, the carbon impact of the built environment is outlined. An important factor is the processes through which energy is delivered to buildings, including the key issue of energy wastage through conversion and distribution, and other impacts of using fossil fuels.

A separate impact of fossil fuel usage is examined through looking at the reduction in reserves available, together with the adequacy of infrastructures to meet the anticipated supply side and demand side of energy requirements in the near future. A further aspect of energy strategy relates to materials used in building construction and operation, and to identifying ways in which their impact can be reduced.

The final part of the chapter looks at general principles that apply to the design of sustainable products and services. These are put into context for buildings, with an emphasis on the need for a whole-life approach and to challenge prevailing solutions, with a primary focus on demand reduction.

It should be noted that this chapter focuses primarily on the carbon and energy aspects of sustainability, rather than the wider factors.

1.2 Principal threats to the global environment

To understand the imperative for sustainable development in the context of the built environment, it is necessary to start from a perspective of the wider nature and range of environmental factors that threaten man's continued habitation on Earth; and then identify those causes that specifically arise from the built environment. By identifying the priorities for attention, it is possible to focus on the key aspects related to design for the built environment, while accepting that a wider range of environmental factors will require attention to contribute to the broader objective of sustainability in practice.

A major study was undertaken by a group of scientists in 2009 to identify the principal environmental processes that could cause significant disruption to human life on Earth. The study, which was under the auspices of the United Nations, also sought to calculate boundaries for these processes which, if exceeded, could limit the planet's ability to sustain human life. Summaries of this study were reported by Foley (2010) and Pearce (2010), and identified nine key environmental processes:

- climate change
- ocean acidification
- stratospheric ozone depletion
- nitrogen and phosphorous cycles
- fresh water use
- biodiversity loss
- land use
- aerosol loading
- chemical pollution.

The study identified target values for all the processes (except for the last two, because it was felt that there was insufficient understanding to do this). Of the seven processes where targets were set, it was found that three processes have already passed their safe limit: climate change, biodiversity loss and nitrogen pollution. It was also found that the others were moving closer to their safe boundary level. For two of the processes – climate change and the increasing acidification of the oceans – the principal cause is increased levels of CO_2 in the atmosphere arising from mankind's use of fossil fuels (Foley 2010; Pearce 2010). As the movement of any of these key processes towards their threshold levels could result in significant environmental damage, the imperative for society is to ensure that each process should be maintained as safely within the boundary figure as is practically possible. While the processes and limits were presented separately, it was acknowledged that they were interconnected in many ways. For example, the increased acidification of the oceans could have a severe impact on their ecosystems, with implications for biodiversity; and as a consequence, threaten the food chain. A further consequence is that the ocean's ability to absorb CO_2 would reduce with acidification, with implications for the rate of climate change as a positive feedback relationship (Foley 2010; Pearce 2010). Climate change is likely to have implications for fresh water, biodiversity and land use.

The key message that emerges is that mankind now has a clearer indication of the limitations of the Earth's resources and their rate of usage. There is also better understanding about the ability of the Earth to absorb the waste and emissions arising from their use. It is incumbent upon society, therefore, to ensure that its activities are maintained within the limiting operational boundaries of the Earth's environmental systems.

The issues outlined above relate to the key environmental processes that need to be addressed on an urgent basis. It is, however, recognised that development in all senses needs to adopt principles that will allow continued and sustainable habitation on Earth. Sustainable development has been defined in the 1987 Brundtland Report as 'Development that meets the needs of the present without compromising the ability of future generations to meet their own needs' (UN 1987). This introduced the concept of sustainable development being a satisfactory balance between environmental protection, social equity and economic development, sometimes known as the 'triple bottom line', as shown in Figure 1.1. While there is a wide range of challenges involved in achieving such a balance (Drexhage and Murphy 2010), there is a prevailing scientific view that the most significant threat to a sustainable future is climate change arising from 'anthropogenic' (i.e. caused by mankind's activities) global warming. This is mainly due to the presence of greenhouse gases (GHGs) in the troposphere, as described in the following section.

1.3 The greenhouse effect, global warming and climate change

There are a variety of natural factors that have altered the climate of the Earth in the past, and there is a natural 'greenhouse effect' that has warmed the Earth's surface for millions of years (DECC 2012a). These natural factors cannot, however, account for the extent of warming that has been observed since 1990 (DECC 2012a). The evidence from the spatial pattern of warming, and the results of modelling, indicate this warming has largely been due to increased emission and accumulation of greenhouse gases (GHG) caused by mankind's activities. This has created an 'enhanced greenhouse effect', alongside which are feedback processes that cause amplification of the warming (DECC 2012a, 2012c).

The physics and mechanisms associated with the interaction between the Earth's atmosphere and fossil fuel consumption are, obviously, extremely complicated and well beyond the scope of this book. For the purpose of understanding the basic concepts and terminology related to climate change, a highly simplified approach is sufficient, as shown in Figure 1.2.

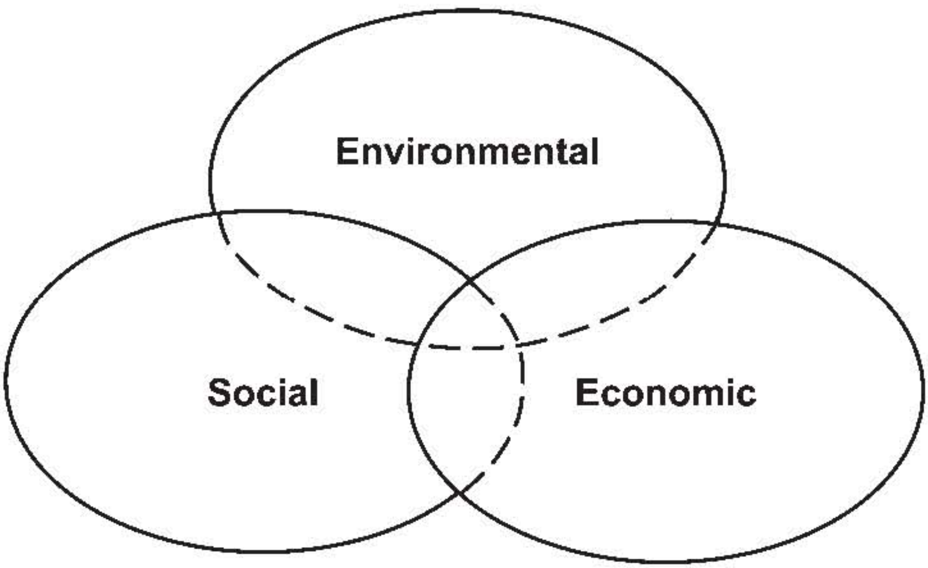


Figure 1.1 Sustainable development: the 'triple bottom line'

Source: UN 1987

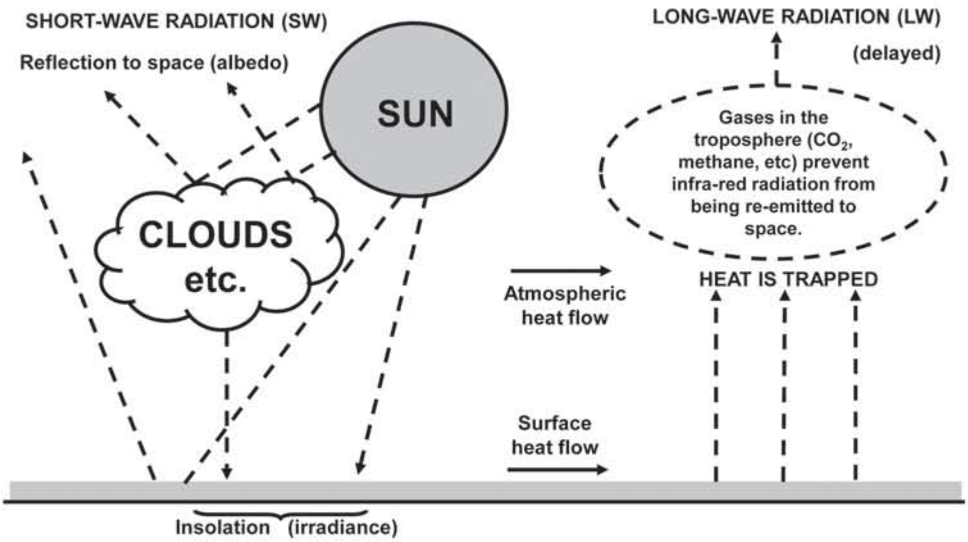


Figure 1.2 The greenhouse effect

Source: derived from Christopherson 1997: figure 4.1

The sun's rays are the sole energy input and the radiation is mostly in the visible part of the spectrum (Coley 2008). This short-wave, high-frequency radiation reaches the Earth's atmosphere where it is absorbed, reflected or scattered. A proportion (about 31%) is reflected back into space by the atmosphere, clouds and the lighter coloured areas of the Earth's surface. This fraction is termed the 'albedo' (Coley 2008). Therefore, the whiteness of cloud cover, and the relative lightness of the different parts of the Earth's surface play a significant factor in the proportions reflected or absorbed. The residual radiation heats the atmosphere and the Earth's surface. The relatively low temperature of the Earth's surface gives rise to long-wave, low-frequency (infrared) radiation back to space.

The radiation from the Earth is, thus, a mix of visible range that is directly reflected and infrared that is re-radiated. Over time, the Earth re-radiates an average 69% of incoming energy to space. The presence of certain greenhouse gases in the troposphere traps the heat and delays it in the atmosphere. Some of the energy is re-radiated back towards the Earth. This is known as 'back radiation', and warms the surface and the lower atmosphere. This warming phenomenon is known as the greenhouse effect (DECC 2012a, 2012c), as the GHGs create an effect similar to that created by the glass in a greenhouse, letting heat in but preventing it from escaping. These climate mechanisms are described in detail in various texts (Boyle 2004; Christopherson 1997; Coley 2008; Goudie 2000). To provide a perspective in terms of heat alone, it has been estimated that the total heat arising from all human activities is only about 0.01% of the solar energy absorbed at the surface (Goudie 2000).

The overall increase in heat that results is called 'global warming'. It is estimated that the Earth is warmer than it has been at any time during the past two thousand years (Coley 2008). The atmosphere close to the surface of the Earth has risen in temperature by about 0.75°C since about 1900, and much of this temperature rise, about 0.5°C, is estimated to have occurred since the 1970s (DECC 2012a). There has been other evidence of global warming in recent times, including rises in sea level and reduced levels of sea ice in the Arctic (DECC 2012c).

Global warming will affect the world's climate in numerous complicated ways, giving rise to climate change. 'Climate change' is a more useful term than 'global warming', because it conveys the understanding that the effect could bring about colder as well as warmer climate impacts in different locations, plus other climate disturbances. It is also necessary to distinguish between weather and climate. Weather relates to the short-term variability in a particular location, whereas climate relates to the long-term pattern of statistics for conditions in a particular region (Coley 2008). The term 'climate change', as used in this context, refers to a change in the climate that is identifiable and continues for decades or longer and often refers to changes arising from man's activities since the Industrial Revolution (DECC 2012a).

The principal international body on this subject is the United Nations Intergovernmental Panel on Climate Change (IPCC). This panel is made up of respected scientists from around the world, and has been publishing comprehensive reports every few years on the scientific viewpoint. The IPCC's 4th Report (also known as Assessment Report 4, or AR4) of 2007 was regarded as pivotal because it provided a consensus of certainty on the influence of human activities on climate change. The Report concluded that most of the global warming that has been seen since the mid-20th century is very likely to be due to the increase which has been observed in the concentration of GHGs caused by human activity creating an 'enhanced greenhouse effect' (IPCC 2007). It considers the probability to be more than 90% (DECC 2012a).

The most important greenhouse gases are carbon dioxide, methane, chlorofluorocarbons, nitrous oxide and ozone. The relative contribution of each gas to the enhanced greenhouse effect depends on its global warming potential and the level of concentration in the atmosphere. The relative contributions have been noted by Coley (2008):

CO_2	65%
Methane	20%
CFCs, HCFCs	10%
N_2O	5%

Because so much impact arises from CO_2 emissions, a key question is: what is the upper threshold of CO_2 that can be tolerated in the long term, and that can, therefore, be a target? Scientists have indicated that a level of 350ppm by volume would be a relatively conservative target. It is considered that this target would maintain the relevant processes on the safe side of the tipping points for the climate (DECC 2012a). It should be noted that the generally assumed figure for pre-industrial CO_2 is about 280ppm. It is estimated that CO_2 levels have risen by about 40% since the onset of the Industrial Revolution, and are now at about 390ppm by volume. The level is now higher than it has been for 800,000 years (DECC 2012a) and has been increasing at a rate of about 2ppm per year during the past decade. Scientists reckon that a reduction of 80% in carbon dioxide emissions below 1990 levels by 2050 will be necessary to halt the rise to an assumed acceptable level, typically related to a 2°C temperature rise (although there is continuing debate on the most appropriate target). Anything less than this reduction is likely to only slow the rate of accumulation. It is clear that, to prevent the most damaging climate change impacts, the level of CO_2 and other GHG emissions has to be stabilised and then reduced to well below the present levels.

The emission of CO_2 into the atmosphere is not the only environmental impact of using fossil fuels. Burning fossil fuels also emits sulphur dioxide and nitrous oxides and particulates, with considerable impact, including 'acid rain' and air quality (Coley 2008). These emissions reduced considerably in the period from 1990 to 2007 (DEFRA 2009a), and have been overshadowed by the far more pressing emission of CO_2; but they have not disappeared.

There are many other direct consequences arising from energy use, such as resource depletion, despoliation of the landscape, heat, radiation, noise, etc.; together with indirect consequences (Coley 2008). Other environmental issues related to energy consumption are the manufacture, use, disposal and recycling of materials, which are discussed in Section 1.9. A separate environmental impact arises from the use of chemicals in the refrigerants of air-conditioning systems. These have identifiable ozone depletion potential, global warming potential and total equivalent warming impact.

1.4 Likely impacts of climate change

There has been continuing debate in the scientific community during the past 15 to 20 years about the likely impacts of global warming and the associated climate change. The IPCC's 4th Report (IPCC 2007) looked at the possible outcomes from a variety of scenarios. It predicted that, if GHG emissions were to continue with no abatement, by the end of this century the average global temperatures could rise by between 1.1°C and 6.4°C above the 1990 levels. This is for the range of 'likely values' related to all the scenarios examined (DECC 2012a). The Report's predictions provide a stark picture of the impact on global climate. However, due to the need to reach a consensus between countries, the Report was considered to be inherently conservative and it only deals with average temperatures.

While much about climate change is uncertain due to the complexities involved, Le Page (2011) has provided a useful overview of those aspects where there is a good level of certainty and those where there is less certainty, which can be conveniently summarised as:

- greenhouse gases are warming the planet (but it is unclear how far GHG levels will rise);
- other pollutants are cooling the planet (but it is unclear how great their cooling effects will be);
- the planet is going to get a lot hotter (but it is unclear how much hotter);
- it is not clear how the climate will change in specific regions (although in general high latitudes will get much warmer and wetter);
- the sea level is going to rise several metres (but it is unclear how quickly it will rise);

- there will be more floods and droughts (but it is unclear whether there will be more hurricanes);
- it is unclear if and when tipping points will be reached, and how serious a threat global warming is to life.

Without mitigation there is a risk of temperature rising to more than 2°C above the level before the Industrial Revolution. It is considered that the impact would be significant and it could possibly cause irreversible damage to ecosystems (DECC 2012a, 2012c). The rise in sea levels could inundate low-lying areas of land (Boyle, 2004). The predicted impacts would be severe across the three main focuses for sustainability – environmental, social and economic. It is likely that the biggest impacts will be in developing countries, which are often highly exposed and vulnerable to change and less able to adapt (DECC 2012c); although the cause to date is largely due to carbon emissions from the developed countries.

The potential economic impact of climate change was assessed in the Stern Report of 2006. This estimated that without mitigation, the cost impact could be from 5 to 20% of gross domestic product (GDP), globally, for each year. It also reported that the cost of reducing emissions to prevent the worst impacts could be much lower, at about 1% of global GDP each year (DECC 2012c).

1.4.1 UK targets and performance for energy and carbon

The UK has international and domestic targets for reducing emissions of greenhouse gases. Under the Kyoto Protocol, there is a target to reduce GHG emissions, over the period 2008–12, to 12.5% below the base year level of 779.9 million tonnes CO_2 equivalent. This is legally binding. Average annual emissions must be below 682.4 million tonnes CO_2 equivalent during this period to meet the target (DECC 2012e). Under the UK Climate Change Act 2008, there is a target to reduce GHG emissions in 2050, by at least 80% below the base year level. The base year for CO_2 is 1990. There is also an interim target to reduce emissions by at least 34% in 2020. These targets are legally binding. The Act also included a carbon budget which requires total GHG emissions to be less than 3,018 million tonnes CO_2 equivalent during the period 2008–12, with further reductions in the budgets for subsequent four-year periods up to 2027 (DECC 2012e). These budgets set legally binding limits for each five-year period.

The UK's emissions of the basket of greenhouse gases in 2010 were about 590 million tonnes of CO_2 equivalent. This represents a reduction of about 24% since 1990. For carbon dioxide the 2010 emissions of 499 million tonnes of CO_2 equivalent was about 15% below the 1990 level (DECC 2012d). All such figures need to be seen in the context of other factors that might be influential on CO_2 performance. Since the 1990s, there has been a general decline in UK manufacturing output and a growth in imports of manufactured goods, as well as a widescale move from coal to gas; so the figures do not necessarily reflect a reduction in relation to economic activity.

The European Council agreed a common strategy to address climate change and security of energy supplies in 1999. The EU's Renewable Energy Directive of 2009 sets a target for the UK of 15% of final energy consumption to be from renewable energy sources by 2020. In 2011, 12% of the UK's energy was obtained from low-carbon sources. This has risen from 9.4% in 2000. Nuclear power provided 7.7% and bioenergy 2.7%. Wind was the next highest at 0.7%. The UK's proportion of energy from low-carbon sources in 2008 was well below the EU average of 21% (DECC 2012b). The provisional figures indicate that 3.8% of final energy consumption was from renewables (DECC 2012b); so there would need to be a major increase to meet the target of 15% by 2020.

1.5 Environmental impact of the built environment

In order to understand its relevance to building services engineering design, the wider background of contemporary environmental challenges outlined above needs to be set in the context of the built environment.

It is useful to see energy in the built environment in the context of all other usage. A breakdown of UK delivered energy consumption in 2011 is shown in Figure 1.3. The services sector figure includes agriculture, but this has traditionally been only about 1%, so buildings are responsible for about 40% of energy consumed. Additional environmental impacts arise from energy used in construction materials and the construction process; and from waste. In 2006, 36% of the UK's total waste, amounting to 102.8 million tonnes per year, came from construction, demolition and excavation (DEFRA 2009b). This was the most for any sector and is a major cause of degradation of the land.

An important factor to appreciate is that the turnover of the building stock in the UK is relatively low, at approx. 3% per annum. Therefore, while there is inevitably a focus

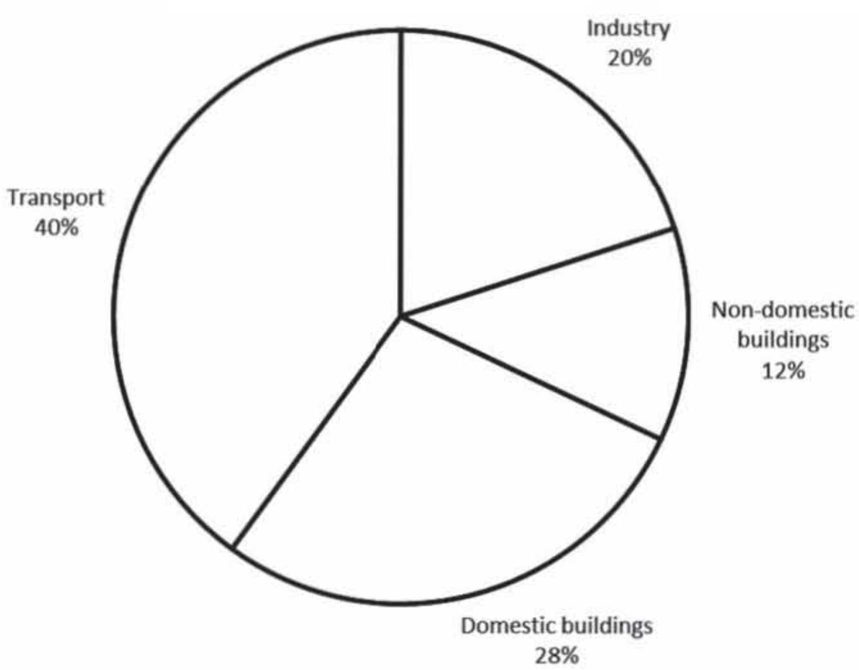


Figure 1.3 Total UK final energy consumption 2011

Source: derived from DECC 2012b

on sustainable construction for new buildings, the greatest potential for reduction in carbon emissions is actually from refurbishment of existing buildings, particularly in the domestic sector. There were 25.7 million households in the UK in 2006, compared with 19.0 million in 1971 (DEFRA 2009a). This provides a social context, as approx. 60% of this rise related to the increase in single-person households (DEFRA 2009a).

It is also useful to see the sustainability challenges in the context of the nature and growth of the urban environment in a global sense. The UN estimated that by 2008, half of the world's population lived in towns and cities (Barley 2010). This is a trend that is likely to continue. Recent studies of the relative impacts of urban and rural areas have shown that urban areas are efficient in land use, as they only take up about 3% of the land surface of the Earth (Barley 2010). Moreover, because cities have high population densities, they provide an opportunity for efficient energy, water and sanitation infrastructure, together with viable public transport networks, all of which reduce the relative CO_2 impact (Barley 2010). Studies of CO_2 emissions in the US have indicated that citizens of New York produce, on average, only about 30% of the average emissions for the country (Barley 2010). In the UK, government statistics for CO_2 emissions for local authority areas for 2007 show that most of the major urban areas had per capita emissions of less than 7.1 tonnes of CO_2, whereas for many remote rural areas the figure was above 10.1 tonnes (DEFRA 2009b). For the majority of the London boroughs, the figure was below 6.3 tonnes. These figures are on an end-user basis and incorporate all industry, commerce, domestic and land use emissions. Overall, the figures are tending to decrease.

A further impact of the growth of urban areas is the difference in thermal response when compared with rural areas. The surfaces of a city absorb more solar radiation during the day, and release it at night. This is due to the high thermal capacity and arrangement of high walls and dark-coloured roofs in city centres, as outlined by Goudie (2000). The densely built-up centres of cities provide the highest temperature anomalies, generally called the 'urban heat island effect' (Christopherson 1997; CIBSE 2007; Goudie 2000); thus, urban expansion can have localised impacts on climate.

To limit environmental impacts, the most direct focus for building services engineers will be on how these issues can be addressed for individual buildings, or groups of buildings, as part of a site development proposal. In terms of wider solutions, however, there will be a need to make our towns and cities sustainable. It is, therefore, useful to see the future scenario as requiring sustainable urban planning for communities whose arrangement and facilities encourage sustainable lifestyles; and to think conceptually about a built environment, rather than groups of buildings. At its most simplistic level this would involve the relationships between buildings and the spaces between buildings; and how they perform as a unified whole. In a wider sense, the built environment can be considered as the complex interrelationships of all the elements and influences from the built forms mankind has created. While there has been high societal awareness of the environmental impact of transport, the awareness of built environment impact has generally been low (Smith *et al.* 1998), although this has been changing in the past decade. Smith *et al.* (1998) have proposed that 'the challenge to contemporary thinking on the built environment, is the adoption of more holistic models of development management and planning which recognise this complex web of interrelationships'.

1.6 Processes for energy usage in buildings

To address the energy and carbon issues related to buildings, it is necessary to understand the processes through which energy is delivered for consumption in buildings. In particular, it is necessary to understand the inherent inefficiencies of conventional energy delivery. The inefficiencies of energy supply do not relate to generation processes alone, but to the whole delivery process from source to consumer.

Energy conversion and distribution inevitably incur losses and it is important to understand the true operational efficiency of an energy system as energy usage in buildings usually involves a diversity of fuel inputs and systems of utilisation. Energy consumption information is only really meaningful if it relates to primary energy on an annual basis, so that it represents the operational performance taking account of diurnal and seasonal patterns and influences. It should not be confused with load assessment. An important concept to understand in relation to the efficiency of energy systems in buildings is the difference between 'primary energy' (the energy of the fuel input at source) and 'delivered energy' or 'final energy' (the energy delivered to a consumer); and to refer to these correctly when assessing energy systems or using figures. Carbon emissions relate to the primary energy.

The high carbon impact of electricity is a consequence of the way in which it is generated, which is dominated by thermal power stations using fossil fuels, as shown in Figure 1.4. Most conventional thermal power stations usually have conversion efficiencies of 30–35% at best, so about 65–70% of the primary fuel input is wasted as

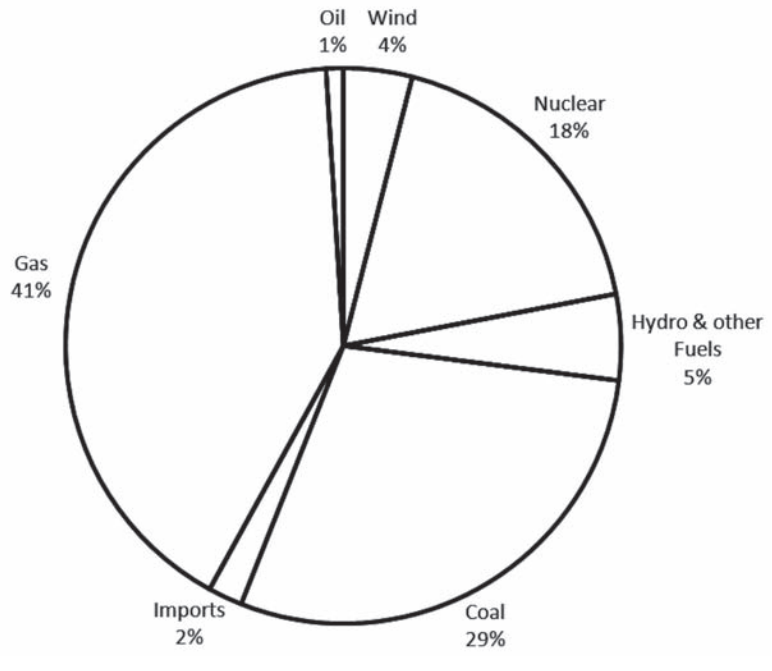


Figure 1.4 UK's total electricity supplied by fuel type in 2011

Source: derived from DECC 2012b

heat to the atmosphere, sea, or rivers. The overall efficiency will be higher than the efficiency of thermal power stations alone, due to the contribution from low-carbon sources: nuclear and renewables. There is continuing evolution of the fuel mix for electricity generation. Since 1990, there has been a major increase in the use of gas, and a decline in the use of coal. Since 2000, there has been an upward trend in the supply from wind, due to the increased levels of capacity (DECC 2012b). The proportion of generation from all renewable energy sources was 9.4% in 2011 (DECC 2012b).

The useful electricity generated is then passed through an extensive distribution system – the transmission grid and local networks – before it reaches consumers. This gives rise to further distribution losses, typically in the order of 10–12%. There is also some energy industry usage. The final delivered energy to all consumers (as measured at their intakes) is, therefore, only a modest proportion of the total primary energy input. The specific efficiency balance between primary and delivered (final) energy will vary on a diurnal and seasonal basis; as the generation fuel mix varies year by year; and as the infrastructure and operating arrangements change. It is clear that there are inherent inefficiencies on the energy supply side in general, although this is most pronounced for electricity. In 2011, 32.1% of all UK inland energy consumption was related to conversion and distribution losses, and energy industry use (DECC 2012b), so only about two-thirds of primary energy was delivered to meet energy needs.

The CO_2 content of electricity will vary with the mix of primary fuel used in generation. In the UK, the CO_2 content of electricity is considered to have fallen in recent decades, largely due to the move from coal to gas and some renewables and increased efficiency in generation. The primary energy carbon factor used in Building Regulations Approved Document Part L 2010 for gas is 0.198kg CO_2/kWh, compared with the figure for electricity (from grid) of 0.517kg CO_2/kWh. On this basis, electricity has more than two-and-a-half times the carbon impact of gas. There is continuing debate about the appropriateness of the carbon emission factor for grid-derived electricity; the extent to which it properly represents the anticipated carbon intensity; and its suitability for comparing energy system options, as described by Jones and Shaw (2011). This is also related to the need to address the required upgrading of grid infrastructure, as outlined in Section 1.7.

All fossil fuels have an environmental impact related to the resources they take from the Earth, and the emissions they give out to deliver energy to consumers. These are set out in a simplified sense for electricity in Figure 1.5, which illustrates the wide range of impacts. It is also necessary to consider the extensive range of materials used throughout the energy generation and distribution process, covering industrial facilities such as mines, rigs, pipelines, power stations, transmission lines, refineries and their related roads, railways, shipping, transport, etc. (Coley 2008). This would include materials such as steel, concrete, copper and plastics. Each of these materials is produced by an industrial process that has an environmental impact in a similar way to the extraction of the fuels. A useful indicator of the effectiveness of an energy generation technology is the 'energy payback ratio' which relates whole-life energy expended in the facility's materials, compared with the useful energy produced during the plant's lifetime (Coley 2008). It has been estimated that the energy payback ratio for fossil fuel power stations is low, at about 5–7 for coal, and 5 for natural gas (Coley 2008). This provides a good illustration of the need to take account of all relevant factors when considering the environmental impact of any particular system or activity.

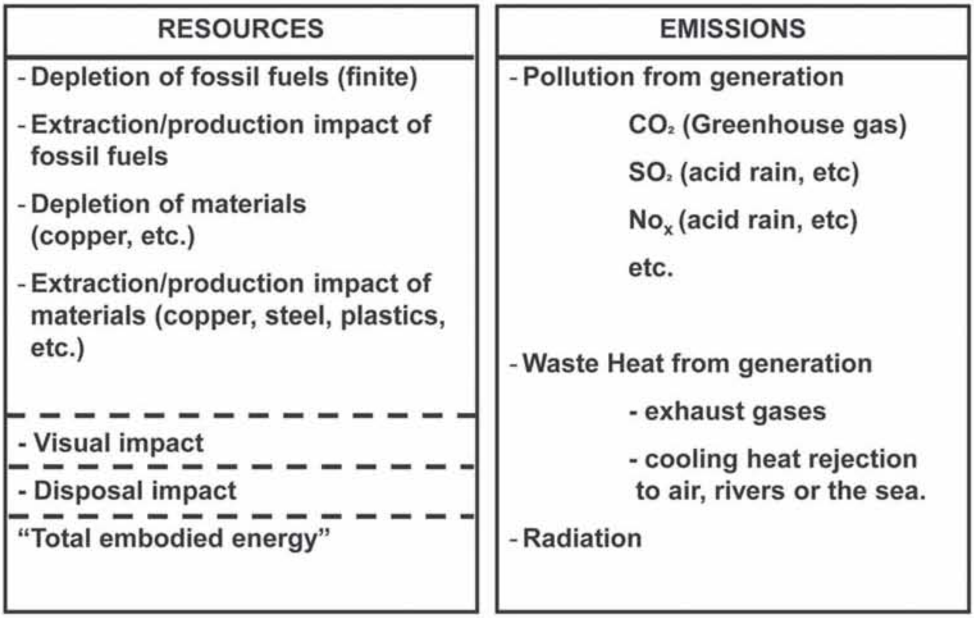


Figure 1.5 The environmental issues in electricity generation and transmission (assuming conventional generation technologies)

Source: author's elaboration[1]

Figure 1.6 is a notional Sankey diagram for the annual energy consumption of a building with a traditional energy provision, using grid-derived electricity and gas-fired heating. It relates to the end-use proportions for commercial offices shown in Figure 3.8, and is intended as an example format only of a typical annual energy flow format. In this example, the delivered energy to the building is shown for simplicity as 100 units. There would be some losses within the building due to distribution, and heat generation from a boiler system but these have been omitted for simplicity. The actual useful energy usage would, therefore, be a little lower than 100. The diagram shows the losses in generation and transmission that are typical in the case of conventional electrical energy. In this case, 125 units of primary electrical energy are required to give 42 units of delivered electrical energy. It can be seen that the total primary energy input to the building is 188 units. So nearly twice as much primary energy is required to provide the total delivered energy.

While Figure 1.6 represents accumulated energy over a year, rather than the daily energy balance, a rational perspective would question the logic of throwing away waste heat from electricity generation that, in this notional example, is greater than the whole thermal energy requirements for the building. It is obvious that, if the waste heat could be made available in the building, it could offset the separate energy demand from gas for heating and hot water services, significantly reducing fossil fuel consumption, CO_2 emissions and fuel costs. This illustrates the wasteful overall energy performance of uni-generation as used in conventional power stations. In comparison,

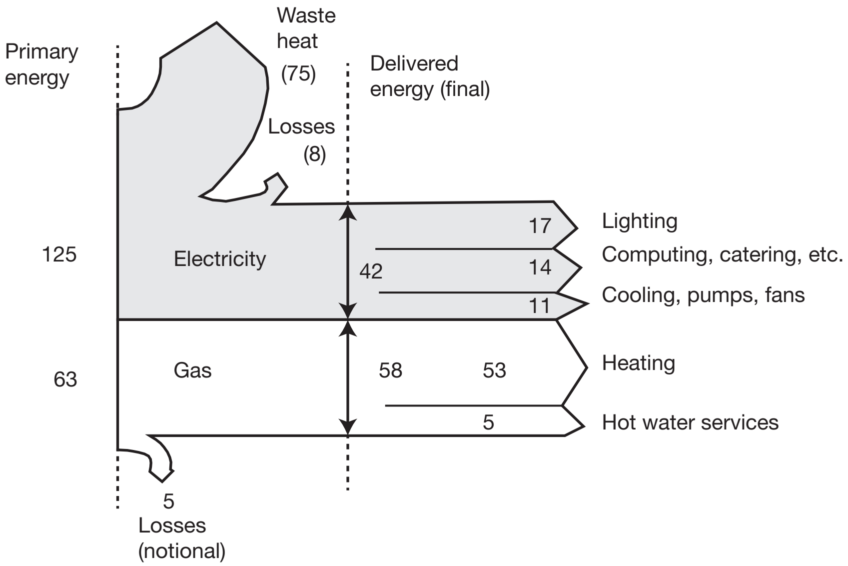


Figure 1.6 Notional Sankey diagram for commercial offices (not to scale)

a co-generation approach using a combined heat and power (CHP) plant recovers a large proportion of the heat that is normally wasted in electricity generation, which is then available (in suitable applications) for use in a local heating system, a district heating system or for process purposes. Figure 3.12 shows a notional power balance for a small gas-fired CHP plant with an efficiency of 80%. For some CHP plants the optimum operating efficiencies can approach 90%. It can be seen that the strategy for energy supply is an important starting point for low-carbon design.

1.7 Fossil fuel reserves, adequacy of infrastructure and security of supply

Fossil fuels are a finite resource. Whether we consider coal, oil or gas, these fuels have been created in complex organic and geological processes lasting millions of years. The depletion through usage as a fuel has been taking place at a significant rate since the Industrial Revolution. Exploration has continually identified new reserves, but these are increasingly in locations where ‘winning’ the fuel is ever more difficult (Quaschning 2005) and where there is often a risk of creating environmental damage. As these locations are often in areas of considerable remoteness, natural beauty and ecological importance, extraction of fuels is likely to have increased environmental impact. It has to be accepted that there are both known and unknown reserves (Quaschning 2005). Differing views prevail about the extent of unknown reserves, but there is a view that availability of fossil fuels can only be extended by decades at best (Quaschning 2005). So, notwithstanding any of the other environmental issues related to fossil fuel usage, there is the fundamental issue that reserves will simply become unable to meet demand, so security of supply is threatened. Moreover, in the near term there are complicated geo-political issues related to the locations of the major sources of oil and gas, which could have an impact on reliability of supply in some parts of the world, and further threaten security of supply.

Alongside the limited reserves of fossil fuels, there are serious concerns about Europe's energy infrastructure – the grids for electricity and gas distribution – and their suitability to maintain the necessary flow of energy from generation locations to consumer locations in the short term. In the UK, there are concerns that there might be future power shortages due to a number of factors, including whether the energy market would be able to deliver secure and sustainable supplies in the coming decade. This includes concerns over the infrastructure of electricity generation plant and transmission systems, and its urgent need for upgrading. The infrastructure aspects include its lack of suitability for incorporating the proposed large-scale renewable generation, including offshore wind generation; and also the need to replace the ageing nuclear capacity and other generation plant that is nearing the end of its planned life.

An indication of the availability of energy supply to meet demand is the operating margin between the maximum supply capacity and the maximum demand. In the case of electricity, there was a major increase in electricity consumption from approximately 242TWh in 1980 to approximately 340TWh in 2000 (DECC 2012b) which provided a stimulus for new generation capacity, primarily gas-fired power stations. More recently there has been a reduction in demand. While this is welcome from an environmental perspective, it is likely to affect the attraction of commercial investment in new power plants. In 2011/12, the total electricity generation capacity was about 43% above the simultaneous maximum demand, i.e. an operating margin of 43% (DECC 2012b). While this might seem like a satisfactory picture, it does not take account of the major replacement of generation plant, including all nuclear power stations that will be required over the next decade or so. Because such a high proportion of UK electricity generation is from gas (about 46%), its reliability is strongly linked to gas security.

There was an increase in gas consumption from approx. 500TWh in 1980 to approx. 1100TWh in 2000 (DECC 2012b), some of which was due to the growth in gas usage for electricity generation. Since 2004, there has been an overall decline in consumption (DECC 2012b). The key issue for the UK's energy security for gas supplies is the sharp fall-off in output from the UK's controlled sources – primarily natural gas from the UK continental shelf. In 2011, production was 58% below the record level in 2000; and the 'proven and probable reserves' in 2010 were less than half the figures in 2000 (DECC 2012b). As a result, the UK is increasingly reliant on the import of gas in order to meet demand. In 2011/12, the forecast maximum gas supply was 60% above the actual maximum gas demand (DECC 2012b) which seems to indicate a good level of reliability. However, the factors affecting security of energy supply are complex. While consumption of electricity and gas has been falling, and gas and electricity capacity margins seem healthy, it is not possible to predict the impact of outdated plant and reduced reserves of controlled gas supplies. It is also imperative to retain some gas capacity for those uses for which it is essential, due to its practicality, such as domestic supplies.

These concerns about reserves, infrastructure and hence security of supply are reason enough to require a concerted endeavour to reduce fossil fuel consumption (Quaschning 2005). Taken together with the issues related to climate change, they provide a clear imperative to drastically reduce consumption and reliance on fossil fuels.

1.8 Materials usage and embodied energy

The preceding sections have mainly focused on the environmental impact of operational energy consumption in buildings that gives rise to CO_2, and hence contributes to climate change and reduction in fossil fuel reserves. Another important consideration, however, is the impact of the usage of materials within the built environment. Materials themselves require energy in every aspect of their life cycle, from extraction, transportation, production and delivery, to construction, maintenance and (eventually) demolition, disposal and recycling. This energy is known collectively as 'embodied energy' or 'embodied carbon'. Embodied energy has been defined as the total primary energy consumed by a product or service from both direct and indirect processes (BSRIA 2012). Embodied carbon is the amount of CO_2 emitted by a building, product or system during the whole-life cycle (BSRIA 2012). As with operational energy, embodied energy involves inputs and emissions. The Inventory of Carbon & Energy database (Hammond and Jones 2011) includes these examples of typical levels of embodied energy for materials widely used in the industry:

- Primary glass: 15.00 MJ/kg
- Steel: 20.10 MJ/kg (general UK (EU))
- Copper: 42.00 MJ/kg (EU tube and sheet)
- PVC: 77.20 MJ/kg (general)
- Aluminium: 155 MJ/kg (general)

For modern buildings and their engineering services, the embodied energy in materials has been estimated to typically represent about 10% of the total energy usage during the life of a building, the rest being operational energy. It is anticipated, however, that as operational energy usage reduces due to the adoption of carbon mitigation measures, the proportion of whole-life energy (or carbon emissions) due to embodied energy will increase. There is, therefore, an increasing focus on materials selection and usage to further reduce carbon impact.

The relevance of material usage as one measure of the effectiveness of a conventional energy generation technology was outlined in Section 1.6. Another important aspect requiring consideration of embodied energy is the viability of renewable energy systems. To take account of the embodied energy in the renewable technology equipment, it is necessary to assess the 'energy payback' in addition to the financial payback. This will show how long it will take for the renewable technology to deliver sufficient 'free' energy to offset the energy expenditure that has been incurred by the materials throughout their life cycle. There is, quite obviously, no benefit in incorporating renewable technologies if they take much of their expected life to recover the energy expenditure that they have already incurred in their usage. In such cases, it would be misleading to view their contribution as a low-carbon feature.

The wider consideration of materials that is relevant to the construction industry is to re-think the whole approach to materials usage during the construction and installation processes, so that materials efficiency is designed into the system from the outset (CIBSE 2007). This is in addition to the desirability of using materials that are environmentally benign and derived from local, sustainable sources. In industrial nations, material usage in construction has traditionally been inefficient, and it has been estimated that waste from building accounts for 50% of packaging and 44%

of landfill (Birkeland 2002). There has been a poor record of recycling in the UK, with a high proportion of waste disposal to landfill sites compared with many other European countries. In 2008, around 54 million tonnes of waste was disposed of in landfill. This represented a decrease of 33% since 2001 (DEFRA 2009b), but is still higher as a proportion than in some other European countries.

There is a new focus on planning the processes and methodologies during a building's life cycle so that waste is minimised and recycling is maximised. The sustainable approach is for all materials to be seen as a useful resource, and utilised accordingly, so that there is no longer a concept of 'waste'. This will include reducing obsolescence of products and increasing their longevity – doing more with less – and using local materials and skills (Smith *et al.* 1998). To promote a sustainable approach, construction projects should have a comprehensive materials management plan as part of their whole-life methodology. Current legislation for carbon emissions only covers operational energy; however, future legislative developments may include embodied energy in materials.

1.8.1 The need to plan for adaptation

It should be recognised that the full effects of greenhouse gases take a considerable time to create their impact, with CO_2 remaining in the atmosphere for about 100 years (Goudie 2000). It is, therefore, inevitable that climate change will arise from CO_2 that has already been emitted over previous decades. Even if all emissions of GHGs were to cease now, it is estimated that there would still be unavoidable further warming of about 0.6°C (+/–0.3°C) (DECC 2012a). This will have a considerable impact on the built environment. It means that, as well as a focus on mitigating carbon emissions to minimise future impacts, building services engineers will also be involved in adaptation strategies so that buildings can cope with the anticipated climate change impacts over the coming decades. So, for designers in the built environment, climate change should be considered as presenting a dual challenge of 'mitigation and adaptation'.

There is no certainty on the climate change impacts, but predictions include a general increase in temperatures; increased intensity of rainfall and wetter winters; drier summers; and increased daily mean wind speeds in winter (CIBSE 2007). It is also likely that there will be enhanced effects of 'urban heat islands' (CIBSE 2007), as outlined in Section 1.5. While there will be a need for specific design considerations for each predicted impact, more generally there will be a need for design to allow adaptability in the future. This is likely to include contingency allowances, such as additional space in plant rooms (CIBSE 2004a) and adopting a more flexible and modular approach to systems design to aid durability.

1.9 Key design principles for sustainability and carbon mitigation

1.9.1 Developing a holistic approach

To develop a suitable approach to the design of building services for minimising carbon emissions, it is necessary to adopt some general concepts that could apply equally to the design of any product or facility. The principles are much the same for sustainability in the wider sense as for the more focused attention here on carbon reduction. Concepts that can help in the understanding and development of a more sustainable approach are:

- *Awareness*. Engineers require an awareness of the background issues related to the built environment, climate change impacts, carbon mitigation and adaptation. This is so that they can contribute to astute decision making and see energy and carbon in the wider context of sustainability.
- *Interrelationships*. The physical interrelationships between energy and materials usage in buildings and their carbon and environmental impacts.
- *Interconnectedness*. People, engineering systems, buildings and the environment are interconnected, so it is useful to have a wider systems-type perspective. The starting point is people and their behaviours, and the ways through which they interact with the engineering and building systems.
- *Holistic whole-life approach*. Buildings should be seen as complex, multi-faceted entities the success of which must be judged on several levels, including aesthetic, environmental impact, functional performance, health and comfort of the occupants, and longevity. It is possible to recognise the wider whole-life potential for mutual benefit and synergy between the different aspects. A broad outlook will overcome the narrow decision making that has often arisen from specialisation and entrenched viewpoints.
- *Commitment*. While there are regulatory frameworks in place to set targets for minimising carbon emissions, the creation of a successful low-carbon built environment that is suitably adapted for climate change will, ultimately, depend on individual and collective commitment to make it happen.
- *Collaboration and communication*. All aspects of the building life cycle involve close teamwork across different organisations and disciplines. It is essential that a collaborative approach is adopted from the outset. Clear and professional communication is a key element to ensure that concepts and proposals are understood, as different cultural backgrounds can differ widely in their understanding and interpretation of the issues.

It has often been said that sustainability is better considered as a journey rather than a destination. A good conceptual starting point is the well-known mantra of 'reduce, re-use, recycle'. This is important for establishing the priority order for attention. It is always preferable to reduce the demand, or the need, for something at the outset through critically questioning the root cause that creates the demand. Only when the demand has been reduced to the practical minimum level to satisfy needs should the focus switch to re-use of the product or service. It is important to understand that re-use means using something again in its existing form, for its original purpose, and therefore involves some further usage of energy and materials. Recycling usually involves considerable materials, energy and cost debits to return something otherwise discarded into a usable commodity. It should be seen as the third priority and is much less attractive than reducing or re-using.

Thus, by, applying the 'reduce, re-use, recycle' principle, the starting point is always to reduce demand, and to do it rigorously. An important point is the finite reserves of fossil fuels and growing concerns at security of supply. As previously outlined, even if one were to disregard the paramount environmental issues related to the predicted impacts of climate change, there would still be a compelling need to reduce fossil fuel consumption due to the other resources and emissions impacts, and to maintain security of diminishing fossil fuel supplies into the future.

In a broader sense, to achieve the scale and speed of improvements required, it is likely that the approaches to sustainable design will need to extend to a 'systems thinking' level (Stasinopoulos *et al.* 2009). A 'whole-system approach' has been described as one in which active consideration is given to the interconnections between subsystems and systems, and where solutions seek to address multiple problems concurrently (Stasinopoulos *et al.* 2009). Under this type of approach designers have to think not just beyond the scope of their discipline, or even the integrated disciplines in building design, but to the much wider systems' relationships between occupants, processes, buildings, infrastructure and environment. The goal of such an approach is to consider the whole system, in its environment, throughout its whole-life cycle (Stasinopoulos *et al.* 2009). Birkeland (2002) notes that 'we need to redesign not only the built environment, but the nature of development itself'. The breadth of such an all-embracing approach is well beyond the scope of this book, but the underlying principles inform many of the proposals.

As a simplistic example of how a systems-type approach might work, we could consider the engineering systems and energy needs for a printing machine that is operating almost continuously within an office environment. A narrow approach would see this as a fixed client design requirement; develop a suitable ventilation system to deal with the particulate emissions and heat generated; and accept the environmental impact of operational and embodied energy, and the less than satisfactory air quality. Systems thinking would involve analysing relationships and looking for better questions to seek prevention (Birkeland 2002). A systems approach would explore the business process and behaviours to see whether extensive printing was really required, or whether it could be located elsewhere; and potentially create a solution requiring less usage of carbon for energy and materials (including paper), and with better air quality within the office area.

As building services engineers seek to address sustainability at the briefing stage, it is necessary to understand the fundamental impact of occupancy behaviour on the eventual environmental impact. A traditional approach largely accepts the building's function as being pre-ordained and the designers seek to accommodate the client's defined requirements with the minimum impact. A more participatory systems-type approach is to seek ways to address the root cause by encouraging behaviours that will minimise the need for active systems, operational energy and materials. So, the designer's attention focuses initially on the human activity behaviour, ergonomics and any associated business processes.

Related to the whole-systems approach is a deeper ecological awareness that requires changing the way people think, and seeing the way we live, and our environment, as part of an ecosystem (Pearson 2005). Wines (2000) and Pearson (2005) describe buildings that have been designed to be harmonious with their environment by adopting these organic concepts.

Some of the concepts outlined above may appear, at first sight, to be too abstract and aspirational for such a pragmatic field as engineering. As solutions are sought for our future buildings – and the built environment more generally – it will be necessary, however, to have a mindset that questions and challenges prevailing technological solutions in a creative but pragmatic way.

1.9.2 Harnessing ambient or renewable energy

Many locations are likely to have some potential for ambient or renewable energy, although this will vary considerably from location to location. For an appreciation of the potential, it is worth starting by looking at solar power, which is the single energy input driving the Earth-atmosphere system and the most significant source of renewable energy (Christopherson 1997; Quaschning 2005). Figure 1.7 provides a much simplified conceptual illustration of global energy potential and usage with the area approximating to quantity. The total annual solar energy received is about 9,000 to 10,000 times greater than the present annual primary energy demand (about 409,000 million GJ) (Coley 2008); even allowing for the present highly wasteful usage of energy. Yet, to meet the demand, developed societies have mainly used finite, polluting and costly energy reserves – with their associated impacts – rather than the free, clean and perpetual energy from the sun. The sun provides radiant power of about 1kW/m^2 when directly overhead, with a clear sky. The amount of radiation received will vary depending on location – and hence the solar path variation throughout the year – as well as the extent to which clear or overcast conditions prevail. Examples of average annual solar radiation on a horizontal surface at ground level (Christopherson 1997) are:

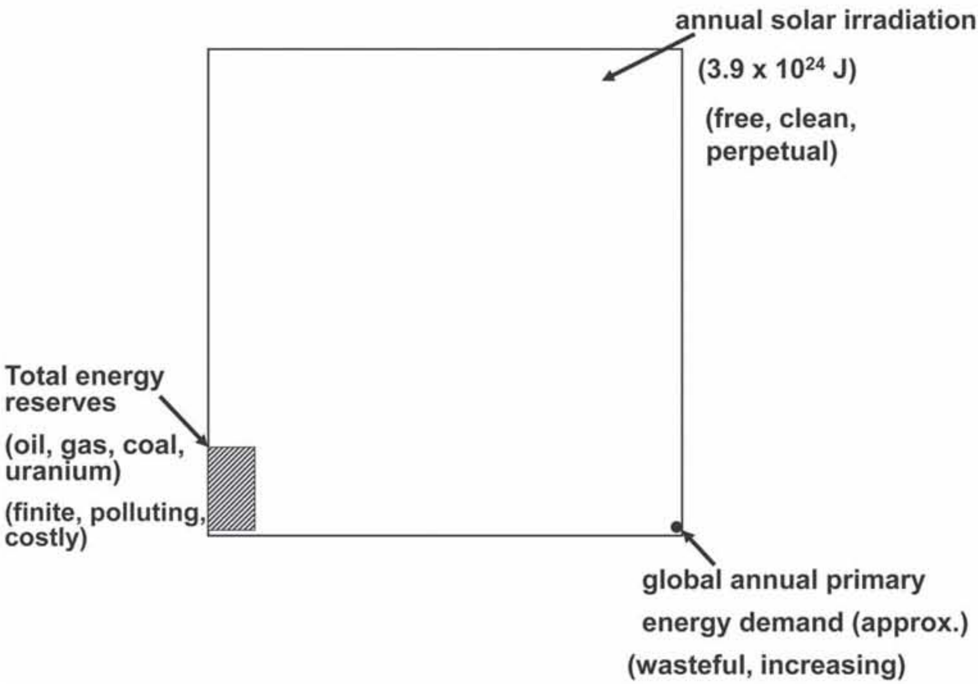


Figure 1.7 Global energy in perspective

Source: derived from Quaschning 2005: Figure 1.9

• UK	90–125W/m^2
• Spain	160–220W/m^2
• North Africa/Arabia	240–280W/m^2

The average for the whole planet is about 240W/m^2 (Coley 2008).

There are several interesting statements (derived from simplistic, average pro rata calculations) that can be useful if understood in context. For example, in one hour the Earth receives sufficient energy from the sun to power mankind's activities for about twelve months.

It is, of course, not always practical to utilise available ambient energy. A key part of the design strategy is to assess the potential usage of ambient energy in the context of the other options and design imperatives, to reduce usage of fossil fuels.

1.9.3 Adopting a whole-life approach

An important concept for sustainability is to address issues, and make decisions, with respect to the whole-life cycle of the building and its services. This whole-life approach is equally applicable for any manufactured product. Figure 1.8 shows a much simplified building life cycle; the inception to handover period is, of course, a much smaller portion than that shown. The stages from inception to handover include the design brief development stage to determine and clarify the client requirements. They also include the various design stages, procurement, construction, testing and commissioning. The design stages are described in detail in Chapter 2. The operational part of the life cycle is where the building is occupied and the active engineering

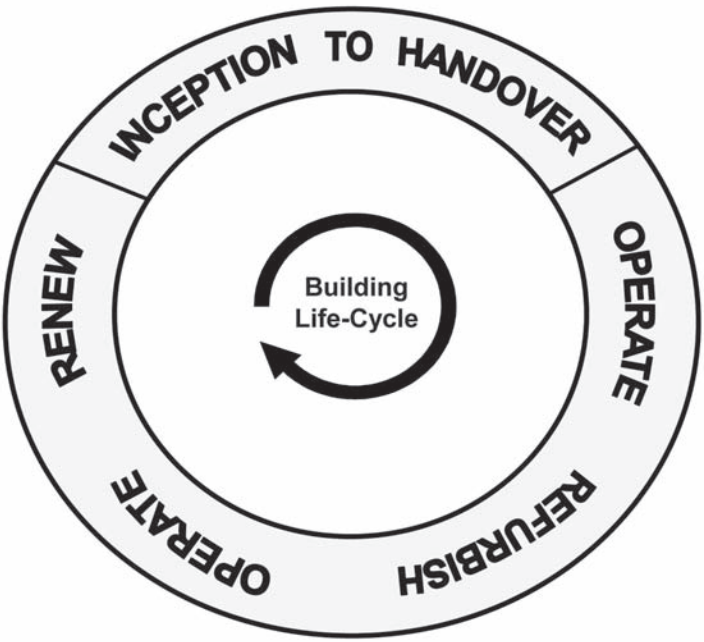


Figure 1.8 Simplified building life cycle (not to scale)

systems are operated and maintained. As the typical economic life expectancy of a building is typically two to four times the life expectancy of the active components of engineering systems, items of plant and equipment will undergo replacement at different times; either due to life expiry or as part of refurbishments or upgrades. The whole building will, eventually, be considered for part or complete renewal. The proposals developed at the inception stage, and the arrangements at handover stage, should address the needs during the subsequent continual operate/refurbish/operate cycle; and the eventual renewal strategy. Adaptation for inevitable climate change should form part of the proposals. To properly address whole-life aspects, designers should, ideally, take into account the ways in which similar buildings and systems have performed following occupation. Unfortunately, there is a paucity of operational performance data to inform the design approach, which is a major challenge for the industry (Tymkow 2006).

In order to deliver buildings that will perform in accordance with the design intentions, it is necessary to have a particular focus on the period from handover to initial occupancy. To achieve this, there should be a planned engagement that ensures the testing and commissioning results are validated; and that the performance during the settling-in period is monitored, so that adjustments can be made to optimise the building performance. This extended involvement is outlined in the BSRIA Soft Landings Framework (2010). Chapter 4 describes the benefits that can arise from undertaking post occupancy evaluation as part of this extended approach.

1.9.4 Focusing on demand reduction as the priority

From the concepts outlined above, a simple concept model for addressing sustainability in relation to energy usage is shown in Figure 1.9. In this diagram, the demand (i.e. final energy consumed by the building loads) can be considered as the output of a range of energy processes whose input is fuel and materials, and whose unwanted side effect is the production of emissions: pollution, waste heat, etc., that have previously been described for conventional supply from fossil fuels. For the purposes of this model, the processes can be considered to be all the processes involved lumped together, covering both the supply side (energy generation, transmission and distribution) and the demand side (usage in the building's systems). So in this model, all energy wasted through inefficiencies can be considered as emissions. The total environmental impact can, for convenience, be considered to be that made by the combination of the input and the emissions. The emissions have an impact that includes the paramount threat of climate change, but also other impacts from other pollutants, waste heat and so on. While climate change might represent the principal environmental threat, the resources have an impact arising from the 'winning' of fuel and materials extraction for the whole energy systems infrastructure. The continuing resources usage also brings about reduction in fuel reserves, and hence the threat to energy security.

It should be emphasised that the three arrows have different measures, as this is a concept diagram and not a conventional flow diagram. However, it should be apparent that the most appropriate starting point for reducing the environmental impact is to reduce the demand; the input and emissions are only there to meet the demand (and – for the same processes – would be roughly proportional to the demand). The next priority is to make all the energy processes as efficient as possible, so that the

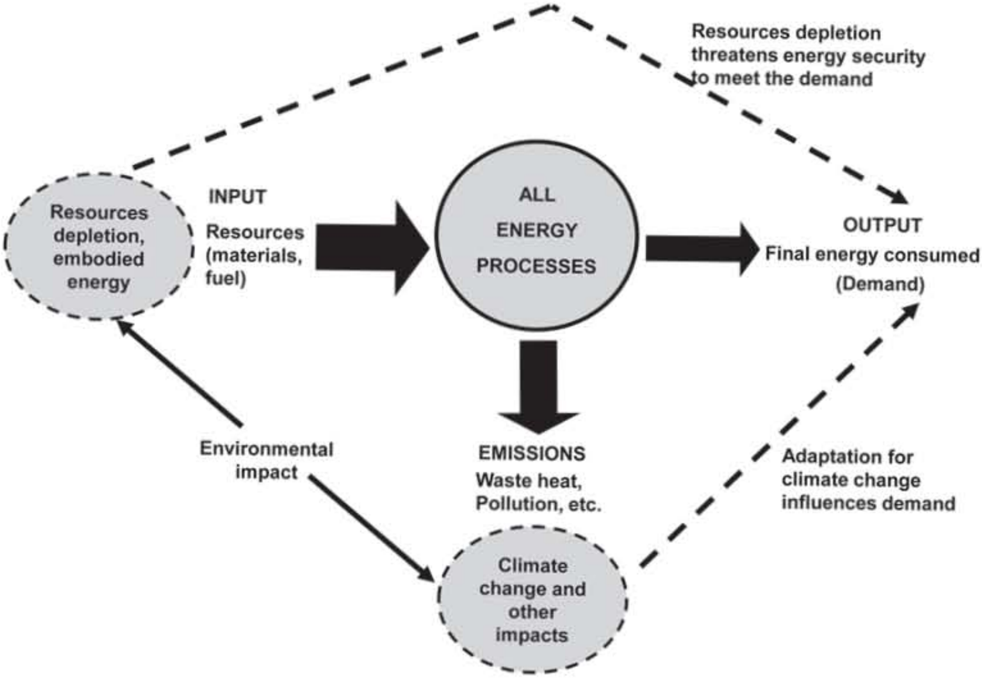


Figure 1.9 Concept model

proportions of input and emissions per unit of useful energy consumed are reduced. An aspect that will influence the demand arises from the inevitable climate change impacts, and the need to design for adaptation to suit. Solutions will therefore need to be energy efficient for adaptation scenarios during the life cycle.

There are, of course, certain limitations in the extent to which building service designers can influence energy processes on the supply side, which are primarily determined by conventional energy suppliers and their regulatory frameworks; and on the demand side, which relate to the clients' functional needs for the building. Strategies for building services designers will largely focus on those aspects of functional needs and energy processes where they can exert an influence.

1.10 Summary

In this chapter we have reviewed some of the key background issues related to the climate change aspects of energy usage and the likely impacts.

The most significant threats to the Earth's life support systems have been identified in recent scientific studies, of which anthropogenic climate change is the principal concern. The primary cause is the emission of carbon dioxide from the use of fossil fuels. The scale and urgency of the need to reduce carbon emissions is one of the principal challenges of sustainable development. Because of the delayed effect of CO_2 presence in the upper atmosphere, climate change is an inevitable outcome from carbon emissions in previous decades. There are, therefore, dual imperatives for building design related to climate change: carbon mitigation to prevent additional future climate change, and adaptation to the climate change that is inevitable.

The built environment has a carbon impact due to both operational energy in use, and embodied energy related to materials usage. The processes for delivering energy to buildings reveal the inefficiencies of the conventional energy mix dominated by power stations, using fossil fuels.

Furthermore, the reserves of fossil fuels are dwindling, and there are concerns that the UK infrastructure for generation and transmission is inadequate for the likely future needs. Reduction in fossil fuel usage is, therefore, an imperative not only to mitigate climate change impacts, but also to maintain security of supply. To understand the potential to reduce carbon impact from buildings, it is necessary to understand the patterns of operational energy usage and material usage, which will inform proposals for energy efficiency. Solutions can be found by adopting key principles for holistic and sustainable design, including a whole-life approach to decision making and usage of ambient energy where this is practical. The starting point for strategies for low-carbon buildings should be demand reduction.

Note

1 Unless stated otherwise, all further figures are attributable to the authors.

Chapter 2

The design process

2.1 Introduction

This chapter provides an outline of the process through which the design of building services takes place as an integral part of the wider interdisciplinary development of the building design. Particular emphasis is given to the key aspects and decision making that influence the building services design strategy, and hence the carbon performance of buildings. As the design of buildings is an interdisciplinary activity, the chapter starts with a brief description of the traditional design team structures, and the roles of the principal design disciplines.

The building services engineer's appointment normally relates to a set of duties for each of a standard series of work stages. The process of design brief development, from the client's initial brief, is an essential early stage activity. The key considerations for the development of the brief are outlined, together with their implications for the engineering systems and energy performance. The essential objectives for this development require an early involvement to influence design concepts. The typical design process at each stage is described as a series of interconnected activities that can form part of the collaborative development by all disciplines. The typical composition of the design information for a building services tender package is explained below.

Designers have to work within relevant codes, standards, regulations and legislation. Key aspects are described, with particular emphasis on the designers' duties for health and safety (H&S) management. Design is a highly professional undertaking, with considerable potential liabilities, so all design work has to be methodical and meet specific quality criteria. The nature of quality management processes for designers is outlined, with an emphasis on the need for auditability of design decisions through all stages.

2.2 Design team structures and roles

2.2.1 Design teams

The design team – or professional team – on a construction project has traditionally provided a consulting service that links the client – as the procurer of the building – with the contractor, who constructs the building. This relationship has become more blurred and complicated in recent times with the expansion of 'design and build' procurement methods, where the contractor undertakes the design as well as the construction, often through ‘novation’ of the consultants who prepared the initial design proposals. In a similar way, the construction for certain types of buildings, particularly commercial office buildings, has become more complicated with a separation of the ‘base-build’ or ‘shell and core’ construction stage for the developer from the fit-out stage(s) for the tenant(s). However, for the purposes of simplicity, to understand the typical design team responsibilities and to convey the underlying principles, it is still useful to think of them in terms of their traditional roles.

The design team are, collectively, the designers for the building, but also act as agents and advisers to the client. The traditional construction contract is between the client and the contractor. The design team also act, in effect, as intermediaries and protectors of the client’s interests in their relationship with the contractor, as shown in Figure 2.1.

The design team is multidisciplinary and varies in size depending on the type, scale and complexity of the building project. As with any multidisciplinary team, it will only succeed if all members understand their own role, and that of the other members, and the disciplines work together with mutual respect. Figure 2.2 shows a traditional design team structure of consultancy organisations.

The principal design disciplines are architecture, civil and structural engineering, and building services engineering. The quantity surveyor also forms part of the team, although quantity surveying is not a design discipline. The architect is usually appointed as the lead consultant, and hence the design team leader; although other disciplines can hold this role, usually for projects of a non-standard nature where the architectural content of the work is much less than the engineering content. In many cases there are also a variety of specialist designers. These could be appointed directly by the client, or could be sub-consultants to one of the principal designers.

It is essential for the appointments to be integrated so that they collectively provide coverage for all the required duties, and so that each consultant has a clear understanding of their own duties and how these relate to the duties of the other designers. It is also essential for the delivery team and the client to work together in a collaborative and coordinated manner.

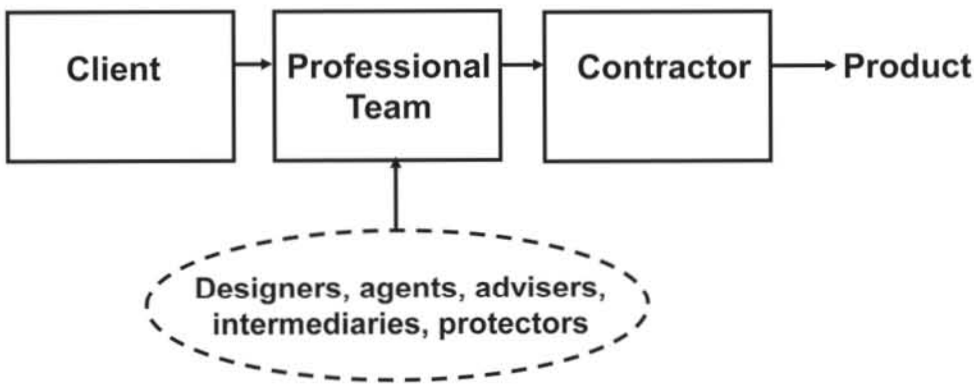


Figure 2.1 Traditional design team relationships

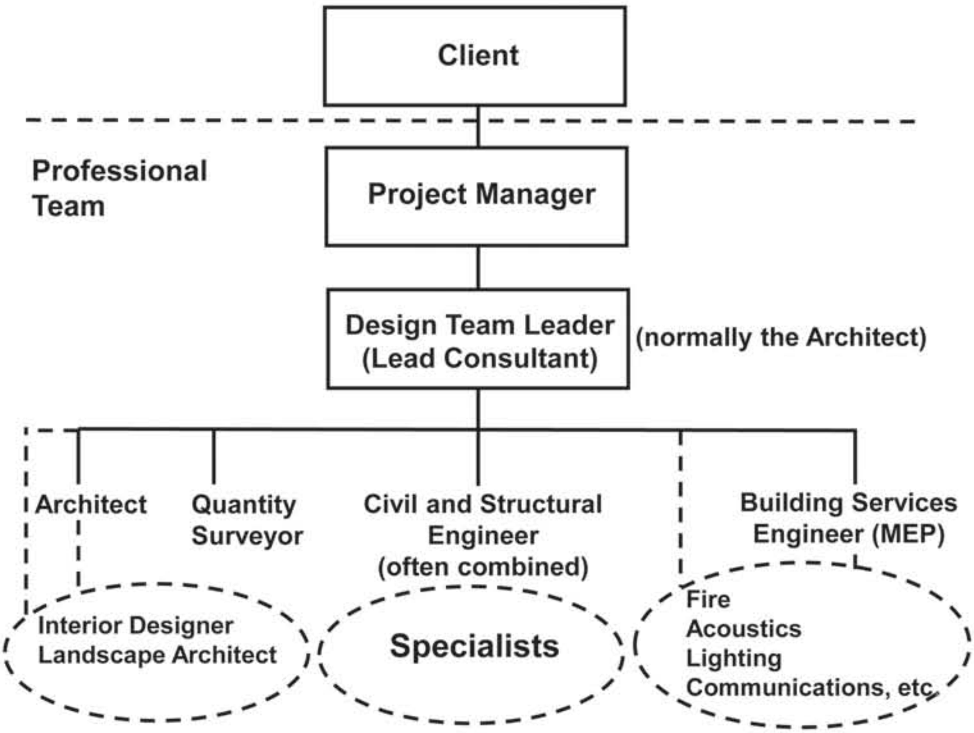


Figure 2.2 A traditional design team structure

In order to understand the role of the building services engineer in the context of the team, it is first necessary to understand, in simple terms, the roles of the other key design team disciplines.

2.2.2 The role of the architect

Architects have a wide-ranging role that includes responsibility for the appearance, shape, form, space usage, finishes and planning for the building. They have traditionally been the principal designers and professionals on building projects, and their appointment is usually as the lead consultant. Much of the documentation and procedures in the industry reflect this role. As design team leaders they are, therefore, concerned with all design disciplines. Architects are the primary coordinators, having a high level of involvement in all aspects of the building design process.

The architect will lead with the initial concepts and will, in effect, act as the overall arbiter on design decisions. From an aesthetic viewpoint, the architect will aspire to a consistent statement or style and seek to maintain the integrity of the design intent (Makstutis 2010). The architect will seek to create balance, harmony and unity of appearance, and therefore try to minimise any visual intrusion of structure and services that might detract from the aesthetic aspirations. Architects have specific responsibility for obtaining the approvals for Planning and Building Regulations.

They usually undertake the contract administration role through the construction period, although other disciplines can also act as the contract administrator.

At the commencement of a project, the architect has an underlying need to understand the nature of the client's requirement at the most fundamental level, to provide a starting point for developing the initial concepts. This can include observing existing operational patterns and use of spaces, and the nature and type of functional activities that will inform the briefing requirements.

From the outset, the architect will seek to create an overall vision or concept to define the character of the proposals. This means the idea behind the form that is eventually developed into a coherent appearance (Makstutis 2010). The Royal Institute of British Architects (RIBA) guidance note on planning policy states that 'clear and demonstrable design principles or a design vision should be established' (Adam 2001). The architect will usually undertake initial research from existing building designs and produce sketches to assess options for the basic massing and form. The architect will often create models (physical as well as computer); and be involved in discussions with interested parties and stakeholders. These will lead to the first, fairly sketchy, outline design representations as a proposed response to the site and the brief. This will include consideration of the location on-site of the building, or buildings; how they integrate with the landscape and circulation routes within and outside the site; and their massing, shape and texture. From an architectural perspective, each project tends to be considered as a unique design challenge. The development of the design evolves through a continuous process of iteration for all disciplines toward a resolution (Makstutis 2010).

As the design develops, the architect will progress from loose sketches that represent the project's basic idea, through numerous stages, to more detailed drawings that start to identify and quantify the sub-divisions, circulation routes and adjacencies between spaces to meet the functional relationships. The drawings will also illustrate key aspects of the proportions, volume and relationship of the building(s) to the site and the surroundings. The drawings will comprise a series of plans, sections and elevations with appropriate scales and levels of detail. The key set of drawings showing the floor plans, with room divisions, columns and structural or planning grid lines, is usually known as the general arrangement (or GA) drawings. The GA set will include the associated site plan, section and elevation drawings from all sides (Makstutis 2010). All design team members use this set to create their layout drawings.

It is an architect's responsibility to specify the range and style of construction materials. The objective will be to choose a suite of materials and textures that create a coherent visual resolution in relation to the overall aesthetic adopted (Makstutis 2010). As the design team takes the project through each successive stage, the design will evolve until it represents a more definite proposal. It will be the architect's duty, when acting as design team leader, to take overall responsibility for directing the interdisciplinary design process, accepting that each discipline will have a team or project leader in their own right. This will normally involve chairing design meetings on a regular basis, to handle the flow of design information to the other consultants. It will also include managing the resolution of client comments, brief development and other brief design changes (Makstutis 2010).

Architects have a unique role among design professionals by virtue of their involvement in the planning process, and often act as the master planners for large site developments (Makstutis 2010). 'Planning' is the process by which a proposed building or development is given consent or approval by the local authority. All other design professionals will normally be involved in contributing to the planning proposals and the planning drawings, but the architect leads this complex process (Adam 2001). This is described in more detail in Section 2.7.1.

2.2.3 The role of the civil and structural engineer

It is normally the case that a single consultancy will be appointed for both the civil and structural engineering design duties for buildings. In its simplest sense, civil engineers are responsible for designing the construction work within the ground below and around buildings. In the wider construction field, this scope covers everything from roads, railways, runways and tunnels to drainage, sewerage, sea walls, docks and harbours. In relation to buildings, civil engineers are normally responsible for all below-ground or 'sub-structure' work, including:

- site excavation, re-distribution of spoil and levelling;
- foundations for the building, including piling, to suit the particular ground conditions or 'geotechnics';
- basements and below-ground enclosures;
- below-ground drainage and sewerage, and site drainage (although this depends on the appointment and is sometimes the responsibility of the building services engineer);
- watertightness of the sub-structure in relation to the groundwater conditions, to prevent water ingress into the building;
- hard surfaces, such as roads and car parks;
- concrete ducts and other construction within the ground to house building services plant, equipment or distribution elements.

Civil engineers normally take responsibility for the external design coordination of all disciplines, covering the work they design along with landscape architecture features and external work designed by the building services engineer. This is similar to the role of the architect who deals with internal design coordination.

Civil engineers seek to create stable foundations to support the load of the building. There can be a lot of building services equipment located below ground, together with incoming services and site distribution, and the associated penetrations of the sub-structure. There is therefore a considerable amount of design integration involved.

The civil engineering work is the first activity as part of the construction process. It can often be lengthy and represent much of the overall construction period. It is therefore essential for the design of civil engineering work to be completed as early as possible. This is so that construction can commence on-site, even if the design of other above-ground elements is still being resolved. The building services engineer will therefore be required to provide key information for sub-structure elements at an early stage.

Structural engineers are responsible for the structure of a building above ground level. This is generally known as the 'super-structure'. This normally comprises a structural frame built up from, and supported by, the sub-structure foundations. In a multi-storey building, the structural frame is usually made of steel or reinforced concrete columns (or a mixture of the two), reinforced concrete floor slabs, and steel or reinforced concrete beams. The structural engineer's role is often, mistakenly, seen as indistinguishable from civil engineers. 'Civil engineering' has often been used as a convenient generic term for those aspects of building design work not undertaken by an architect.

Structural engineers are usually also responsible for miscellaneous structures within the overall structural frame of a building, such as primary supports, bases and platforms for plant and equipment. They need to have an awareness of all load disposition and load movement within the building, whether designed by themselves or not. This will include architectural elements, building services equipment (and often the vibration and thermal expansion associated with it), people and external forces such as wind. The structural engineer will seek to guarantee the structural integrity of the building in an economic way, while also seeking to realise the other design aspirations. This would include trying to create clear open spaces to maximise flexibility for usage of the space, by minimising the number of columns within occupied areas. To achieve this in multi-storey buildings, there is usually a trade-off between the number of columns and the depth of the floor slab and/or downstand beams; and hence the floor-to-floor height.

In addition to the design integration for plant rooms, a key aspect of integration is the incorporation of vertical and horizontal spaces for services distribution. This requires pre-formed openings in structural elements such as reinforced concrete and steel. All such spaces need to be designed in, and allowing for these clear spaces and holes is a major design consideration for the structural engineer. This is discussed in Chapter 12.

2.2.4 The role of the building services engineer

From the brief descriptions of the roles of the other principal design professionals outlined above, it can be seen that the architectural, civil and structural engineering designs alone would create, in effect, enclosed spaces, aesthetic treatment and internal finishes together with the associated sub- and super-structures. However, without active engineering systems, such spaces would, for the most part, be inert. In its simplest sense, the role of the building services engineer can be considered to be primarily about designing features to make the internal spaces habitable and safe. This could, perhaps, be better considered as facilitating the desired functional performance within spaces through integrated features that form part of an overall coordinated building design. But it is much more than that; it is the work of the building services engineer to allow spaces to function in their intended manner throughout their period of occupancy. An essential aspect of the role is the interdisciplinary involvement so that the resulting outcome satisfies the objectives of the different disciplines.

The design role largely relates to the mechanical, electrical and public health (MEP) systems that create the required internal environment, or climate, to satisfy comfort criteria; provide electrical services for power consuming equipment, and water and sanitary services; and provide life-safety facilities to protect life in an emergency. This is shown in a simple diagrammatic form in Figure 2.3 as the traditional part of the spectrum of building services engineering. In addition, there has always been a need

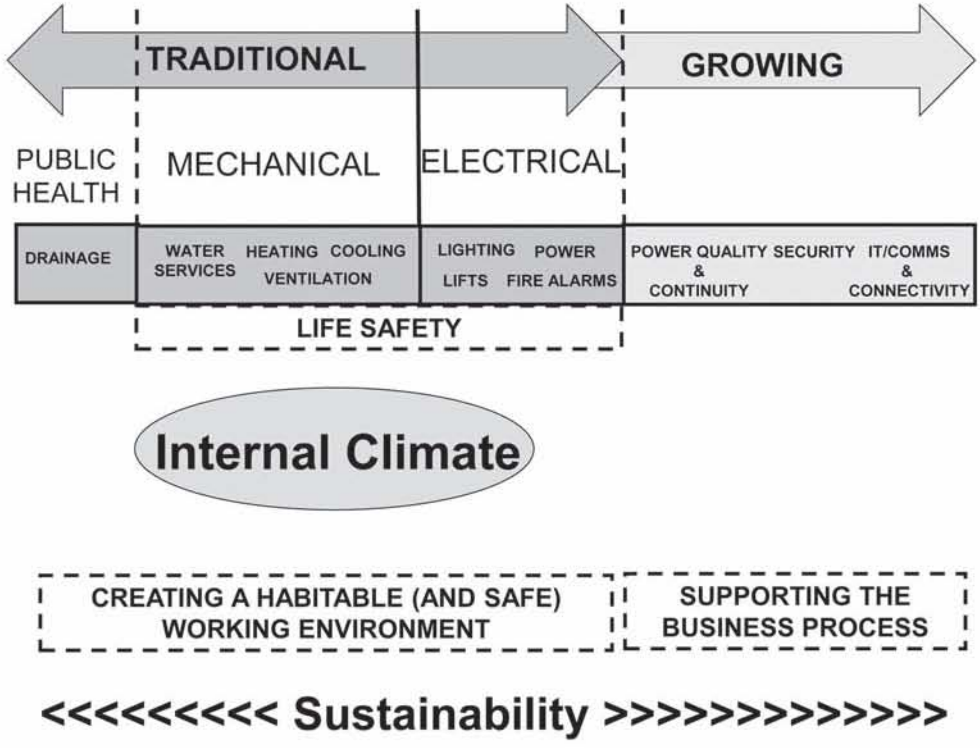


Figure 2.3 The spectrum of building services engineering

to provide facilities for the processes undertaken in the spaces (although the process equipment itself does not normally form part of the fixed building services). More recently, there has been a growth in the spectrum of systems, with a particular focus on the quality and continuity of power supplies and a range of security and communications systems. This often arises from a need to support modern, and often complex, business processes, alongside maintaining a suitable internal environment. The imperative to achieve sustainability requires an involvement to consciously design proposals to address carbon mitigation, energy security and adaptation, as outlined in Chapter 1. Sustainability is therefore an overarching consideration across the whole spectrum.

The engineer will be seeking to satisfy the client's functional objectives in an economic way, while supporting the overall architectural aspirations. For the outcome to be successful, the role should not be limited to design, construction and handover; it is equally about creating buildings that will achieve predictable performance for the likely climate scenarios, and that will be amenable to effective operation and maintenance. Thus building services engineers need to consider the whole-life issues, including aspects such as testing, commissioning and optimal initial occupation; and the strategies for operation, maintenance, upgrading and renewal throughout the building's life.

It is usually the case that engineers have either mechanical or electrical engineering as their primary discipline. Mechanical and electrical engineers tend to act as generalists, but with an expectation that they should have sufficient awareness of the whole building services discipline in order to make overall decisions covering the whole spectrum of systems. Alongside the generalists, many specialist sub-disciplines have emerged, such as public health (plumbing), acousticians, lighting designers, vertical transportation and communications engineers.

2.2.5 The role of the quantity surveyor or cost consultant

The quantity surveyor (QS) or cost consultant is responsible for all aspects of the cost management of construction projects. Most projects will have a formal cost plan that sets out the plan for expenditure on each element of the construction works, together with costs for associated aspects, including fees, applications and consents. The scope of the role covers a wide range of financial and contractual issues, including:

- preliminary advice on economic and investment aspects of a construction project;
- initial estimating and creating the cost plan;
- updating cost estimates and the cost plan through each design stage;
- contract selection and creation, including creating the contract preliminaries;
- cost monitoring, control and reporting throughout the design and construction stages;
- staged evaluations of progress during the construction stage, to allow staged payments to contractors in accordance with the contract;
- creating the final account at the conclusion of a contract;
- general project financial advice to the client on matters such as taxation.

The QS will maintain the cost plan as the primary reference document for cost control, throughout each stage of the project's design iteration.

2.2.6 The role of the project manager

Within the construction field, the traditional role of a professional team's project manager usually relates to an organisation or individual whose specific role and responsibility to the client is to manage the overall process for delivering a complete project. It is separate from the internal management of a project within one of the design disciplines (which tends to be known as 'project leadership').

The project manager's role has grown considerably in prominence in recent years. The project manager is usually appointed at an early stage to work with the client to understand their intentions and help them to formulate a suitable plan for delivering the objectives of the complete project. In this context, 'complete project' relates to the overall business objective of the client. This could, for example, cover the movement of a department within an organisation, and not just the creation of a new building or buildings for them, although this might be the principal element of the project.

A project manager's role within the client's professional team usually covers a wide range of management matters, including:

- direct and close liaison with the client to ensure that the project is delivered in line with the client's requirements, programme and budget;
- assembling the design team and arranging their appointments;

- determining the client's initial objectives and requirements, and briefing the design team;
- directing the design team leader as the client's objectives and requirements evolve;
- determining the procurement method for a contractor, in liaison with the QS and other design team members;
- determining the programme, together with the project procedures for the design team and others. this would usually include meetings, communication methods, information exchange and management of change;
- overall control of the programme of design, procurement, demolition and enabling works (if required), construction, removals, occupation, phasing, etc.

2.2.7 Other specialist design disciplines

Depending on the type, scale and nature of the project, there might be a need for other specialist designers and consultants.

Most projects will have a construction design and management (CDM) coordinator to effect the coordination of H&S for the project. This role is described in Section 2.7.3.

There will also be an assessor on most projects for the chosen method of environmental assessment. This role is described in Chapter 4.

Interior designers are often involved in the spaces within buildings that require particular attention to the design ambience, aesthetic, style and finishes. This could include most areas in high quality hotels and foyers; and reception areas in office buildings. They work closely with the architect to achieve an overall coherent interior design solution. They can play a major role in prestige hotel projects and the more high quality residential projects.

Landscape architects are involved in external areas of the site covering aspects such as planting, landscape form, paving and water features. They could be involved in selecting materials for soft and hard landscape surfaces.

On some projects there might be catering consultants, audio-visual consultants, or various other specialists.

2.2.8 Facilities managers and operational engineers

All organisations that own or lease property have to operate and maintain their facilities once they have been constructed and 'handed over' by the contracting team. This function is sometimes called 'aftercare' and, in its broadest sense, is known professionally as facilities management. The specific aftercare management role for the MEP engineering systems is sometimes known as 'operational engineering'. Operational engineers need to have a thorough understanding of their property and MEP systems and maintain up-to-date record information. They usually have, or employ, specialist personnel to:

- operate plant;
- maintain plant;
- undertake an appropriate maintenance regime, such as planned preventative maintenance, to make effective use of the facilities and provide a reliable service.

This would normally include planning to minimise the incidence of failures and the need for breakdown maintenance;
- undertake minor works, adaptations and modifications.

The record information would include drawings of the installation 'as-built', together with log books, and operational and maintenance manuals, which, taken together, should provide all the necessary technical information required to run the systems as intended by the designers.

Although they are not part of the design team, it can be highly beneficial for the design team to engage with the client's operational engineering team at an early stage in the design process, so that operational and maintenance issues can be properly addressed in the design. See Chapter 3.

2.3 Design appointments and work stages

The designers appointed by clients to undertake design services for building projects often have a standard general contractual agreement for their professional services. In the UK, standard appointments for consulting engineers in building services engineering are often based on the suite of agreements of the Association of Consultancy and Engineering (ACE). The appointments for the whole design team should be arranged so that the full range of duties is covered across all the disciplines; and so that there is an unambiguous allocation and demarcation of responsibilities. In the majority of cases it is likely that the architect will be appointed as the lead consultant under the appropriate RIBA agreement, with the building services engineer appointed as a non-lead consultant for mechanical and electrical engineering services design.

The standard range of engineering systems to be covered would typically comprise:

- mechanical systems
- electrical systems
- public health systems
- fire protection systems
- incoming utility supplies
- lifts and escalators
- acoustic control of noise arising from engineering systems.

It is often the cases that other responsibilities will be included as a schedule of 'additional services'.

The design duties can be to different levels of detail. Duties were formerly defined as 'full', 'abridged' and 'performance' levels, and these terms are still in common usage. Sometimes the designer is appointed to produce 'coordination drawings' or 'working drawings' that would traditionally be the responsibility of the contractor. It is useful to define at the outset the understanding of what is included under the relevant level of design detail for the benefit of all parties. A useful reference document is published by BSRIA (Churcher 2012).

In order to achieve a sustainable outcome, building services engineers should seek to be involved in projects as early as possible so that relevant sustainability issues can be raised; and so that opportunities are not lost to influence the disposition of buildings on-site, and the form and envelope of buildings, as outlined in Chapter 3 (CIBSE 2007). All design team members should work in a collaborative way to deliver a design that is integrated and energy efficient (CIBSE 2004a).

Design is usually undertaken in a series of defined stages, as shown in Figure 2.4 based on the RIBA Outline Plan of Work (RIBA 2008). The work stages represent a standard framework that provides the client with an awareness of the process, together with the expectations for the outcome at each stage. They also provide key points for payment of staged fees for the design team and signing-off approvals (Makstutis 2010). It should be recognised that the sequence of the work stages, or the content, may vary; and they could overlap to suit different procurement methods (RIBA 2008). The intention at each stage is to develop the team's design proposals to a position whereby as many of the considerations as possible have been resolved. Following completion of each stage, it is normal to seek client approval of the proposals, and consent to proceed to the next stage. Traditional programmes have a sequential process through the design stages to procurement, construction and occupation, with formal client sign-off at each design stage. Business imperatives have meant that 'fast track' programmes have become commonplace, and there is often pressure to overlap stages to achieve earlier completion.

2.4 Design brief development

2.4.1 The nature of the briefing process

An essential activity for the whole team at the beginning of the design process is to liaise with the client to develop the design brief. From the building services perspective, the brief should be developed to a sufficient level so that the full extent of the client's functional requirements, and the key performance criteria influencing the engineering systems, can be determined. The briefing criteria should, ideally, be agreed to the most detailed extent possible during the appointment stage. However, in reality, there is usually considerable further development of the brief during Stages A and B,

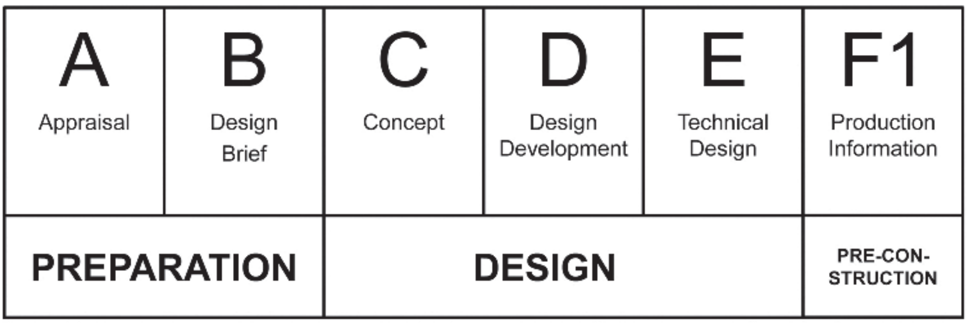


Figure 2.4 RIBA design stages

Source: RIBA 2008

and some ongoing development during subsequent stages. It is inevitable that some of the detail of the brief will continue to evolve as the client's needs change. However, to facilitate design in the most effective way, the key factors should be recorded and agreed at the outset.

In many cases, a client might be unsure about the specific functional performance that they need, or may not be able to articulate it clearly. It is important for the design team to critically examine and question the initial brief in a rigorous way. This is so that they can get to the root of the need, rather than accept and adopt a pre-ordained or preferred starting point that implies a particular solution that might, in reality, be inappropriate. This aspect of client collaboration will be essential to achieving a sustainable solution.

An important source of information for the briefing process is feedback from existing buildings. This includes feedback from the users and on the operational performance. This real-life information should be a primary reference and is, in many ways, more valuable than theoretical design guidance. Chapter 4 describes how post occupancy evaluation from similar buildings can provide a useful input for the design briefing; and help designers to achieve low-carbon building performance in practice.

It should be expected that the design brief will continue to evolve as the project moves forward. It is, in effect, continually developed right through the staged design and approvals process until the design can be said to be in an agreed and finalised format. Thereafter, the nature of development is primarily related to information production for use in the procurement process (RIBA 2008).

2.4.2 Standard and institutional design criteria

The design of many engineering systems can be progressed, within reason, by reference to standard published criteria by professional institutions, such as the Chartered Institution of Building Services Engineers (CIBSE). These criteria will provide the normal design parameters for generic or common types of spaces. More specific guidance on criteria and acceptable design solutions for particular building types can be found in publications of the relevant public sector bodies for health, education and other public buildings. In the private sector, many large organisations – such as large hotel or airport groups – have their own standard design briefing publications. There are also publications by specific property sector bodies, such as the British Council for Offices which covers the offices sector. Many client organisations, particularly investment organisations, will often defer to such established 'institutional criteria' as these are seen as the norm for the industry, and therefore represent a safe and reliable way to protect the value of their asset. However, every building is unique to some degree and there is a requirement of the client to state specific objectives and criteria in order to describe the desired functional performance of the building and its engineering systems.

2.4.3 Specific briefing development

Building types that are well established, and that do not deviate markedly from the norms for their type, might require little in the way of brief development. However, building types, or parts of buildings, that are inherently complex in nature, or that tend to have uniquely defined criteria, are likely to require considerable brief development. Such buildings might include laboratories, research centres, data centres, factories, entertainment centres, exhibition centres, conference centres, museums, media centres, industrial facilities, archives, distribution and storage buildings. Some of these buildings contain spaces that are primarily dedicated to equipment or materials, with minimal occupancy levels. They might have design criteria that are markedly different from those for spaces that are primarily for occupancy and whose criteria largely derive from human comfort parameters. It is therefore most important to establish any non-standard criteria prior to commencement of the design. Typical aspects that might be clarified at this stage are:

Numbers and types of occupants

The anticipated numbers of occupants for the whole building, and individual spaces within the building, together with any transitory aspects, should be confirmed so that concurrent occupancy needs can be determined. The types of occupants will also be relevant as this will indicate their activity and hence the related comfort criteria. The nature of activities will also determine functional requirements of services; for example, power and data provision for workstations.

Functional performance of spaces

Each type of space should be defined according to the performance requirements. This might be directly in terms of design parameters; or indirectly, as a description from which an appropriate design parameter can be proposed. It is normal to summarise the criteria on a room data sheet for each space. This would record engineering design parameters for thermal, lighting and acoustic performance, together with facility requirements for power, communications, public address, security and so on.

Special equipment or facilities

It is often the case that a client will require certain items of proprietary equipment to be incorporated within the building. This could be process equipment, production equipment, computers, audio-visual facilities or other specialist or bespoke equipment. The technical details, connection facilities and so on should be defined.

Facilities management and operational engineering requirements

So that the engineering systems may lend themselves to successful operation and maintenance throughout their life – and hence provide sustainable operational energy efficiency – it is essential for the design to take into account the client's operational and maintenance regime. This aspect of the brief development is likely to require extensive engagement with the client's facilities management or operational engineering staff. It should include the proposals for energy management. It should also include the requirements for such access, facilities and spaces that will be necessary to allow: effective testing and commissioning; effective monitoring and data logging of performance; planned preventative maintenance or other maintenance regime; plus inspection, operation and periodic partial or full replacement of equipment. This will include automatic controls and metering facilities, as described in Chapters 3 and 9.

Phasing

The extent to which the construction work, and associated activities, might be undertaken in more than one phase must be described. This is often the case on large projects. It is sometimes necessary to provide enabling works or temporary facilities as a prior contract to effect conventional or phased construction.

Expansion and flexibility

This relates to allowances that must be included within the design to accommodate future expansion of the facility; and flexibility in the way the building and the individual spaces will be used. This is sometimes called 'future-proofing', although the term has much wider connotations.

Design margins

This covers any specific requirements to design to larger, or more exacting, margins than would normally be the case.

Environmental target

The environmental assessment methodology should be agreed. The target should be agreed and the design team should work with the client to assist in this process. The client should be encouraged to set a high target (CIBSE 2007). This is an important step in providing clear objectives for the design; and also when creating a building with identifiable sustainable credentials (see Chapter 4).

One example of where it is necessary to develop a highly specific brief is when determining the level of resilience for engineering systems for buildings housing business-critical facilities. Certain engineering systems will require a particular level of 'resilience' or 'redundancy' (CIBSE 2008a) to provide the desired level of reliability or availability of operation. This is particularly the case for facilities where continued operation is essential for security or business reasons. This would include data centres, communications centres, transport control centres and certain industrial, security and defence facilities. This is different from the criteria for life-safety facilities that are defined in statutory regulations. Systems' resilience is usually defined in terms of either a numerical reliability or availability level, or, using the well-known N-based redundancy statements, such as 'N+1', 'N+2', '2(N+1)' (CIBSE 2008a). The definition of such statements, as understood by the client, is all-important and should be agreed explicitly. It is preferable to use industry-standard definitions, such as the tier levels described by the Uptime Institute or other institutional body. The resilience definition should cover not only the primary function requiring continued operation – such as electric power for data processing facilities and equipment – but also the relevant support systems, such as cooling and controls, upon which the primary systems' function will also be reliant for continued operation.

The importance of defining and agreeing resilience criteria in the design of these facilities cannot be over-emphasised. It will have a fundamental impact on the numbers, sizes, arrangement and types of equipment such as transformers, switchgear, uninterruptible power supply (UPS) modules, generators, cooling equipment and other ancillary equipment. This will, in turn, have a fundamental influence on the plant space requirements (and potentially the shape and size of the building), planning issues, and capital and running costs. It will also have a major influence on operational energy performance, owing to the usually lower overall energy efficiencies of multiple, parallel items of plant sharing load. It will also have a carbon impact due to the increased influence of the embodied energy in relation to multiple parallel items of equipment, and their operation and maintenance demands. System resilience criteria can therefore fundamentally influence the whole-life carbon impact of certain types of building.

2.5 The design process for building services engineers

2.5.1 The essential aspects

Typical design activities at each stage are discussed in Sections 2.5.2 to 2.5.7 below. However, it is probably more important to understand the *essence* of the design process, and what is trying to be achieved, rather than just thinking in terms of specific activities at each stage. The key behaviour that should be established from the outset is for all disciplines to work as a team in a collaborative way. This will allow the design to develop in a way that addresses mutual objectives and aspirations, rather than as an outcome of different interests pulling in different and contradictory directions. In particular, the three principal design disciplines of architect, civil/structural engineer and building services engineer need to work in harmony as a team with a common understanding and mutual respect.

In the traditional sense, the objective of the building services engineer is to provide sufficient information for the procurement of competitive tenders from contractors, and to show the general intention of the engineering systems installations. The specific level of detail of the consultant's design will depend upon the particular appointment and duties. The BSRIA publication (Churcher 2012) is a useful reference for typical expectations of the level of detail in the design deliverables for different types of appointment. Under the traditional consultant–contractor relationship, the actual working drawings used for installation are developed by the contractor based on their development of the consultant's design.

It is important to understand that building design is an iterative process involving the development of concepts, ideas and proposals from the different disciplines; and regular re-working and refining of those proposals as the design evolves toward an integrated and coordinated resolution. Figure 2.5 shows a simplified view of the design process, emanating from the need, which should be identified through the design brief development process. Ideas develop through concepts, to a form for the enclosed spaces. There will be division of the form into zones – designated spaces or areas. This leads to proposals for treatment of spaces and selection of appropriate

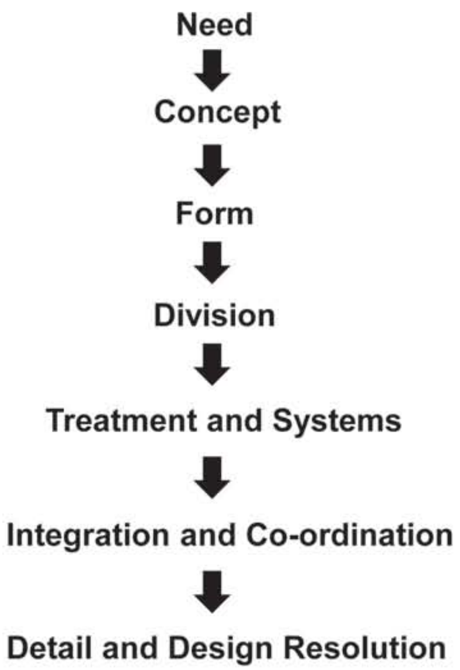


Figure 2.5 A simplified view of the design process

systems. System design includes decisions on the numbers, types and arrangements of terminal devices, with suitable duties, capacities or ratings to cover the relevant zones or spaces. Design integration covers building services and their coordination with other elements. As the design continues through integration to the greater level of detail required for eventual design resolution, it will include integration of terminal devices with architectural features and finishes to satisfy aesthetic criteria. In a more general sense, the services design throughout is intended to be robust, discreet, reliable, safe and energy efficient. The design approach should address risk management aspects.

There is an opportunity to bring together holistic influences that can create buildings that will perform in a sustainable way, and also meet the architect's aesthetic aspirations, at the design brief and concept stages; making these the key periods in design. The opportunities for influencing both the design outcome and the whole-life performance reduce sharply with time. The potential for change diminishes, and the resistance to change grows, along with the cost of change (CIBSE 2008a).

As outlined in Chapter 1, there is a compelling need for carbon mitigation through the whole building life cycle, as well as a need for the design to address adaptation to climate change. The generic measures for carbon reduction through energy efficiency are outlined in Chapter 3, and expanded upon in later chapters. In simple terms, the key considerations for energy efficiency can be represented as three interrelated elements, as shown in Figure 3.3: the passive elements of the building fabric; the active elements of the mechanical and electrical engineering systems; and the whole-life operation, which will be determined by the management strategy for the building. As such, early design considerations should include durability, buildability and commissionability. Taken together, these can be considered to address the energy efficiency aspects of sustainability that have the primary carbon influence, while accepting that sustainability is a wider objective, embracing other factors.

From the outset, the building services engineer should be involved in influencing the conceptual development of the shape, form, orientation and performance of the building envelope, in order to achieve suitable performance from the passive elements to minimise the need for active engineering systems and their energy usage. As the conceptual development of the active systems commences, in line with the energy strategy, it will proceed through iterative development generally, as shown in Figure 2.6. The most important drawing for each system is the schematic, as this identifies the engineering system components and their interrelation. In essence, each system comprises central or distributed plant, or a mixture of both; an infrastructure of distribution elements from the plant to the relevant branches or circuits; and terminal devices that treat the space, or provide a functional requirement or life-safety feature. Alongside these there are the controls and controlling components.

The schematic diagram is the primary reference for the system design and therefore, as any significant change occurs, it is the series of schematics that should be amended first. The design development should ensure that several aspects are addressed concurrently and reconciled at each stage, with the system schematics as the reference: load assessments, which will in turn affect the utility connections required, and the space planning for plant and equipment; system layouts in relation to the architectural floor plans and sections; and the integration and coordination of building services elements with architectural and structural elements on both layouts and sections, including the interfaces for terminal devices. As each iteration in the design occurs, the same re-working and reconciliation take place across these aspects of the system designs,

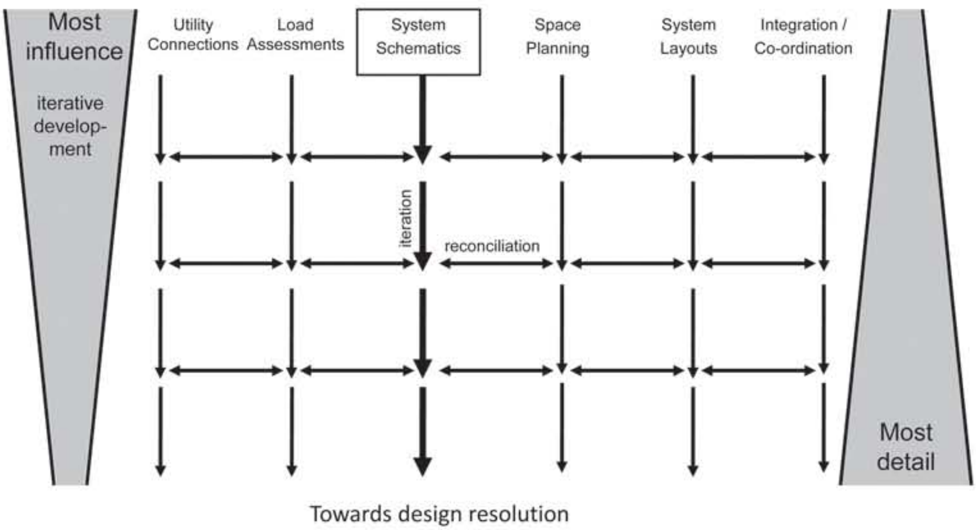


Figure 2.6 Concept for iterative development of the building services design

as they move toward design resolution. It cannot be over-emphasised that the earliest design stage is the most influential, but with little detail; while the later design stages have much less influence, but much more detail.

Three particular developments have had a significant influence on the design process activities in recent years: environmental assessment methodologies; dynamic simulation modelling; and building information modelling (BIM).

There is widespread adoption of environmental assessment methodologies, such as BREEAM and LEED, which are described in detail in Chapter 4. Under these methodologies, an assessor is appointed and works with the design team throughout the design period to provide a continuous focus and guidance on how individual elements of the design might be developed to achieve the credits that contribute to the target rating. The use of dynamic simulation modelling to demonstrate compliance with Building Regulations Approved Document Part L is described in more detail in Chapter 3.

There is growing use of BIM software as a design tool. BIM is a major development in the design process that uses a variety of software tools to create a single information source for use by the project team, with all designers contributing to the model. This provides the potential for a high level of integrated and coordinated design, which allows the processes for design, and for construction, to be better managed with a greater degree of accuracy and consistency. This will facilitate closer collaborative working to make the whole process more effective and hence more cost effective. For all disciplines there will be improved flow of information. As the capabilities of BIM software develop, building services designers hope that their model will be used not just for calculations, but also for simulations covering specific aspects of dynamic performance, such as thermal modelling; together with other aspects of the design process. A key objective is that the greater accuracy available from the integrated model will improve the construction and installation processes on-site. This should have widespread benefits, including better planning of delivery and construction methodologies. It is expected that this will provide better management of materials – with a benefit to sustainability – and reduce time and errors during construction, installation and commissioning. Although design using BIM is not covered here, it is likely to have a considerable transformative effect on the design process, and on construction more generally.

Typical areas of involvement are outlined below against each RIBA stage (RIBA 2008), focusing on the intended outcome rather than the software tools that might be used. It must be emphasised that this is not intended to represent, in any sense, an interpretation of formal duties under any agreement or appointment criteria. Instead, it is intended simply as a useful list of design aspects that can be considered at each stage, with a particular emphasis on achieving an energy efficient solution. One should recognise that design is not always carried out with such strict adherence to the formally defined stages; and certain aspects might move from one stage to another; for example, for different procurement methods, or if the architect decides to submit a planning application at an earlier or later stage than normal (RIBA 2008).

2.5.2 Stage A: Appraisal

The first stage of preparation is focused on the project inception and ensuring that the team is fully aware of the client's intentions for the building project. The initial briefing will include identifying the client's needs and objectives for the building's function. There is likely to be an indicative maximum cost figure and a preliminary programme. The client's initial brief should identify their business case in general terms, together with any key factors that might constrain the development. It may also include the client's initial views or aspirations for environmental or sustainable performance, normally in terms of a score or category for an environmental assessment methodology. The design team should encourage the client to aim for a high target. At this stage the design focus is on the feasibility of the development. Appropriate studies will be undertaken and options assessed so that there is sufficient information to allow the client to make a decision on whether to proceed with the project.

2.5.3 Stage B: Design brief

The focus of the next stage is on obtaining a standard range of background documentation from the client in relation to key aspects of the brief and the site. This will allow the initial statement of requirements to be developed into a design brief. (See Section 2.4 for an overview of key aspects of design brief development.)

For the building services engineer, two site aspects are particularly important for identifying key requirements and constraints: the existence, extent and capacities of utility supplies; and physical site restrictions that might impact upon the design proposals. The standard utility supplies are: electricity, gas, water, sewerage and telecommunications. The specific utility arrangements will vary from country to country and location to location, e.g. some regions will not have a mains gas network; or in some circumstances, the availability of district heating (or, much less commonly, district cooling) might influence the energy strategy.

The client is likely to have record drawings available in relation to the site that will show the nature and locations of existing utilities on the site. This will include the sizes of the infrastructure elements, such as pipes and cables, and the terminations within substations, gas meter rooms and similar utility-owned buildings, rooms and enclosures. Such record information showing the presence of both 'live' and disconnected underground services is also of vital importance to discharging the designers' duties under H&S management, as described in Section 2.7.3.

While the concept design development takes place in Stage C, it can be useful to develop initial ideas for the energy strategy to help inform the commencement of concept design across the disciplines; specifically with a view to ingraining energy efficiency into the design thinking at the outset. To develop the initial concepts for the energy strategy, as outlined in Chapter 3, it will be necessary to analyse the site opportunities. These would cover aspects such as the solar path and high and low sun angles; the prevailing wind direction; and the possible locations for an energy centre, as shown in Figure 2.8. As the early concepts evolve, it is beneficial to undertake simple load assessments for heating, cooling and power (perhaps using 'rules of thumb') that will allow initial enquiries to commence with suppliers for gas and electricity; together with water, drainage and communications connections, as shown in Figure 2.7. The designer should make initial enquiries to the relevant suppliers and network operators to establish the up-to-date scenario regarding available service capacities to feed the development's needs. This should confirm any recent developments to the situation shown on the record drawings,

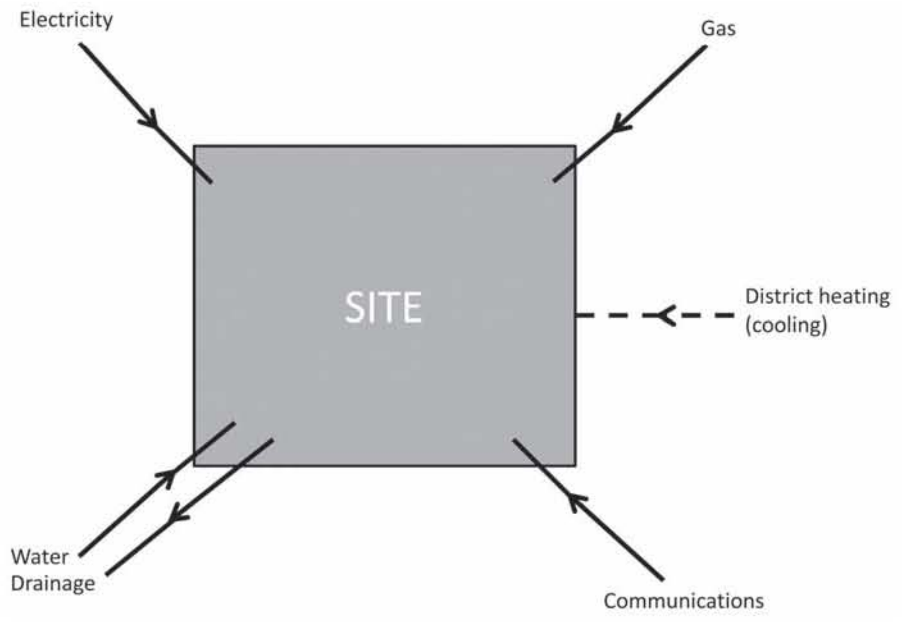


Figure 2.7 Utility connections

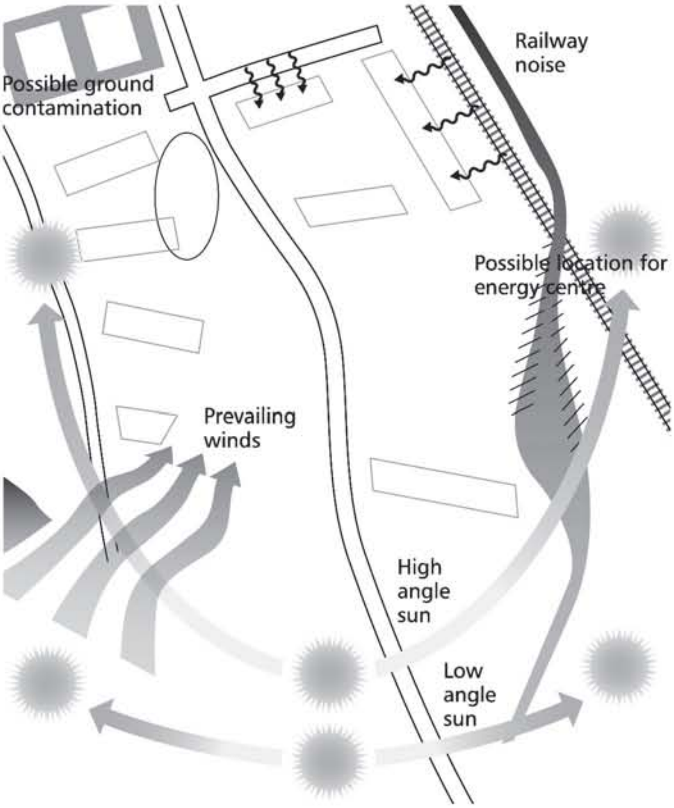


Figure 2.8
Energy strategy: site opportunities and constraints

Source: reproduced from CIBSE Guide L (2007) with the permission of the Chartered Institution of Building Services Engineers and can provide information on planned or proposed infrastructure developments in the vicinity that could influence the level of availability for the proposed building or site. It must be emphasised that the availability of services connection of the required capacities have an influence on energy strategy, and could even determine whether the building is a feasible proposition. Where the existing infrastructure is insufficient, the network supplier will advise on the level of local reinforcement required to provide the capacity of connection necessary, for which there could be considerable cost implications.

There are many physical constraints that could impact upon the engineering systems design, including access limitations, noise, relative site exposure and shelter, wind, electromagnetic interference (EMI) and air quality. Any access limitations might restrict the maximum sizes of components that can be delivered to the site for the initial construction (or subsequent replacement) and might influence the equipment selection in the design, or methodologies for construction. High ambient noise levels might require acoustic features to be incorporated into the site landscape layout, building envelope and heating, ventilation and air-conditioning (HVAC) systems to provide attenuation to satisfy internal acoustic criteria. Similarly, a site in an area with very low ambient noise levels might require higher levels of acoustic attenuation than normal in the engineering systems to minimise noise influence from the new development. Sites in different locations can vary widely in their levels of exposure to the elements – from low level city centre sites which are relatively sheltered, to sites on higher ground and which might have very high levels of wind and precipitation, to marine environments with a saline atmosphere. The ambient air quality might be affected by heavy traffic or industrial activity, again influencing the selection and disposition of HVAC system equipment.

Many of these factors will be relevant to planning matters and the feasibility assessment for utilising ambient energy; and might require special features and materials selection in the design proposals. For example, sites close to sources of EMI (such as railway lines or power lines) or radio frequency interference (such as radar facilities), might require special features to minimise any undue influences within the building, to achieve electromagnetic compatibility.

At this stage the structure of the design team, and the roles of the individual design disciplines, will usually be established. The design team leader will be identified – usually the architect – and the interrelationships and lines of reporting will be confirmed. It is usually at this stage that any necessary specialist sub-consultants will be identified. Stages A and B might be merged on smaller projects.

The outcome from this stage will normally be an initial recommendation on the feasibility or viability of the building in relation to the client's initial brief, budget and programme.

2.5.4 Stage C: Concept

During this stage the team will develop the concept design from the fairly loose and sketchy feasibility proposals to an outline design of meaningful shape and form. For the design to be developed to the required level, the building services engineer is likely to visit the site to obtain detailed information on existing services and features. It is also likely that any relevant surveys will be undertaken.

The communication with authorities is likely to have been minimal prior to this stage, but will now involve more detailed consultation on the key principles affecting the engineering systems, particularly those for life safety, which would be related to the fire strategy, and 'means of escape' routes.

While the initial concepts for systems may have been considered at the previous stage, it will be necessary to consider alternative ways in which different systems might satisfy the requirements. The building services engineer should critically examine those aspects of the brief, budget and programme that will have most impact on the energy performance and engineering services design. The programme should be examined and assessed in terms of practicality for the extent of design work and studies required under the scope of duties in the appointment. For complex projects that are likely to require non-standard solutions, sufficient design time will be required for the design team to undertake the necessary research and specialist studies, and to develop a range of solutions. Similarly, for sites with inherent complexities – such as congested inner-city 'brownfield' sites; or sites of irregular shape, on difficult terrain, in remote areas or with limited access – sufficient design time will be required to assess the impact of these restrictions on possible design solutions.

The building services engineer will create an outline design to summarise the proposals. This will comprise drawings, sketches and design advice, which the architects will use, along with outline design information from the civil and structural consultants, to prepare concept proposals. The proposals will represent an integrated, but not especially detailed, solution covering all disciplines in the form of a Stage C report, together with outline specifications (RIBA 2008).

There will be a preliminary cost plan compiled by the project QS. This is likely to show all the costs associated with the project activity, covering not just the construction value of the building but also aspects such as land purchase, design team fees, local authority charges and fees for statutory authority services connections. There is usually a requirement to produce a building services cost estimate at this stage. This is normally based on unit costs, either £/m^2 or £/room, or other useful unit basis. Although the QS normally has responsibility for the overall cost management (including the costs for building services), it is important to recognise that the cost estimate produced by the building services designer is a useful figure that is likely to be discussed in relation to this element of the cost plan.

2.5.5 Stage D: Design development

A client's decision to give approval for the design team to proceed to Stage D is usually an indication that the client has a considerable commitment to proceed with the project, for the process through Stage D and beyond is primarily one of adding more detail to the concept proposals and therefore incurring further design costs (Makstutis 2010). The previous discussions on the design brief should be continued and concluded. The intention is that, while some further minor development of the brief is inevitable, in effect, it should be considered as concluded at this stage for the functional aspects.

At this point, the programme will be of a simple form and should indicate the design, procurement contractor mobilisation, construction, handover and occupation. It is essential to determine the client's imperatives for the completion date, which might have absolute limitations related to immovable dates, or might have an inherent degree of flexibility. It is also important to identify any further complexities, such as a requirement for staged completion with partial occupation.

The development of proposals for the incoming utility services with the relevant providers is key and will receive significant attention. This will involve estimated load (or demand) requirements. The discussions are likely to cover aspects such as allocated capacities, services sizes, terminations and demarcation, and metering arrangements. Equally important will be the provision of spaces for the service providers' equipment, which will require dedicated rooms or enclosures in accordance with their standard criteria. The nature of space planning for utility providers is different from that for the other building services equipment as it will require:

- external connections
- external access, usually on a 24-hour basis
- possibly wayleaves or similar reserve rights over the external services routes.

The integration of these spaces forms a fundamental part of design during these stages (see Chapter 12 covering space planning).

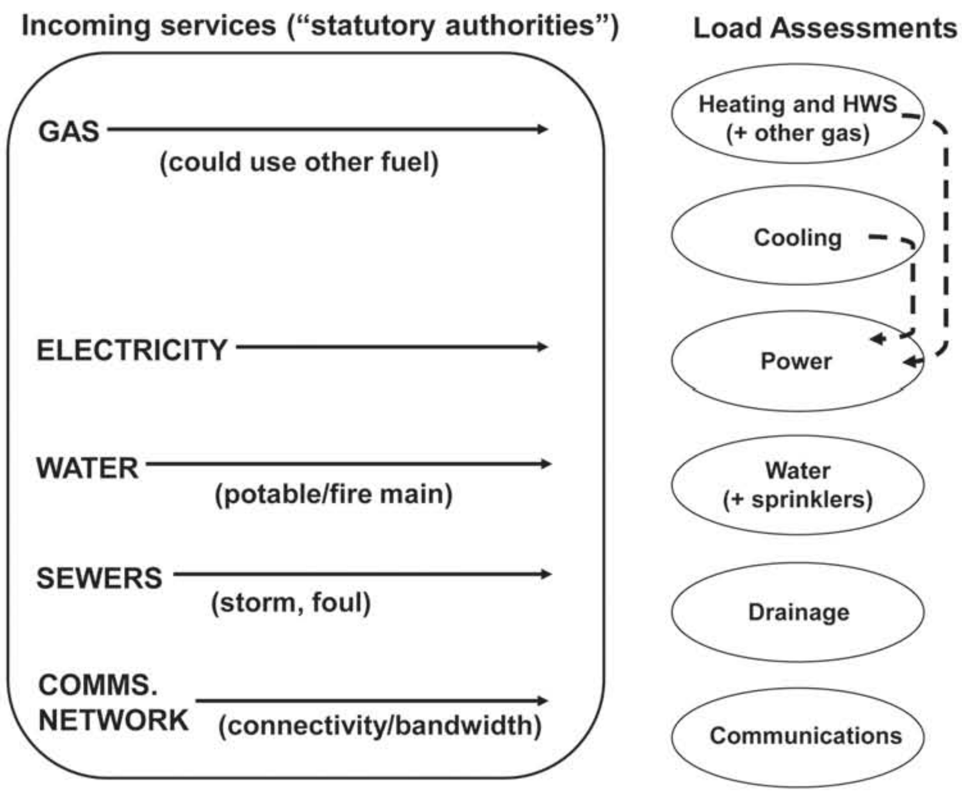


Figure 2.9 Load assessment and incoming services

For the design of civil and structural engineering to progress, it will be necessary to provide details of the key structural loads related to MEP equipment. This will require drawn information showing the location of the heaviest equipment, with footprint dimensions and mass for each item. The equipment items of most relevance are large water-filled items such as tanks, thermal storage vessels and large pipes; together with large and heavy individual items of equipment such as chillers, boilers, transformers, generators, switchgear, cooling towers and UPS modules.

The structural engineer is likely to allocate a uniform loading density throughout all plant areas, to cover a normal arrangement and distribution of MEP equipment. However, the heaviest items may require additional structural features, such as thicker floor slabs that will impact upon the structural design and cost. The structural engineer might impose limitations on the locations of heavy equipment, and once these have been agreed there is limited scope for changing the locations of equipment.

The load assessments for heating, cooling and power will be further developed as the design detail progresses. As the architectural proposals for the envelope – facade and roof – are developed, the HVAC system proposals will become more detailed so that preliminary sizes can be allocated for components such as boilers, air-handling units (AHUs), fans, pumps and chillers.

The building services engineer will prepare drawings and sketches so that the lead consultant's design can be developed. The required calculations will be undertaken for load assessment and equipment sizing. The drawings will normally include schematic diagrams for the main MEP systems, block plant layouts for plant rooms and key layouts for risers; together with floor layouts on architect's GA drawings for the main systems. It is likely that updated outline specifications will be issued to indicate the materials and workmanship standards. This information package will allow the QS to prepare a cost plan. A Stage D report will be prepared to summarise this stage of design development.

It is likely that the application will be made for detailed planning permission, with the building services engineer providing supporting information to the necessary level of detail (see Section 2.7.1).

2.5.6 Stage E: Technical design

When the client gives the team approval to proceed to Stage E, the design can be developed sufficiently to allow a good level of coordination of the various components and elements. This will involve detailed calculations for all items of equipment, and detailed development of all drawn information. While the Stage D design would have shown the generality of the design for all spaces, the Stage E design is likely also to cover all particular and non-standard aspects. This will normally include each terminal device (diffuser, grille, luminaire, socket, radiator, chilled beam, etc.) and branch or final circuit from the on-floor distribution point. Schedules can be created with the key design and performance parameters to summarise the important information for items of equipment.

The coordination of design between building services sub-disciplines, and between building services, architecture and structure, will have been a necessary consideration up to this stage, and will have involved sketches to test and resolve specific coordination issues. At Stage E, the coordination information becomes more formal as a demonstration of spatial resolution to avoid clashes at key nodes and pinch-points. Coordination drawings would normally show key sections through plant rooms, ceiling voids and floor voids.

The design coordination up to this stage will have required the incorporation of the principal builder's work features into the architectural and structural designs. The scope of the builder's work is described in Chapter 12. At Stage E, the continuing development of the builder's work requirements will be identified in the form of schedules or on drawings. This is necessary so that it can be incorporated into the designs of other disciplines, and hence be reflected in the cost estimate.

Relevant information should be prepared for statutory requirements, including information necessary for the management of H&S (RIBA 2008).

2.5.7 Stage F1: Production information

This stage is about creating design information of a sufficient level of detail for the tender package(s) that will be used in the procurement process. This will become the formal set of design material from which the tendering contractors will be able to understand all requirements of the systems, and submit tender bids accordingly. During the tendering process, the information is issued alongside the relevant architectural, civil and structural drawings, so that the coordination and integration aspects can be appreciated.

The design information created for the tender package will include drawings, specifications and equipment schedules.

Drawings would typically be of these types:

- schematics of the engineering systems
- layouts of each floor, usually to a scale of 1:100 or 1:50
- layouts of plant areas, usually to a scale of 1:20
- sections, particularly key sections through plant spaces
- elevations showing equipment integration locations
- standard details for engineering systems
- special details for engineering systems.

The drawings would typically cover these systems:

Mechanical:

- heating system
- domestic hot and cold water system
- mains water system
- ventilation/air-conditioning system(s)
- cooling systems
- fuel storage and distribution
- specialist pipework system(s), where required
- building management system and controls
- fire protection system(s).

Electrical:

- high voltage (HV) distribution
- low voltage (LV) distribution
- earthing and bonding
- lighting and emergency lighting systems
- small power systems
- power to mechanical plant
- fire detection and alarm system
- public address/voice alarm (evacuation) system
- security systems
- communications system
- lightning protection system
- specialist systems (such as audio-visual)
- external lighting system.

Public health:

- sanitary system
- rainwater system
- specialist drainage system(s).

On larger projects there is usually a separate set of layout drawings for each system, but, where practical and legible, a combination of systems on a single set of drawings may be appropriate.

Specifications:

While the drawings contain visual information about the engineering systems, and are supported by notes and annotations, they cannot contain all the information that a contractor would require. A written document, the specification, provides the more general information on the systems, together with the requirements for materials and workmanship. The general contractual requirements are usually set out in a set of preliminaries, depending on the particular contractual format. The building services engineer would normally provide a separate set of preliminaries that is related to the overall preliminaries, but specifically covers the general clauses related to the MEP package or packages. This would include information about the contractor's designed portion, to clarify the relevant design responsibilities. So there would normally be three types of written document:

- preliminaries
- standard specification (system-by-system), including materials and workmanship
- particular specification (system-by-system).

Equipment schedules:

As there is much information to be conveyed about the particular design duty, performance and features of equipment, this is better presented in a tabulated schedule form, rather than in the specification text. It is normal for schedules to be produced for equipment such as air-handling plant, boilers, fans, pumps, control panels, transformers, switchgear and distribution boards.

Application for statutory approvals is usually made at this stage. Then the tender documentation is prepared (Stage G) and tender action undertaken (Stage H). This is followed by mobilisation (Stage J) and construction (Stage K).

2.6 Provision for testing and commissioning

It has previously been noted that a key design objective is to facilitate whole-life performance. Testing and commissioning is the conclusive stage of the construction process in which the various installed systems are separately tested, and then set to operate in the required integrated operational mode to achieve the intended design conditions. As outlined in 2.4.3, the planning for the testing and commissioning process should commence at the briefing stage. The testing and commissioning activity will establish plant operation in accordance with the design parameters; and set the systems to maintain the conditions for the likely range of load conditions, and to the tolerances that have been defined. For this activity to be successful, the systems should have such features to allow ease of commissioning. The engineering systems designs must, therefore, include all necessary features required to effect testing and commissioning to satisfy the design parameters; achieve optimum performance; and allow for ongoing adjustment to maintain the design criteria. This will include standard features, such as:

- For air systems: dampers, test points
- For hydronic systems: regulating valves, pressure-tapped valves, commissioning stations
- For electrical systems: meters, instrumentation, control panels, adjustable settings (protection relays).

It might also include non-standard features required for more complex testing and commissioning procedures and sequences, such as temporary connections and test loads (fixed or temporary).

All of these features should be identified within the design material. Information should be provided on all system parameters to be achieved during the testing and commissioning process.

2.7 Legislation, regulations and consents

There are four key areas of approvals or legislation in which building services engineers are involved to a significant extent: Planning Consent; Building Regulations, or Building Control Approval; Designers' Duties for Health and Safety; and the Energy Performance of Buildings Directive. The nature of the involvement for these aspects is briefly outlined below. The regulatory framework and processes will vary between countries; but it is likely that most countries will have regulatory frameworks, national or local codes with similar objectives.

There are also, of course, numerous standards (such as British Standards) relevant to most technical aspects of buildings and engineering systems. These are often referred to in codes and regulations.

2.7.1 Planning

Planning relates to the appropriateness and suitability of a proposed construction project in relation to its location. A project should not proceed to construction unless the required planning permission or consent has been obtained from the relevant planning authority, such as a local municipality or council.

In the UK, the processes for achieving Planning and Building Regulations approvals are separate. Both are based on submission of drawn information, together with other design material, as required. Planning approval is sought first, with a series of drawings of a relatively simple nature, but suitably informative about the nature of the proposals. Building Regulations approval is applied for at a later stage, using more detailed drawings and other technical information covering most disciplines. In some countries, it might be normal for both applications to be made at the same time (Makstutis 2010)

For most locations in most countries, there will be some type of policy for planning approval so that the process for development of a neighbourhood, village, town, city or region can be managed. In essence, planning is a method of regulating land use in its widest sense (Makstutis 2010), so that only certain types of use considered suitable and appropriate can be undertaken in any particular location. Policy can be at a local municipality level, or for an area, district or region. For some developments of a particular type, scale, potential impact and significance, the approval process might be at the national level. In other cases, a city or other locality might have its own unique set of outline and detailed planning requirements, usually in the form of policy guidelines. The intention is that these allow for growth and development of the built environment, but in a sensible and properly managed way. They also provide a degree of control of the visual impact of development. The policies seek to ensure that the distribution and pattern of types of buildings is suitable, along with their scale and uses. They also seek to protect and conserve buildings or areas of historic character and provide built development that is in the interests of the locality and those who may be affected by development (Makstutis 2010). Planning policy sets objectives in a general sense, and provides some opportunity for negotiation. The RIBA guidance note on planning policy describes recommended design stages and procedures for preparing full planning applications (Adam 2001).

Planning can be a complex issue covering many aspects of the proposed development, including its context, function, appearance, scale, impact and the transport issues related to goods, people and vehicle movements. It will also consider zones, heights, noise, views and overlooking of other properties. For a building services designer, the main aspects that will normally require particular attention are:

- plant locations and appearance, where they might have a visual impact
- visible features on the elevations, such as louvres and flues
- noise breakout from plant that might have an impact on ambient noise levels
- fumes or other emissions from plant
- energy strategy, which is increasingly a consideration in planning policies.

The planning approval process consists of submission of a range of drawings and other technical material that describes the intended development. For outline planning approval, the information does not usually need to be in detailed form, and tends to be fairly general. The visual information mainly relates to the massing of the building(s) and the layout and character of the proposed development, so that this can be seen in context and its wider impact assessed (Adam 2001). The objective of the submitted drawings is to provide suitable information so that the authority can appreciate the key features of the development, and make a decision accordingly (Makstutis 2010). The level of information is likely to vary depending on type of development, or the scale (Adam 2001). A more comprehensive set of drawings will be required for detailed planning approval.

The planning departments of local authorities seek to ensure that proposals comply with the relevant policies governing the nature of the built environment as it develops in their locality. Most urban areas will have a unitary development plan (UDP) or similar, that allocates zones for particular types of development, such as residential, industrial, commerce, retail, etc. The objective is to protect the interests of residents and other parties that might be affected by changes taking place (Makstutis 2010).

Planning can be a lengthy process for certain types of proposals and will often involve public consultation, meetings and negotiations. In some cases, buildings might obtain approval without going through the formal procedure of a full planning process. It should be noted that planning only considers the nature and acceptability of the proposed development in relation to the prevailing policies for the area. It does not consider any safety aspects, which are covered in Building Regulations. In the UK, key planning criteria are set out in a series of planning policy guidance notes (DCLG 2012).

2.7.2 Building Regulations

'Building Regulations', or 'Building Control', relates to the compliance of the specific design for the building and its engineering systems in relation to the relevant codes or regulations, such as the Building Regulations approved documents in England and Wales (DCLG 2010a). In contrast to planning, Building Regulations are standards for the performance of the construction works. The regulations cover aspects such as fire safety; health, air, water and noise; accessibility; and energy conservation.

The Building Regulations applicable in England and Wales exist principally to protect the public by ensuring the health and safety of people in and around buildings. They also cover access to and around buildings. The regulations apply to most new buildings and many alterations of existing buildings, whether domestic, commercial or industrial. The regulations cover most aspects of a building's construction, including its structure, energy conservation, fire safety, sound insulation, drainage, ventilation and electrical safety. Details of certain elements of the design have to be submitted for approval. The construction on-site is monitored by a local authority official or approved inspector, previously known as the Building Control Officer.

For building services designers, the most important aspects will normally be:

Part B: Fire safety
Part F: Ventilation

Part G: Sanitation, hot water safety and water efficiency
Part H: Drainage and waste disposal
Part J: Heat producing appliances
Part L: Conservation of fuel and power (see Chapter 3)
Part P: Electrical safety.

2.7.3 Designers' duties for health and safety (H&S)

An important duty for all professionals involved in the design of construction projects is to manage the H&S implications of the structures or systems they design. The construction industry has, unfortunately, given rise to a significant number of injuries and fatalities and, historically, its record has been poor in comparison with other industries. It is useful to consider situations in terms of 'hazard' (something with the potential to cause harm) and 'risk' (the resultant likelihood that harm will occur from the hazard, taking account of the controlling measures introduced). Certain specific aspects of the construction process have easily identifiable potential hazards – for example, activities involving craneage manoeuvres; working at high level, particularly in exposed areas such as roofs; working in trenches and tunnels. These are generic hazards relevant to the designs of all disciplines.

For those designing mechanical and electrical systems in buildings, however, the nature of the fuels, systems and equipment involved means that they have specific inherent hazards that need to be properly managed and controlled. Specific H&S hazards could potentially arise from a variety of sources: electricity, gas, combustion, water, drainage, sewerage, steam, hot surfaces, rotating plant, noise and vibration, fumes, fibres, particulate matter, confined spaces, chemicals, compressed air and many others. The nature of the construction process provides a sense of impermanence – the creation of a one-off, short-term, in situ activity, where the 'workplace' is undergoing continual change and can have a high degree of workforce density and on-site mobility. This inevitably makes it more difficult to manage risks, when compared with industrial activities in surroundings of a more permanent and easily controlled nature.

It is important to have a whole-life approach to H&S management, and the recent legislative developments (HSE 2007, 2012) have recognised this. In some ways, it parallels the life cycle approach required for sustainability, by looking beyond just the delivered and completed construction to cover lifetime usage and, ultimately, dismantling or demolition as well. The building services designer must, therefore, consider the potential hazards that could arise during the whole-life of the building:

1 Construction and installation: H&S hazards arising from the delivery, assembly and installation of systems and equipment as part of the overall construction process.
2 Testing and commissioning: H&S hazards arising from the process of testing equipment and systems, and making adjustments during the commissioning process; and when setting systems to work in their final operational state.
3 Usage: H&S hazards arising from usage of the building by occupants.
4 Operation and maintenance: H&S hazards arising from the activities required to operate and maintain systems and equipment throughout their operational life.

5 Dismantling, replacement and demolition: H&S hazards arising from the activities at the end of its useful life for systems, equipment and components.

While (1), (2), (4) and (5) relate to activities undertaken by competent personnel, the hazards at (3) relate to building occupants who are not competent with MEP systems, and these obviously require careful consideration. Building Regulations are largely concerned with this aspect of H&S.

Normal good practice is for most potentially hazardous items of MEP plant and equipment to be located in segregated plant rooms and risers, so that they are only accessible by competent personnel. The selection and arrangement of spaces for plant therefore needs to take into consideration relevant H&S matters. This aspect of building services design is covered in Chapter 12.

In the UK, regulations are in place to improve the management of H&S related to the construction process, and the use of the building throughout its life – the CDM regulations (HSE 2007). The primary aim of the regulations is to integrate H&S into the management of a project and to encourage everyone involved to work together in order to:

- improve the overall planning and management of H&S considerations on construction projects from the outset;
- identify potential hazards at an early stage in order to eliminate, or at least reduce, them at the design stage. This will allow the remaining residual risks to be managed properly.

The regulations introduced the role of the CDM coordinator, who coordinates the activities of the design team members to manage H&S aspects during the design process; to compile all information for future use by others; and has a continuing role during the construction stage.

The regulations place certain specific duties directly on all designers:

- to eliminate hazards where it is feasible to do so;
- to reduce through design the risks from those hazards that cannot be eliminated;
- to provide suitable information on the nature of residual risks if they are significant, so that they can be communicated and consciously addressed by others.

Designers are specifically required to avoid foreseeable risks, where it is practicable, taking account of other design considerations (HSE 2012). In order to discharge these duties, a competent building services designer will need sufficient knowledge of how their system components are delivered and assembled, together with experience of the construction and installation process. For instance:

- know how to identify the potential hazards that will arise throughout the construction, operation, maintenance, cleaning and dismantling of the works designed;
- satisfy themselves that they can identify at least one safe method for constructing or installing the work they have designed.

In the recent past, designers often sought to discharge their duties under the CDM regulations by creating formal risk assessments for each identified hazard, in which they made a numerical or relative evaluation of the initial and residual risk. This risk assessment approach has been considered to be unsatisfactory. This is because, while it created a considerable amount of 'audit trail' paperwork, it was questionable as to the real impact it had on reducing H&S risk, which is the whole purpose of the regulations. Rather than creating paperwork, the main focus of the designer should always be on eliminating the hazard from the design. If this is not economically practical, they should always seek to reduce the hazard and communicate in explicit terms the nature of the residual hazard to those who must manage it during the construction stage; and during later stages, where this is appropriate. The principal contractor is the construction organisation that manages the hazards during the construction stage (HSE 2012).

Following elimination of as many hazards as possible, a 'Residual Hazards' list can be passed to the principal contractor. This will enable them to properly plan and cost the construction phase, taking into account measures that will be necessary to address the residual risks. This list could include (HSE 2007, 2012):

- the nature of the activity that gives rise to the hazard;
- the specific hazard identified;
- the types of people who are likely to be at risk;
- an outline of the specific measures that have been taken within the design to eliminate or reduce the hazard;
- explicit information about the residual hazards that the design team has identified.

The type of information to be provided to the principal contractor for the significant residual hazards would include the nature of the hazard, and what has been done by the designers to allow the principal contractor to manage the hazard effectively. It is essential that designers in each discipline communicate effectively on H&S matters, and liaise with the appointed CDM coordinator. It is preferable for information on residual hazards to be clearly identified on drawings, where they will be seen by the relevant parties, rather than just covered in specifications.

An example of a design feature that can eliminate or reduce hazards is a prefabricated plant room. These can be provided for MEP equipment, such as boiler houses, generator rooms and switchrooms. This approach allows construction to be undertaken off-site in a factory environment where H&S and quality control measures can be better managed than in a construction site environment. In situations where plant rooms are located at roof level – as is often the case – the use of a prefabricated enclosure complete with the required MEP equipment can significantly reduce the extent of activities in this potentially hazardous location. It will primarily require lifting the prefabricated plant room into location by a crane, followed by fixings and connections to the relevant distribution elements. Such an approach might also be preferred for its cost effectiveness, reduced time involved and (potentially) lower embodied energy of materials; but it should be clearly recognised as a good solution to reduce H&S risks.

2.7.4 EU Energy Performance of Buildings Directive (EPBD)

The EU EPBD has introduced three legal requirements to promote reduction in carbon emissions from buildings during their operational life: Energy Performance Certificates (EPCs); Display Energy Certificates (DECs); and air-conditioning inspections.

EPCs must be produced when a building is constructed, sold or rented out. The EPC will grade a building's energy performance on a scale from A to G, in a similar manner to domestic 'white goods' products. At the conclusion of the design stage, relevant information about the building and systems is required to allow production of the EPC by a suitably qualified person. The certificates are valid for 10 years and must be accompanied by a recommendation report.

DECs are provided on an ongoing basis following occupancy. They provide an overall picture of energy consumption, but this is not apportioned to individual systems.

This Directive is covered in detail in Chapter 4.

2.8 Quality management for designers

It can be seen that the design stage for construction projects is a complex process involving many individuals of different disciplines, usually across a number of different organisations. For a consistent and successful outcome, the design stage must be undertaken as a professionally controlled and managed process. So that a design can be developed in any discipline, it is essential that all relevant design related information is stored, updated and maintained in a properly structured manner. This allows easy access for all the designers and others to the relevant information. It is also necessary so that it is formally defined in relation to provenance – authorship, date, revision, and cross-references to other material. A formal quality management (QM) procedure is required for the design process in the same way as for many other quality controlled processes in business and industry. Most design organisations hold QM certification for their design activities from an independent accreditation body, in accordance with criteria such as British Standards or the ISO. This requires a comprehensive set of principles and procedures to be in place to ensure that quality can be maintained throughout the design process. This normally includes a filing management regime that covers aspects such as:

- appointment and brief;
- recording any subsequent client instructions and changes in a sequential manner. This will cover all confirmed changes to the brief and the associated correspondence;
- recording design stage approvals and any client conditions and directives that need to be addressed in subsequent stages;
- complete sets of design calculations and evidence of the checking regime. This will include manual calculations; computer calculations together with the associated input data, and the interpretation of the output; sketches and diagrams; and formal drawings;
- registers of the issue history of drawings and updates from the designer, and the receipt of those of other designers with whom the design has been integrated and coordinated;
- registers of the issue history of equipment schedules;
- details of all design reviews: usually at an interim stage and at output stage, immediately prior to tender issue for procurement (see below);
- registers of the issue history for all specifications, studies and reports.

An important part of the QM process is the undertaking of design reviews. Careful consideration should be given to the strategy for the review process at the outset, so that it is appropriate for the project's scale and complexity. It is normal for all calculations and drawings to be checked independently, usually by a competent colleague. Most projects have independent design reviews, usually at an interim or scheme design stage; and at the output stage, prior to the information being issued for tender and procurement. Where the project involves a non-standard brief or design approach involving innovative principles or technologies, it is important to have a detailed peer review of the concepts prior to proceeding. The design review activity will normally involve checking the developed design against the original brief and changes to the brief, together with checking adherence to (and acceptability in relation to) standard engineering principles and the relevant statutory and industry standards and regulations. It will usually result in marked-up comments related to calculations, drawings and specifications recording the reviewer's recommended aspects for attention. There should be a mechanism through which the designer absorbs and acknowledges each comment, and records that this has been done. Large, important and technically complex projects might have many design reviews, both within the design organisation, and externally. Clients sometimes appoint a separate consultant as a monitoring or 'checking consultant' for this purpose.

One important objective of the QM process is to create an 'audit trail'. This means to retain all necessary information to demonstrate how the final design came about, such that this could be inspected by a third party. An audit trail is essential should there be any future litigation in relation to the design. Project files, including the design and calculations files, are usually archived for a number of years in accordance with the conditions in the designer's appointment agreement with the client.

With the growing use of modern common electronic information exchange systems for projects, the emphasis has shifted to auditable electronic filing.

2.9 Summary

To undertake their role successfully, building services designers must have a clear understanding of their own duties, and the duties of other professionals within the design team. It should be recognised that building and engineering systems design is an iterative and interdisciplinary process, requiring cooperation, integration and negotiation. Teams should work together in a collaborative manner. The design normally proceeds to a programme through clearly defined stages, with cost reporting on the proposals and client sign-off before approval to proceed to the next stage. A key early activity is the development of the design brief to confirm the specific aspects influencing the building services concepts. Sustainability matters and targets should be considered from the outset by all disciplines. In order to influence these aspects, building services engineers should be involved in the decision making at the earliest concept design stage. The design proposals eventually form a detailed set of production information that is issued for tender and procurement of a contractor. The building services designer must adhere to relevant legislation, policies and codes; and has particular duties in relation to the H&S management of the systems designed, and an involvement in submission for planning consent and building control compliance. Designers' work should be undertaken within a QM process to maintain the quality of the design outcome and delivered material; and to create an audit trail of the design decisions and information exchange that resulted in the final design.

Chapter 3

Generic design strategies for low-carbon buildings

3.1 Introduction

This chapter outlines a strategic approach to reducing carbon emissions in buildings. The focus is on appropriate generic design considerations that can be addressed in priority order as practical steps to promote energy efficiency. Specific technical aspects are not covered in depth here, as most of these are explored in Chapters 5 to 9. Reference is made to selected aspects of the approved documents to the Building Regulations in England and Wales, to provide some context of regulatory frameworks for energy conservation. It should be noted that this chapter only covers strategies related to carbon mitigation. It does not address the many other issues relevant to sustainability in buildings – such as water, drainage, materials, recycling and biodiversity – which should also be considered as part of a wider strategy for sustainable design.

3.2 Developing a focused approach

A useful approach to achieving low-carbon buildings is shown in Figure 3.1, and involves a sequence of planning, designing and managing. The design process stages were described in Chapter 2. The early stages will involve appraisal of the site to assess the physical features and ambient conditions, and hence the options available to satisfy the development's requirements with minimal use of carbon. The site appraisal can influence the locations and layout of building(s) on the site. The next step is to design the building(s) and systems based on a logical energy hierarchy. The third step is for the building(s) to be operated in an efficient way, while meeting the functional requirements.

In Chapter 1, a conceptual model was presented of an approach to reduce carbon emissions in buildings. This proposes that the focus should, first of all, be on reducing energy demand. The energy demand is a function of both necessity – to achieve comfort and functional criteria – and demand management. The energy demand will depend on many factors, and will vary with the building type and function, but for most building types it will be largely determined by the characteristics of the envelope – primarily the thermal performance of the external walls, glazing and roof. The initial focus is, therefore, on optimising the envelope, building form, orientation and massing; and incorporating such passive features that might be appropriate to beneficially utilise available ambient conditions, and thereby reduce the need for active energy. Another aspect of demand reduction is to put in place such management regimes and controls

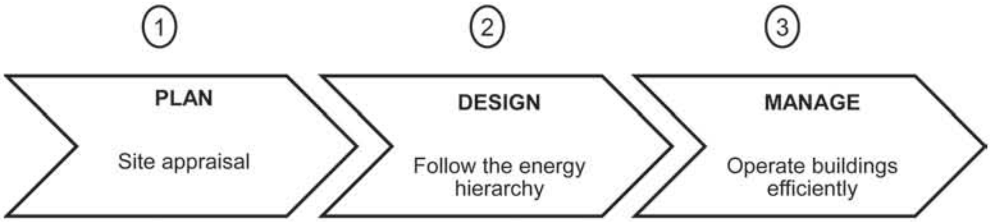


Figure 3.1 Path to low-carbon buildings

facilities that will reduce the usage of active energy to only that amount required to satisfy the occupancy criteria, adjusting accordingly as requirements and occupancy patterns vary. The intention is always to do this without reducing the 'enjoyment' or the functional performance of the occupied space. This aspect of demand reduction is a function of technology (automatic controls, monitoring and metering); the management regime for operation and maintenance; and occupancy behaviours.

An important starting point, therefore, is appropriate engagement with the client at the design briefing stage, and to seek an opportunity to communicate with the operational and maintenance (facilities management) staff who will be responsible for running the building's services. This will provide an opportunity to explore features that can be incorporated to allow ease of operation, maintenance and energy management consistent with their preferred approach. It will also provide an opportunity to review any assumptions about occupancy behaviours that might be amenable to review, with the intention of adopting a less energy intensive approach. These measures will reduce the need for active energy. Such early engagement may not always be possible, however, particularly for speculative buildings.

The second priority is to address the active energy provision process, which can be considered as comprising all of the processes for energy generation, supply, distribution and the active energy using systems in the building. The emphasis is on efficient energy supply and simple energy efficiency measures that have traditionally been good engineering design considerations. Systems should be designed to be inherently energy efficient, and incorporate the simple steps that can be taken to minimise carbon emissions, such as recovery of heat in thermal systems.

The use of renewable energy systems should be considered as the third stage of the hierarchical energy strategy. Provision of renewable energy might be subject to specific local authority planning policy, requiring a proportionate on-site contribution. However, renewable energy should be seen in the context of other carbon reduction measures, so that the relative effectiveness and potential limitations are understood. In many cases renewables may not be an appropriate choice compared with investment in more rigorous energy efficiency measures. There is no real sense in incorporating renewables where they would be merely offsetting carbon emissions arising from the use of inefficient systems; the active systems should, instead, be made more efficient. Simple energy efficiency measures may not be glamorous, and may have no visible presence to occupants or the public, but are usually far more effective than some of the more 'token' renewable technologies that are often – incorrectly – seen as the essential hallmarks of sustainability.

A sensible order of priority for addressing carbon mitigation through design would be:

- optimise the building envelope by utilising passive design strategies to reduce the energy demand. 'Passive design' means utilising the building itself to assist in creating the desired internal environment, through suitable design and selection of the shape, form and orientation; and the thermal and light transmission characteristics of relevant building elements;
- further reduce the demand through energy efficiency measures in the active systems;
- supply energy efficiently, for example by incorporating combined heat and power (CHP) (co-generation) – but only where there is a suitable load pattern;
- incorporate suitable renewable energy technologies, where appropriate.

Renewable energy technologies generally come under the term 'low and zero carbon' (LZC) technologies.

In the UK, a useful example of an energy hierarchy of this type is the London Plan of 2008 (GLA 2008). This can be expressed in simple terms as:

- Be LEAN: be energy efficient (i.e. reduce the demand);
- Be CLEAN: incorporate low-carbon energy sources (i.e. supply energy efficiently);
- Be GREEN: incorporate renewable energy sources.

This was adopted as the planning policy for London and has laid particular emphasis on promoting connections to district heating schemes, and the use of site-wide energy networks and on-site CHP. Figure 3.2 shows an energy hierarchy based on this approach.

By undertaking passive design and energy efficient design for the active systems, the energy demand will have been reduced to its 'leanest' level, and will make the 'clean' energy supply measures most effective. An appropriate incorporation level of renewables can further reduce the level of carbon emissions.

In essence, the factors affecting energy efficiency can be broken down more conveniently into passive aspects, active aspects and the arrangements for the whole-life operation, as shown in Figure 3.3. These overlap to some extent, and cover both design and operational aspects, but need to be considered together in the decision making at the design stage. Sections 3.4, 3.5 and 3.6 respectively cover generic strategies for passive aspects; active engineering systems (including renewables); and whole-life aspects, for operation.

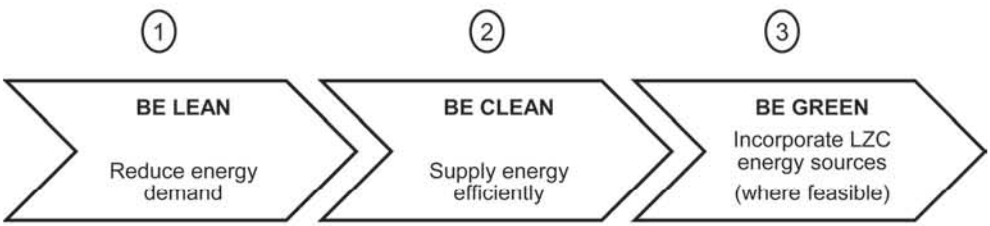


Figure 3.2 Energy hierarchy

Source: London Plan, GLA 2008

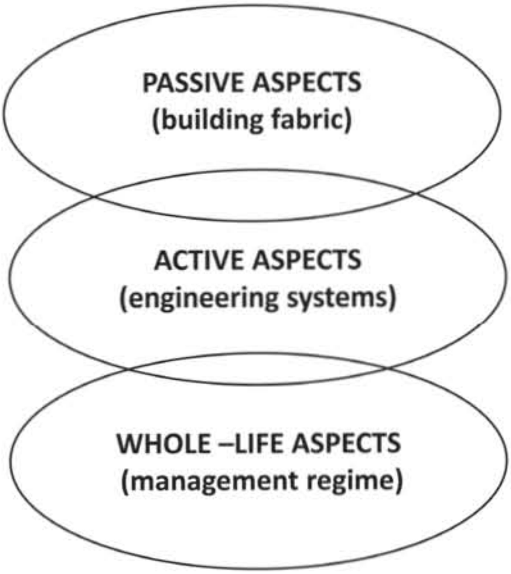


Figure 3.3 Key considerations for energy efficiency

It will, of course, be necessary for the design to comply with any relevant statutory and/or local codes and policies related to conservation of energy and/or carbon reduction. So a design strategy can be established as outlined here, while also ensuring that the design achieves compliance with prevailing regulations, which are likely to include similar considerations to achieve similar objectives. Section 3.7 provides a context for regulatory criteria, using the Building Regulations approved documents in England and Wales as an example.

3.3 Energy strategy reports

The best way to encapsulate an appropriate approach is to set this out as a formal energy strategy report. A report of this type is required for obtaining planning consent by a number of local authorities in the UK, and should ideally be an integral part of the early stage design process outlined at Chapter 2. It is good practice to include a suitable energy strategy statement for all large planning applications (CIBSE 2007). An energy strategy report should provide recommendations on the principles affecting the energy and carbon performance, including:

- site factors;
- available energy infrastructure, including community energy schemes;
- estimated thermal and power loads;
- statutory legislation and other standards and regulatory criteria;
- benchmark data or building-specific energy analysis based on modelling;
- initial energy assessment outcomes;

- initial proposals for shape, form, orientation, envelope and other passive design features;
- fuel selection, energy generation and distribution proposals;
- energy efficiency measures for active energy systems;
- ambient energy potential and incorporation of renewable energy technologies, where appropriate;
- approach to compliance with regulations, codes and planning; and targets for environmental assessment methodologies;
- initial data, metrics and predictions for energy consumption, carbon emissions and the associated cost implications;
- correlation of the energy strategy with wider objectives for sustainability and whole-life matters.

The following sections provide an introduction to the key generic strategies. Where appropriate, each refers to other chapters where the particular aspect of design is covered in detail.

3.4 The building envelope and passive design measures

3.4.1 Concepts for passive design

The energy performance of a building is, to a very large extent, determined by the location, shape and form of the building and the properties of the envelope in contact with ambient conditions: the roof, external walls and relevant floor slab(s). Using a passive design approach, the envelope can be designed to minimise the amount of carbon emissions from active energy systems. The site's potential for renewable energy should be assessed at the same stage, and should form part of the energy strategy report.

Figure 3.4 shows the basic concept for a passive approach in very simple terms in relation to reducing the demand for cooling. An inappropriate approach is shown on the left, in which there is no solar control for the windows, resulting in overheating. With this approach, to maintain an acceptable indoor climate, an extensive mechanical cooling system will be required, resulting in a major operational energy demand, which will use carbon intensive electrical energy. This is also a high 'embodied energy' solution for the building services equipment required; needs space and ongoing maintenance for the equipment; and, furthermore, involves refrigerants with global warming potential and ozone depletion potential impacts. A passive or holistic approach is shown on the right, in which solar control features are provided in terms of louvres and carefully specified glass (body-tinted, low-emissivity) or interpane blinds. This will minimise the solar gain in the space, requiring no, or only minimal, mechanical cooling and much reduced operational energy usage. This will also result in lower embodied energy (for the louvres and blinds), compared with that for an extensive mechanical cooling system. This approach is all about reducing the demand using passive features so that the requirement for active energy systems and the associated operational (and embodied) energy is reduced.

The complex subject of building physics and passive design is beyond the scope of this book. However, all building services designers should recognise that the performance of the structure and fabric should be the initial focus for their attention.

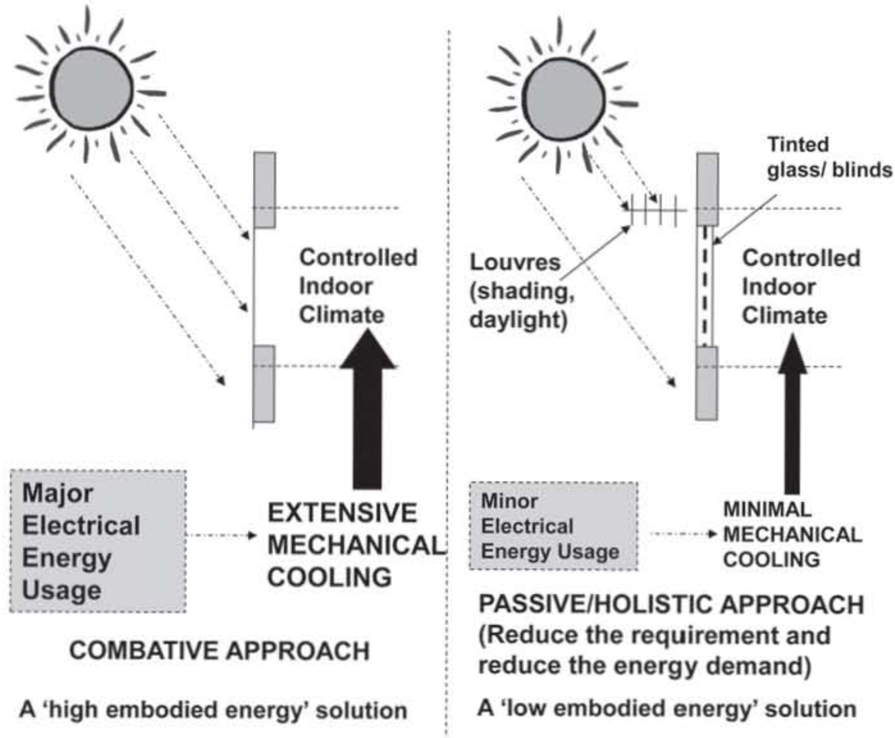


Figure 3.4 Developing a passive approach: concept

We describe them here in a fairly simplistic sense as an introduction to some of the main considerations. For detailed guidance, reference should be made to other publications covering building physics, building science and information on the thermal performance of building materials (Rennie and Parand 1998). There is a renewed focus on the need for research and education in building physics, to address the relatively limited guidance available, as outlined in the 2010 Report from the Royal Academy of Engineering (King 2010a).

In order to create an acceptable envelope, it will be necessary to work closely with the architect from the outset to explore and evaluate site considerations and the practical options for location and orientation of the building(s). These issues are complex, because all aspects are interrelated and cannot be viewed in isolation. Computer modelling is used extensively as a tool to inform design and/or check compliance with Building Regulations. The specialist area related to the interdisciplinary design of the external facade is an evolving discipline sometimes termed 'facade engineering'. The objective is to achieve an optimum balance for the envelope's energy performance, alongside achieving a satisfactory outcome for non-energy aspects, such as aesthetics, planning, acoustics and fire performance. The intention, from an energy perspective, is for the envelope to modify the climate through moderating those aspects that are undesirable, and encouraging those aspects that are beneficial (CIBSE 2004a; Rennie and Parand 1998). This will usually include:

- providing useful levels of daylighting;
- providing natural ventilation, where practical;
- minimising heat losses from fabric and infiltration during cold periods;
- minimising solar gains during hot periods;
- maximising solar gains during cold periods.

The specific intentions will depend upon the geographical location (and hence the prevailing climate conditions) and whether the building type means there will be a predominant need to limit or attract solar intrusion. However, it is worthwhile listing key features individually, as outlined below.

3.4.2 Location, shape and form

If the size and nature of the site provides some freedom to select the location of the building, use can be made of features that might assist the energy performance. The main features that can be beneficial are shown in Figure 2.8. Existing trees or buildings can provide a shelter belt to minimise exposure to prevailing winds, as well as providing visual delight, a sense of well-being, better air quality and biodiversity. There is less opportunity to benefit from trees in urban settings. Where there is a significant slope in the ground, partial burying can provide energy benefits. The use of ambient conditions to provide renewable energy is discussed briefly at 3.5.13, and in more detail in subsequent chapters.

The form of a building is an important starting point, as the requirements for other aspects of the nature and physical characteristics of the building envelope will follow on as consequences from the three-dimensional shape (CIBSE 2004a). Desirable features that should be sought are:

- seek a shape that minimises the surface area in relation to the volume, so that the heat losses (and gains) from outside air are reduced to the minimum for each unit of occupied space. This tends toward seeking a form that is compact, rather than long and narrow;
- minimise elongated exposed blocks (or elements) protruding from the main body of the building, as they will have relatively higher heat losses (or gains) per unit volume;
- avoid exposed overhanging floor slabs, which will give rise to additional heat losses compared with floor slabs in contact with the ground;
- a narrower floor plan will assist daylight penetration and improve the potential for natural crossflow ventilation, as outlined in Chapter 5;
- include or encourage internal courtyards, light wells or 'streets' to promote daylight and natural crossflow ventilation.

3.4.3 Orientation

Where a building is likely to require cooling during summer periods (such as an office building) seek a shape that is orientated on an east–west axis. This will minimise solar gains from low sun angles in the early morning and late afternoon. Solar gain from higher sun angles in the middle of the day can be more easily controlled by horizontal shading.

3.4.4 Thermal insulation

To minimise static heat losses (and heat gains, where appropriate) from heat flow due to external design temperatures, the overall envelope should be designed so that the proportion of glazed areas is minimised compared with non-glazed, or opaque, areas; and both opaque and glazed areas should have the lowest U-values that might be economic and practical for these elements. However, it is usually necessary to seek a balance, as some solar gain is beneficial; and it will, of course, be necessary to take account of other considerations, such as the desirability of providing good levels of daylighting. It is often the case that walls will require high levels of insulation. Compared with other desirable features of the envelope, this can be achieved in a relatively easy way through selection of suitable fabric 'sandwich' construction for walls related to materials, air gaps and thicknesses. There is a tradition in cold northern climates to have 'super insulation' at levels well above those that have been the norm in the UK. However, highly insulated spaces with low levels of air infiltration can potentially give rise to condensation problems.

3.4.5 Solar control

While selecting a suitable orientation will limit the total amount of solar radiation on the facade of a building, further reduction must be achieved through control features on the facade that will shade the glazed areas, and thus reduce the transmission of solar heat gain through the glazing. Solar control features should be considered alongside the glazing characteristics and inter-pane blinds, as part of an overall approach to minimising the impact of solar gains. In each case, the key determining factor is the sun's path at the building's location in relation to the orientation of the facade. There is a wide variety of features, some of which can only be integral to the architectural treatment, and the resulting geometry, of the facade; and others that can be considered more as discrete control features, as listed below.

- overhanging roofs and eaves that provide shading to glazed areas;
- balconies and other overhanging or protruding structural elements arising from the geometry of the facade that provide shading to lower levels;
- window reveals, or balconies with inset walls, that are deep enough to provide shading, both horizontally and vertically;
- horizontal slatted louvres that provide interception to the sun's rays, but which will allow some daylight to penetrate at particular angles. The louvres can be in the horizontal or vertical plane. The most effective (optimal) blade spacing and angle geometry can be selected through computer modelling. It is possible to incorporate motorised horizontal louvres that will adjust the pitch of the blades as the sun's angular position changes, to optimise solar control performance. However, practical experience has shown that the motors and actuators require considerable maintenance due to weather impact. The best solution is nearly always the simple solution of fixed-position louvre blades;
- louvred shutters;
- vertical fins that can be narrow, but can be placed on east and west-facing facades to provide useful shading from the lower angles of the sun path earlier and later in the day;

- a natural solution that can bring wider benefits is to locate deciduous trees close to the south facade. This solution can provide solar shading in summer, when the trees are in full leaf; and allow beneficial solar gain to penetrate into the building when the leaves have been shed in the winter;
- awnings and external blinds – which allow manual adjustment so as to control the solar cut-off angle – can be useful, provided that they are not exposed to windy situations and suitable maintenance is undertaken.

3.4.6 Glazing and rooflights

The locations, shapes, sizes and characteristics of glazing – whether windows or glazed panels within cladding on facades, or incorporated as rooflights or similar – will have a fundamental impact on the internal environment and energy performance. From a thermal point of view, glazed areas will always have higher U-values than opaque areas, so they are major areas of static heat loss and heat gain, and solar gain. This is normally undesirable, but can be desirable in circumstances where solar space heating is a viable proposition. From a lighting point of view, of course, glazed areas provide the natural lighting that is an essential amenity requirement for occupied spaces and suitable provision can significantly reduce the energy required for artificial lighting. From an acoustic perspective, glazed areas are a weak point in the envelope and will often have a detrimental impact on the acoustic integrity of a space, particularly where there are exacting noise criteria.

There are, therefore, conflicting positive and negative impacts from glazing. Inevitably, a balance is usually required between the appearance and the thermal, visual and acoustic issues. The design of the glazed components of a facade is one of the key areas requiring a cooperative and integrated approach with the architect in order to reach an optimal solution. It is one of the main aspects of design resolution that will impact upon the passive energy performance, and hence the requirements of the active engineering systems. Among the characteristics of glazed components that should be considered are:

- U-value, thermal transmission index and light transmission index;
- body tints that might be useful in certain circumstances, but these should be considered with care as they can have a detrimental impact on daylight and cause spaces to appear gloomy;
- for retrofits in existing buildings, light tubes can provide a useful way of introducing daylight into areas that would otherwise have little or no daylight from glazing.

In seeking a balance, there should be a particular emphasis on achieving good levels of daylight, as this has such a significant impact on creating a satisfying interior with a sense of well-being. A robust solution is to select low-emissivity double glazing with a thermal transmittance similar to triple glazing; and an 80% light transmission factor (CIBSE 2004a)

3.4.7 Thermal mass (external and internal)

While the (area-weighted) thermal transmittance of envelope components will determine the static heat flow, the thermal mass will determine the dampening of temperature changes due to thermal inertia, and the extent to which the structure can act as a thermal buffer. Buildings and parts of buildings can be considered as more 'heavyweight', or 'lightweight', depending on the amount of thermal mass. External and internal walls (and floor slabs) can be thermally massive due to the specific heat capacity of their materials and their thickness. This will cause these parts of the building structure to absorb and store a proportion of the heat (or coolth), rather than letting it pass through, resulting in a thermal time lag which evens out, or smooths, the internal temperature variation. By selection of suitable arrangements of thermal mass of appropriate specific heat capacity, the time lag can be such that heat (or coolth) can be stored when not wanted and released when beneficial. For example, when utilising solar space heating, heat can be stored in well-insulated floor slabs and walls through exposure to solar radiation during the daytime; and can be released in the evening, when required as the external temperature falls. Similarly, where cooling is required during the day, it can be achieved by 'night-time cooling' through ventilation, i.e. by introducing naturally ventilated air at high level to exposed soffits at night, to cool them down. This is so that, when the external temperature rises during the day, the internal temperature swing is reduced (see Chapter 5).

A useful arrangement when seeking to minimise solar gains is for the east and west walls of a building to be provided with significant thermal mass, where practical in relation to the architecture. This reduces the effect of the prolonged periods of lower sun angles early and late in the day, and thus limits the temperature levels resulting from the solar influences later in the day. Solar shading can be provided on the south facade to shade against the high level sun during the middle of the day.

The thermal effects of the multitude of structural elements within buildings of different thermal transmittance and mass can only be assessed in detail through dynamic modelling. Chapter 10 describes the principles of thermal load assessment using admittance, to demonstrate the impact of thermal inertia.

3.4.8 Control of air infiltration

It is necessary to control the level of air infiltration to avoid additional heat losses in cold periods, and heat gains during hot periods. This requires good sealing and attention to architectural details for elements of the building envelope. Controlling air infiltration can be more problematic when the pressure differential increases, for example in tall buildings and buildings in exposed locations. Controlling air infiltration can also contribute to satisfying acoustic criteria by reducing noise infiltration. Section 3.8 describes the limiting design criteria in Part L. Chapter 5 outlines the design approach to air infiltration in relation to natural ventilation.

3.4.9 Arrangement of internal spaces

The allocation and disposition of spaces within buildings should be planned so that, where possible, their comfort criteria can be achieved in the most energy efficient way. This goes beyond passive design for the envelope; it is about appropriate adjacencies for spaces and the suitability of locations for areas with different functions. Of course, it must always work alongside architectural aspirations for the internal planning and circulation; and the functional interrelationships between spaces. In many cases there might be limited scope to achieve this, but it is usually worth exploring. Examples could be locating areas which are more sensitive to temperature variation, and which require good daylighting, on the north side; locating space which is transient with low environmental requirements in more problematic perimeter areas; and grouping spaces with similar environmental requirements together, providing the potential to utilise local plant.

3.4.10 Influence on architectural form

The need for energy demand reduction through passive design is likely to have a continuing influence on the appearance of contemporary buildings. There is now much more evidence of solar control features, sometimes incorporated within more complex facades that are a fundamental aspect of the architectural expression. There is likely to be a move toward well-insulated, thermally heavyweight construction; and much less evidence of lightweight buildings with continuous facades of unshaded glazing. This trend is likely to continue.

Figure 3.5 is of a contemporary office building showing a good example of an energy efficient approach. The building's orientation and envelope have been designed to provide optimum energy performance. The wide horizontal louvres extending from the south facade, and the deep overhang roofs on the east and west, are prominent

Figure 3.5 Low energy office building: Red Kite House, Wallingford, UK

Source: Redshift Photography's image

solar control features and are becoming more commonplace on modern buildings. The building has been orientated to benefit from the prevailing wind direction so that it can use natural ventilation. This is also used at night-time for pre-cooling the office spaces in conjunction with the thermal mass of the exposed concrete soffit. The building also uses building-integrated renewable energy systems: photovoltaics and solar water heating. Chapter 4 includes a post occupancy case study on this building.

Figure 3.6 shows a residential development where particular attention has been given to the energy performance of the envelope through the characteristics and spatial relationship of opaque and glazed elements. The building features low U-values for walls, windows and doors, together with low thermal bridges and air permeability.

Figure 3.7 shows a distribution warehouse for a brewery where the envelope has a high level of thermal mass, a 'green roof' and minimal glazing. This provides a suitable level of thermal inertia to maintain stable internal temperature conditions for storing beer, with minimal use of active energy.

Figure 3.6 Low energy residential building: Mariners' Quay, Newport, UK

Source: Andrew Hazard's image

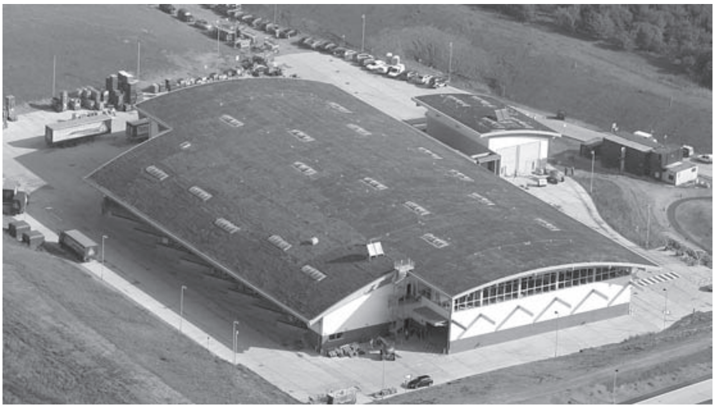


Figure 3.7 Low energy storage building: Adnams Brewery Distribution Centre, Suffolk, UK

Source: image courtesy of Adnams Brewery

3.5 Active elements: engineering systems

3.5.1 Key energy consuming systems

Having explored the potential for utilising passive design to reduce energy demand (and minimise the need for active systems), the next requirement is to look at the strategic approach for the required active engineering systems. It should be noted that there is an overlap between features that minimise energy demand (i.e. reduce the magnitude of the load and/or its duration) and those that improve the energy efficiency of the system itself. The measures are noted generically here and most are covered in detail in other chapters. Many of the features listed are interrelated, to some extent. To provide a focus for measures to reduce carbon, it is useful to examine the systems that account for the highest emissions and which would benefit from most attention. This will vary with the building type, so it is useful to look at the typical breakdown by end-use in different sub-sectors of the built environment.

Figure 3.8 shows the breakdown of final energy consumption in commercial office buildings in the UK, by system. It can be seen that delivered energy consumption in offices is dominated by heating. The figure for lighting is next highest, at about one-third the value for heating, followed by cooling and ventilation. A process load – computing – is higher than the next fixed building service – hot water services. As a comparison, the final consumption breakdown by system for the retail sub-sector is shown in Figure 3.9. Here the highest energy consumption is for lighting, which is just above the figure for heating. A process load – catering – is next highest, followed by cooling and ventilation. It should be noted that Figures 3.8 and 3.9 represent an aggregate for all buildings in the relevant sub-sector. As such, they are representative of the

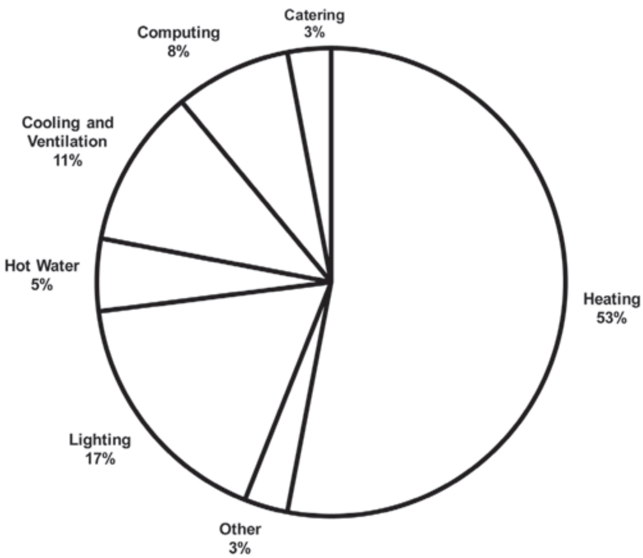


Figure 3.8 Breakdown of final energy consumption in commercial office buildings

Source: DECC 2012

building stock as a whole, and do not, therefore, represent contemporary standards and design approaches or specific new building types. For both sectors, the energy consumption under 'other' is not defined, but it is likely to primarily relate to lifts and escalators. This would be expected to be higher in the retail sector, with high levels of inter-floor traffic throughout the day, compared with the commercial offices sector.

The pattern for the hotels and catering sub-sector is different. The proportion of end-use energy consumption for heating (at 33%) is not too far ahead of catering (at 26%); and hot water (at 17%) is above lighting (at 14%) (DECC 2012). For warehouses, heating (at 52%) and lighting (at 20%) together account for nearly three-quarters of the overall consumption (DECC 2012). In the UK residential sector (which represents the majority of the building stock), energy consumption tends to be dominated by heating, followed by hot water and lighting; although the specific pattern will be depend upon the nature of the accommodation and occupancy. These are general figures, but still provide a useful indication of how energy usage patterns differ across building sectors.

Examining system contributions by carbon emission (rather than final energy consumption) will present a different picture. Because grid-derived electricity has a carbon impact about 2.6 times that of gas, then for the system contributions shown in Figure 3.8, the carbon emissions due to lighting would be just below those from heating (assuming heating to be gas-fired). For Figure 3.9, the carbon emissions due to lighting would be about three times those due to heating (again assuming heating to be gas-fired).

A further consideration for carbon mitigation strategies is 'process' or 'uncontrolled' loads. This covers loads such as electronic equipment in offices, data processing or computer installations, audio-visual, catering and other equipment that

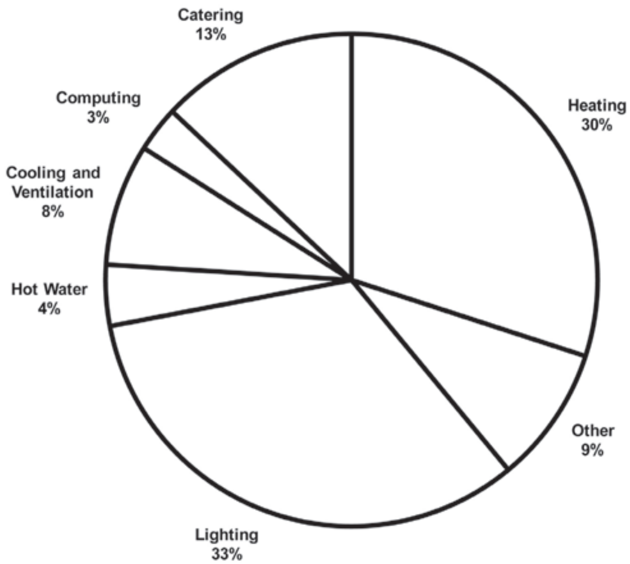


Figure 3.9 Breakdown of final energy consumption in retail buildings

Source: DECC 2012

can be deemed to be part of the business processes, rather than 'servicing' the occupied spaces in the building. These loads receive little attention in regulatory frameworks. While this can help to focus attention on the fixed building services systems, it can be seen from Figures 3.8 and 3.9 that process loads (computing and catering) can be significant. Moreover, process loads will contribute to the internal gains, and hence energy demand for cooling and ventilation. Carbon reduction strategies should address process loads.

3.5.2 Energy strategy and fuel selection

The main features of an energy strategy are outlined in Section 3.3. In order to choose the most appropriate fuels for the different energy using services, it is necessary to understand all of the relevant factors. These will consider aspects such as anticipated loads, availability to meet the capacity, access, space, delivery and storage (where required), as well as the environmental impact and costs.

The load or demand assessment aspects are described in Chapters 10 and 11. At the earliest design stage, it is useful to develop simple demand profiles for heating, cooling and power (CIBSE 2007), which will aid the decision making for fuel types and provide a focus for the main areas requiring attention. Figure 3.10 shows typical 12-monthly demand profiles. In the UK, natural gas is usually the preferred choice for heating where a suitable capacity of mains supply is available. For the present grid supply scenario, electricity should be considered to be a premium secondary fuel – due

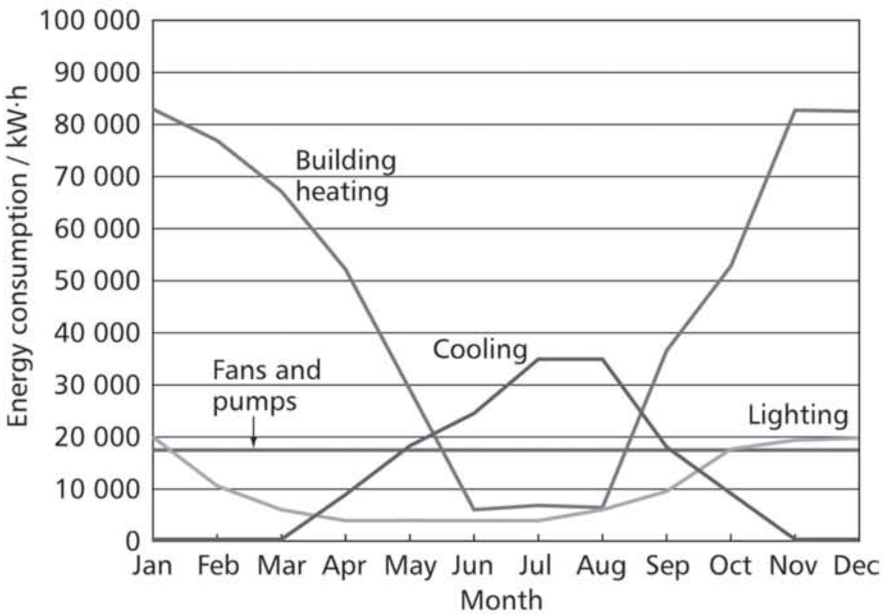


Figure 3.10 Typical 12-monthly heating and cooling demand profile

Source: reproduced from CIBSE Guide L (2007) with the permission of the Chartered Institution of Building Services Engineers to its high primary energy carbon factor – and should therefore be used sparingly. It is, therefore, inappropriate for heating purposes, except in special cases. However, as the planned de-carbonisation of grid electricity takes effect, some re-consideration may be necessary. This is due to the versatility of electricity – the majority of energy using equipment can utilise electricity – and its ability to be derived from a variety of sources.

Where the concurrent thermal and electric load pattern is suitable, CHP/co-generation can provide a low-carbon solution for a proportion of the annual requirements. A CHP engine provides a means of concurrently generating heat and electricity that is both highly cost effective and has a considerably reduced environmental impact. CHP can only be used in certain circumstances where there is a suitable load scenario; but where this is the case, it is likely to be the single most beneficial active engineering measure to reduce the level of CO_2 emissions and running costs (CIBSE 2004a; IET 2008) (see Section 3.7).

3.5.3 Energy efficient plant and distribution arrangements

A key consideration for any active engineering system is the extent to which plant will be centralised or dispersed, as this will have a considerable impact on the energy losses due to distribution, and hence the overall energy efficiency. The basic approach should be similar for power, heating and cooling distribution, namely to locate the plant close to the main load centre(s), to minimise distribution losses in relation to the anticipated annual load pattern. The plant arrangement (i.e. the numbers and sizes of items of plant to meet the required installed capacity) should be selected to provide the best overall performance through the range of load scenarios. The norm might be a part-load condition well below full load, so diurnal and seasonal variations in energy efficiency should be considered. This will often require selection of multiple equal-sized modules or components to provide the best opportunity for optimised energy performance for the anticipated load pattern, and for future load growth. The selection should consider base-load capacities and shared part-load efficiencies. The need for energy efficient distribution relates not only to primary distribution (or infrastructure), but also the distribution elements of systems, such as cabling, ductwork and pipework. The intention is always to design distribution elements so that they are inherently energy efficient by reducing lengths and resistance per unit length.

Spaces that are remote or used on a highly intermittent basis should be served by separate localised plant that can be sized accordingly and run independently of central plant. In such cases, it is usually better to run smaller, slightly less efficient plant, rather than running central plant with significant distribution losses, and/or running in an inefficient mode for long periods.

It will also be necessary to minimise standing losses in all systems and equipment. This applies most obviously within thermofluid systems, to reduce energy losses from bypasses and redundant legs. It also applies to electrical systems, including lift systems, multiple parallel UPS systems and standby loads for process equipment.

3.5.4 Energy efficient HVAC systems

The systems for controlling the indoor climate are pivotal to the overall building services design strategy and the energy performance. Suitable HVAC systems should be selected to satisfy the comfort criteria for the spaces served and to provide a healthy indoor climate. This will include considerations of the characteristics of the emitters or terminal devices, and their locations within the spaces, so that the conditions are maintained effectively within the occupied zones. It will also include the methods for generation of heating and cooling power; the types of thermofluid circuits and their operating modes; and the arrangement and characteristics of fans or pumps for circulation. Treated spaces should be subdivided to allow separate control in a meaningful and representative way, so that spaces with different conditions or criteria act differently. It should be possible to match the particular energy demand with fast response, through suitable controls, so that energy consumption is no more than necessary to meet the requirements.

Systems should minimise the creation of waste heat; and maximise the beneficial re-use of any waste heat that is unavoidably created, including heat recovery and recirculation of 'valuable' treated air, where this is viable. Designs should seek to minimise unwanted heat gains into cooled spaces; and similarly maximise unwanted heat gains into heated spaces, where this is practical (CIBSE 2004a) (see Chapters 5 to 8).

3.5.5 Explore the design parameters

Design parameters, particularly those related to comfort conditions, should be explored and challenged, where appropriate, to see whether there is some scope to relax them – or perhaps to seek a partial relaxation, for certain times and circumstances and thereby reduce energy demand (CIBSE 2007). This relates primarily to thermal and illumination criteria, which have a fundamental influence on energy demand. It also relates to acoustic criteria, which can influence attenuation requirements in ventilation systems, and hence fan power (and embodied energy). The opportunity to relax criteria will depend, to some extent, on the client's flexibility. However, the designer can identify, as part of the design brief development, the order of carbon (and hence cost) benefit versus the perceived shortfall in conditions for specific parameters, so that an informed choice can be made.

3.5.6 Motive power for fans and pumps

The main motor-driven components within the HVAC systems are circulation pumps for heating or chilled water systems, and fans for mechanical ventilation systems. The motors that drive pumps and fans can consume a considerable amount of energy. This can be optimised through selection of the motor drive equipment, as outlined in Chapter 9; and through selecting suitable parameters for the hydronic or ventilation systems, as outlined in Chapters 5 to 8.

3.5.7 Coolth generation

The carbon impact related to the generation of cooling power will depend upon the types of equipment, choice of refrigerant and system parameters. This is covered in Chapters 6 to 8.

3.5.8 Lighting

Artificial lighting systems should be selected so that they maintain appropriate lighting of the spaces, utilising natural daylighting wherever practical. There is a particular need to minimise lighting energy usage in spaces that require cooling, as it represents an internal gain that will require additional cooling energy to offset (see Chapter 9).

3.5.9 Process or uncontrolled loads

Process, uncontrolled or unregulated loads can represent a significant level of energy consumption, which can, in turn, increase the energy consumption for cooling and ventilation in many buildings. However, there is often considerable wastage of energy from small power systems and other process loads, so it is one of the main areas requiring attention by the management regime (see Chapter 9).

3.5.10 Hot water services

Hot water services usually account for a relatively minor proportion of energy consumption in most commercial and public buildings, when compared to HVAC systems and lighting, but it varies with building type. The relative proportion will be higher in buildings with high water usage, such as hospitals, hotels, leisure centres and certain types of residential accommodation. The primary focus should always be to reduce demand through incorporation of water efficient devices, such as low flow showers (see Chapter 8).

3.5.11 Lifts

In some types of buildings there can be high levels of lift passenger traffic, either due to the disposition of the occupants by floor and/or the nature of the occupancy activity. In such cases, lifts can account for significant levels of energy consumption. Various measures can be taken to optimise energy performance (see Chapter 9).

3.5.12 Controls, metering and monitoring

All of the active engineering systems will require suitable controls to ensure that regulation takes place to maintain the functional performance at relevant times, while minimising energy usage. Metering and monitoring will also be required for the ongoing involvement and attention from the management regime. The provision of controls, metering and monitoring can be considered as an aspect of both the active engineering systems and the management regime, as outlined in Section 3.6 (see Chapter 9).

3.5.13 Renewable energy technologies

The potential for utilisation of a site's available ambient or renewable energy should be considered within the energy strategy report. The main site considerations for renewable energy are the solar path and the wind pattern, as shown in Figure 2.8; together with ground (and possibly water) conditions for ground source energy systems. Solar and wind aspects will depend on the location and site factors, such as latitude, elevation and exposure. As stated earlier in this chapter, renewable energy technologies should not be considered as the first step in a low-carbon energy hierarchy. They should, instead, be a lower priority consideration and assessed in the context of the relative benefit of other available carbon reduction measures. Renewable technologies should only be considered as viable if they provide a cost-effective solution; or if their environmental or social benefits can be deemed to outweigh any additional costs when compared to alternative measures (CIBSE 2004a).

The range of renewable technologies that could be considered would typically include the list below (see subsequent chapters)

- wind power
- photovoltaics
- solar thermal energy for hot water
- ground energy sources.

The key to selecting appropriate renewables is to understand the site potential and make a careful assessment of the likely, and most appropriate, renewables contribution that would be sensible within an overall coherent energy strategy. All renewable technologies will have a capital cost and an energy 'cost' related to embodied energy, together with some operational and maintenance costs. All renewables could involve some of the issues listed below, to a greater or lesser extent, which basic energy efficiency measures may not require:

- capital cost justification and/or client approval;
- grants, to make an economically viable case;
- planning permission, particularly where equipment is visible, or where water courses or groundwater might be affected;
- novel or untested technologies;
- maintenance;
- complexity and risk related to integration with the site, building and active engineering systems;
- additional space allocation within the building or on the site, which has a cost impact and might limit other design aspirations.

The cost comparison will vary with location, load pattern and other factors. It is likely that the cost assessment will be subject to regular change, due to variations not only in the capital and operational energy costs, but also in the availability of grants and (where applicable) the tariffs for the sale of exported energy. It is always necessary to distinguish between cost per unit of carbon reduction (which relates to primary energy) and cost per unit of delivered energy reduction. It should be emphasised that the cost assessment, and hence the viability, will be highly dependent on location.

3.6 Whole-life operation: management regime

As outlined previously, the realisation of good energy performance will, in practice, depend upon the way in which the building is occupied and managed. We can consider the 'management regime' to encompass both the formal arrangements for operating the building, and also the behaviours of the occupants – which can, in turn, be influenced to a considerable extent by the management regime. The desired outcomes can only be achieved through the combined involvement and commitment of both the operational staff and the occupants.

In order to encourage the occupants to adopt the most appropriate behaviours, it will be necessary to get their commitment and engagement, which can be assisted through providing education and information on the building's energy performance. This should directly relate the energy and environmental impacts in a way that can be understandable in relation to occupancy behaviours, management and personal intervention (CIBSE 2004a). The psychology of behavioural engagement is well beyond the scope of this book, but it should be recognised that creating a sense of ownership and involvement can be an essential factor in the success of the building.

The management regime should include an active strategy for energy management (CIBSE 2008a). This would be in the form of a comprehensive energy management policy that forms an integral part of (or is developed alongside) the overall plan and regime for operation and maintenance (CIBSE 2004a). This is also a function of plant space allocation to ensure maintenance effectiveness, as outlined in Chapter 12. A monitoring plan should form a key part of the policy, and include a metering strategy to allow continuing monitoring and control of the energy consumption. This will require a mixture of automatic and manual controls, metering and monitoring facilities that jointly provides the human–machine interface (HMI). The concept is shown in Figure 3.11 Appropriate automatic and manual control features should

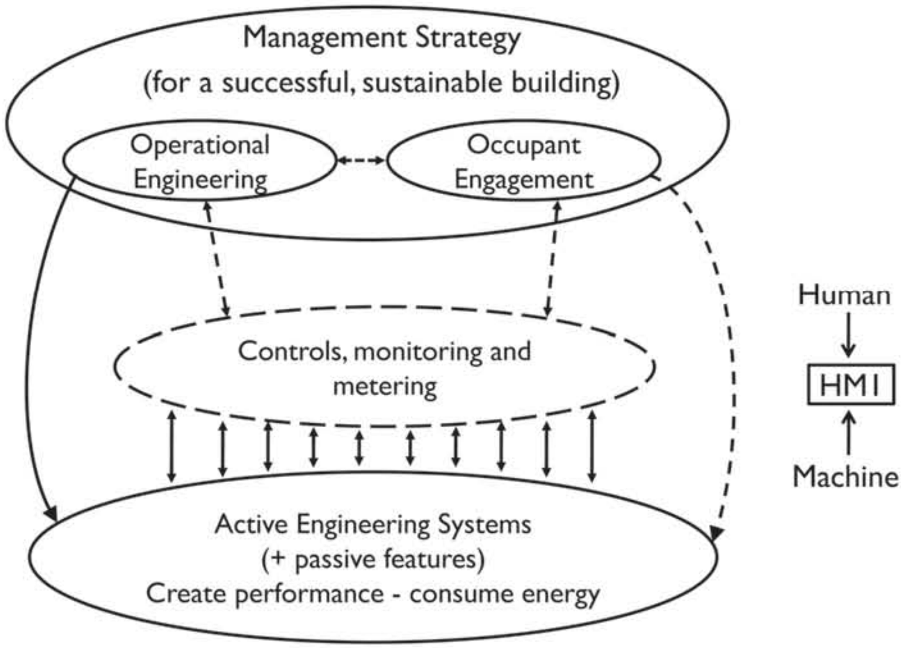


Figure 3.11 Concept for controls, metering and monitoring

be incorporated within designs to facilitate matching system usage against actual requirement. This can include exploiting the operational variables in systems so that the mode selected is the most appropriate for the changing usage pattern of the building (see Chapter 9).

The active engineering systems should be amenable to initial testing and commissioning in an integrated way, allowing the building and systems to perform in the manner intended by the design (CIBSE 2004a). This should include demonstrating achievement of design conditions for the anticipated range of scenarios. It is also useful to provide independent validation of the results; and to seek optimisation through extended involvement during the initial period of occupation, as outlined in the BSRIA Soft Landings Framework (Bunn and Usable Building Trust 2009).

The systems should also be amenable to subsequent operation, adjustment and regular fine-tuning throughout the building's life, so that optimal energy performance can be achieved and maintained as the norm. This can be achieved through close agreement with the client and operational staff and the adoption of a suitable strategy for planned maintenance, usually including schedules of maintenance activities for all building services equipment, which will contribute to its energy efficiency. For example, to reduce fan energy consumption, there should be a planned activity for cleaning filters on a regular basis and replacing them periodically, so that the pressure drop does not increase. Because the occupancy arrangements and functional needs will change with time, it is inevitable that some periodic fine-tuning will be necessary. This will include making adjustments to the systems, so that they match more closely the changing needs. Certain systems might require occasional partial re-commissioning from time to time so that the range of likely changes can be accommodated. This could include changes of usage; changes of occupancy types and levels; re-arranged layouts; or new departments, functions and associated equipment resulting in changes in internal gains (CIBSE 2008a).

3.7 Combined heat and power (CHP)

The basic principle and logic for co-generation of heat and power has been outlined in brief in Chapter 1. Conventional heat engines used for electricity generation only convert about one-third of their fuel (primary energy) input into mechanical energy, which is then available for conversion to electrical energy via an alternator. In a CHP plant, the engine is fitted with heat exchangers to capture the heat that would normally be rejected (e.g. from exhaust, jacket cooling, lubrication oil) and use it for applications such as space, water or process heating. Heat and power are therefore generated simultaneously, which provides a significant increase in overall energy efficiency. The specific efficiency will depend on the engine type and rating, the load cycle, and so on. Typically, up to 80% (and possibly more) of the fuel input can be converted into useful energy (IET 2008; CIBSE 2009a). Figure 3.12 shows an energy balance for a typical small gas-fired CHP plant. Utilising CHP not only reduces emissions of carbon dioxide and operational energy costs, but can also reduce the relative levels of other pollutants that arise from conventional generation.

The prime mover for CHP systems used in buildings is normally a gas engine. It could also be a micro gas turbine. These are reciprocating engines fuelled by natural gas. Heat is recovered from the engine's exhaust and the cooling water jacket. The

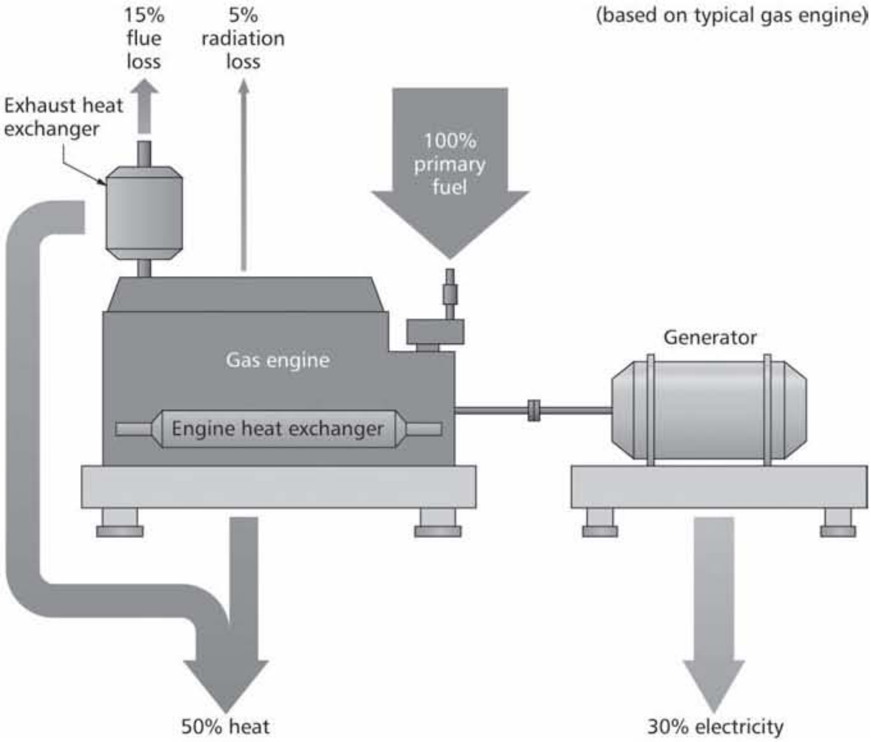


Figure 3.12 Energy balance for a typical small gas-fired CHP plant

Source: reproduced from CIBSE KS14 (2009a) with the permission of the Chartered Institution of Building Services Engineers

low grade heating requirement for space and water heating allows a high proportion of heat recovery from otherwise wasted heat. However, it must be recognised that CHP is only viable in certain situations and applications. For CHP to be viable it usually requires specific site load criteria, namely daily demand for heat and power for the whole, or a considerable part of the year. If the thermal demand is not coincidental, there should be a facility to store heat to suit the usage pattern. The main factor to consider in selecting a CHP size is the building's base heat load, so that the heat utilisation can be maximised. The most favourable sites will have heat demand throughout the year; while a good guide for economic viability is that the plant should operate at, or close to, full load for more than 5,000 hours p.a. (CIBSE 2009a) Assessing the balance between economic and environmental benefits is complicated, as it relates to fluctuating energy prices (IET 2008). But typical cost payback can be in the order of 5 years in suitable applications. However, the electricity output can be considered as more valuable than the heat output, in both economic and environmental terms (IET 2008).

The CHP plant is normally sized so that the daily heat output is equal to the daily base heating load; so the presence of a base-load heating demand is the key. The control system should ensure that the CHP plant always operates as the 'lead' heat generator (IET 2008; CIBSE 2009a). The electric power available is used when the CHP plant is running to meet the thermal demand, and operates in parallel with the mains grid supply. When planning the sizing and integration of a CHP plant into the main heating and power systems, there are important design considerations on both the thermal and electrical sides (CIBSE 2004a). On the thermal side, there are issues concerning temperatures, pressures and thermal storage in relation to the heating demand and the operating characteristics of other items of heat-generating plant. On the electrical side, there are considerations related to parallel operation, controls, protection, earthing and the load characteristics, including harmonics.

To allow a CHP unit to generate electricity to a level where the corresponding heat output is more than required at that time by the system and/or thermal store, a 'heat dump' facility would have to be included to reject the excess waste heat. If the plant is oversized, at times there will be an excess of heat that has to be dumped. It is obviously undesirable to have an operational cycle that involves significant dumping of heat, as it will be less beneficial in environmental and economic terms (IET 2008).

CHP has widespread applications in industries where there are continuous process thermal loads. In terms of buildings, typical applications are:

- swimming pools, because of the continual requirement to heat pool water, and for space heating;
- leisure centres and large hotels, because of the continual requirement for hot water;
- hospitals and similar institutions, because of the continual requirement for hot water;
- large residential developments or campuses, because of the continual requirement for hot water;
- district heating schemes.

The assessment of viability for CHP should be based on detailed profiles for the thermal and power loads. These should be both realistic and reliable so that they represent diurnal and seasonal load variations with a high level of confidence (Carbon Trust 2010; IET 2008). It should be noted that the relationship between power and heat output varies with the engine size. In most cases, the power ratio increases with engine size while the heat ratio reduces. Each CHP machine will have two efficiencies: one related to power generation, and one related to heat generation. The power efficiency is more important in economic terms (IET 2008). It is most important to ensure that the assessment for CHP plant does not result in a plant capacity that is oversized. This has been the problem with many installations that have not yielded the anticipated energy savings. In order to provide most benefit, it is preferable to design for a smaller plant capacity that is utilised for a greater proportion of time (i.e. has a high duty cycle), rather than a larger plant capacity that is under-utilised.

For CHP plant in new and existing buildings, the guidance for Building Regulations Part L includes two specific criteria for annual operation. The power efficiency, which is the total annual electricity output divided by the annual fuel input, should be greater than 20%; and the plant should be sized so that it supplies at least 45% of the annual total heating demand (DCLG 2010b).

The overall efficiency of the CHP plant, n, should take account of the part-load operation, and can be expressed as:

$$n = \frac{Q\ \text{heat} + Q\ \text{power}}{Q\ \text{fuel input}} \tag{3.1}$$

Where:
Q heat = annual useful heat supplied
Q power = annual electricity generated (net of parasitic electricity use)
Q fuel input = annual energy of the fuel supplied (in gross calorific value terms)

Similarly, the heat to power ratio, R, can be expressed as:

$$R = \frac{Q\ \text{heat}}{Q\ \text{power}} \tag{3.2}$$

Large-scale CHP is the norm in some parts of northern Europe where there is a commendable energy policy based on total energy generation, rather than narrow considerations of electricity generation alone. There are numerous city-wide schemes that provide district heating in an economic way due to the high load density. Certain types of residential developments can benefit from community energy networks fed from CHP and district heating systems where the load pattern and density is appropriate. For such schemes to be successfully integrated, the overall planning should include the necessary space for the infrastructure in the street, with suitable allowance in ducts for the pipework and cabling; and buildings should have 'wet' heating systems for future-proofing to allow heat exchange via heat interface units, with the potential to benefit from other low-carbon sources, as well as CHP (Bateson 2009). In contrast, the UK has traditionally had a relatively small amount of CHP generation; however, this has been rising in recent years. In 2011, the UK had an installed CHP electrical capacity of 6,111MWe, having risen from 4,451MWe in 2000 (DECC 2012b). In 2011, the proportion of electricity in the UK that was generated from CHP plants was about 7.4%, or just over 27,000GWh; while the total heat generation was over 48,000GWh (DECC 2012b).

3.8 Regulatory context: Building Regulations Approved Document Part L in England and Wales

3.8.1 Background

Many countries have legislation in place to regulate the conservation of energy in buildings. Building services designers must create and submit their design proposals to the relevant authorities in the required format to achieve compliance in accordance with the prevailing legislation, at the design stage and post-completion. In England and Wales, the Building Regulations Approved Document Part L (DCLG 2010a) is the document covering conservation of fuel and power. The Approved Document provides practical guidance on ways in which compliance can be achieved for the relevant energy efficiency requirements of the Building Regulations. Reference is made here to selected aspects of Part L 2010 only, providing some context of regulatory frameworks and how they influence the design approach.

The 2010 regulations are a development of earlier versions in which regular improvements have been made to reduce environmental impact. The 2006 regulations represented a significant tightening of the carbon emissions criteria compared with the previous version (2002), with typical reductions in target levels for non-residential buildings in the order of 28%, and about 20% for residential buildings. The strategic objective for Part L 2010 was to further reduce carbon emissions from the building stock, and also to improve compliance by closing the performance gap between that predicted at design stage and the actual emissions as measured at completion. The stated aim was to achieve an overall reduction in carbon emissions of 25%, relative to the 2006 regulations, as cost effectively as possible. The objective was to achieve this in two ways: first, as a flat 25% reduction for domestic buildings; and second, as an aggregate 25% reduction for non-domestic buildings. Similar incremental levels of reduction are planned for the next versions due in 2013 and 2016. It is likely that similar step-changes will take place every few years (driven by EU directives) as part of the move toward the concept of 'zero emissions' buildings (however this might be defined); so the anticipated future scenario is for continual reduction in the permitted emissions.

It is usual for the primary energy fuel factors used within the CO_2 emissions calculations to change with each update. In the 2010 regulations, the carbon emission factor for grid gas increased by 4% to 0.198kgCO_2/kWh, and for grid electricity by 22% to 0.517kgCO_2/kWh, compared with 2006. These figures are historically dependent upon strategic government fuel and energy generation policies and the time-frame considered.

With the urgent need to reduce emissions, and the anticipated significant tightening of criteria in the near future, it is appropriate to see the Part L criteria as the minimum acceptable performance standards, rather than the actual preferred target. They represent a set of overall regulations for carbon reduction against which designers need to demonstrate compliance; but that does not prevent designers from aiming for further improvements in performance, some of which may not be too difficult to achieve. This aspect of the project brief should be discussed with the client as part of environmental target-setting during design brief development. Indeed, other aspects of environment benchmarking may override Part L targets (such as targets set by an environmental assessment methodology).

The regulations cover new buildings and changes to existing buildings, for domestic and non-domestic buildings:

Part L1A	Domestic buildings (new)
Part L1B	Domestic buildings (existing)
Part L2A	Non-domestic buildings (new)
Part L2B	Non-domestic buildings (existing)

Because of the relatively higher energy impact per unit area of non-domestic (i.e. commercial and public) buildings, the following sections mainly relate to Part L2A as an example of the requirements. While they are not included in the regulations at present, it is likely that the criteria for future revisions will be expanded to include additional energy efficiency benchmarks of building services design performance, such as external lighting and vertical transportation. Indeed, they might include these within the calculations for the building target CO_2 emissions.

3.8.2 Criteria for compliance in Part L2A

The regulations have five criteria, which have a sequential relationship. Of these, Criterion 1 is a regulation, while Criteria 2 to 5 are for guidance.

Criterion 1 relates to the building's calculated emission rate for CO_2, called the building emission rate (BER). This figure is required to be no greater than the target emission rate (TER) for the building. In order to achieve compliance, a target-achieving building has to be presented in the design submission. The regulations do not provide a direct target figure for CO_2 emissions. Instead, the building design has to be input into approved software. This creates a notional building with specific properties that is geometrically similar to the proposed building. The TER figure is the CO_2 emissions rate from the notional building. This provides a flexible approach as a BER which is equal to or less than the TER can be achieved using any mix of design factors for the envelope, active engineering systems and LZC technologies, as long as the building meets the limits on design flexibility in Criterion 2.

Criterion 2 relates to the performance of individual elements of the building fabric and the fixed building services, i.e. the fixed systems for heating, hot water services, air-conditioning or mechanical ventilation and internal lighting systems (but excluding emergency escape lighting or specialist process lighting). The regulations require that these should be no worse than the stated limiting design figures. The intention is to place limits on design flexibility. In reality, the various aspects will need to be considerably better than the limiting values in order to meet the TER figure under Criterion 1. Selected examples for Part L2A are:

- For the system efficiencies of the fixed building services, these must be equal to or better than the minimum efficiencies in the Non-domestic Building Services Compliance Guide (DCLG 2010b).
- For ventilation systems, there are limitations on fan power per unit of air flow rate. The specific fan power (SFP) in watts per l/s is the total design circuit watts of all the fans that supply and exhaust air in the air distribution system, divided by the system's design air flow rate. It includes losses in switchgear and controls. For example, there is a limiting SFP of 1.8 for a central mechanical ventilation system that includes heating and cooling, or 1.6 with heating only. There are allowances for components such as additional fine filters and heat recovery devices. The guidance suggests that fans rated at more than 1100W should be equipped with variable speed drives.
- There are minimum efficiencies for heat exchangers for dry heat recovery, e.g. 50% for a plate heat exchanger and 65% for a thermal wheel. However, it should be noted that the notional building in Criterion 1 utilises heat recovery, with sensible efficiency of 70%, in zones with mechanical supply and extract.
- There are design limits for fixed lighting. For general lighting in office, industrial and storage areas, the average initial efficacy (100 hour) should be not less than 55 luminaire-lumens per circuit-watt. This is the average for all luminaires in the

relevant areas of the building, divided by the total circuit watts. Luminaire-lumens is (lamp lumens × LOR), where LOR is the light output ratio. Control factors may be applied to reflect the energy reduction arising from controls. For example, for a luminaire in a daylit space with photoelectric switching or dimming control, a control factor of 0.9 can be applied.

- For cooling systems, chiller performance is expressed as a seasonal energy efficiency ratio (SEER), which is defined by calculation. There is also a cooling system seasonal energy efficiency ratio (SSEER). This takes account of distribution losses and fan energy associated with heat rejection.
- For heat generators there are seasonal coefficients of performance (SCOP).
- For elements of building fabric, the limits on design flexibility have not changed since 2006, as shown in Table 3.1.

The design limit for air permeability relates to the airtightness of the building envelope that encloses 'treated' spaces. It is the air leakage rate per hour for each square metre of envelope area (i.e. the total area of all floors, walls and ceilings bordering the internal volume) at the reference pressure differential of 50Pa. The regulations provide a design limit of $10m^3/(h.m^2)$ @ 50Pa. While it is allowable for air permeability to be as high as $10.0m^3/(h.m^2)$ @ 50Pa, the notional building assumes an air permeability of $5m^3/(h.m^2)$ @ 50Pa. Therefore, an increase in air permeability beyond this level is likely to make it more difficult to achieve the target BER.

Criterion 3 relates to control measures to limit solar gains. It requires that appropriate measures are provided to limit solar gains through glazing to each space that is occupied or mechanically cooled, with the intention to reduce the requirement for mechanical cooling.

Criterion 4 is about measures for ensuring that the performance of the completed building is consistent with the predicted performance of the BER assessment. This includes a requirement for testing of the achieved permeability, the air leakage rate from ductwork and the commissioned fan performance.

Criterion 5 relates to the operation of the building. It requires that certain provisions are put in place to enable the building to be operated in an energy efficient way. This includes provision of information in a log book, including the data used in the TER/BER calculation and the Energy Performance Certificate recommendations.

Table 3.1 Part L2A: limiting U-value standards (W/m^2K)

Element	*U-value (W/m^2K) (worst acceptable standard based on area-weighted average for all elements of that type)*
Wall	0.35
Floor	0.25
Roof	0.25
Windows and rooflights	2.2

Source: DCLG 2010a

3.8.3 Key features or likely combinations to achieve compliance

For many buildings it is likely that the *easiest* way to reduce carbon emissions would be simply to reduce the U-values to well below the limiting values in the regulations, for example by using triple-pane glazing or higher levels of insulation. However, care needs to be taken, particularly with low levels of air infiltration, to avoid condensation. It is likely that achieving compliance for many buildings might require a mix of features, such as (Wisby 2010):

- glazing U-value of about 1.5W/m^{2}K and proportions reduced to about 40%;
- energy efficient lighting with passive infrared plus daylight controls;
- mechanical ventilation with heat recovery with an efficiency of 70%;
- larger cross-sectional areas for air-handling units (AHUs) and distribution ductwork, to lower the SFP (see below);
- variable speed pumping on all variable volume systems;
- energy efficient terminal units;
- integration of one or more LZC technologies.

The building is likely to require a ‘tighter’ envelope and to meet Criterion 3 the facade solar gain analysis will be of crucial importance, which requires attention to the facade detail by the architect. A good approach at the outset is to seek to reduce infiltration and provide a controlled level of mechanical ventilation with heat recovery.

In order to meet the limiting fan power targets, it is likely that the cross-sectional areas of ducts will have to increase considerably to reduce velocities and hence system resistance and pressure drop. AHUs and fans are, therefore, likely to increase in size. To meet thermal targets, heat recovery will be an important feature; and to realise the potential for heat recovery in ventilation systems, it is essential to bring supply and exhaust ductwork close together at a suitable location, so that there can be an efficient heat exchange. So, in terms of both the sizes and locations of supply and extract ventilation plant, there are clear implications for space planning (see Chapter 12).

It is likely that, for some buildings, energy efficiency measures alone will not be sufficient to achieve compliance, and there will be a requirement for some form of LZC technologies, typically in the form of CHP plus some contribution from renewables. One effect is that ground source and air source heat pumps are likely to be regarded more favourably for heat generation than gas boilers. There has been recent growth in the use of air source heat pumps for domestic developments, although noise issues and the visual impact of external units can be difficult to address.

3.9 Summary

In this chapter we have seen the need for a focused approach to carbon mitigation, based on a logical hierarchy of measures. The starting point should be to reduce demand by optimising the building envelope with respect to heat loss, heat gains and daylight. An introduction has been provided to passive measures that can be considered. The next priority should be to incorporate energy efficiency and demand reduction measures in the energy supply and the active engineering systems. Efficient energy supply systems, such as CHP, can provide major carbon reductions in appropriate building-integrated applications. A brief introduction has been provided for the generic energy efficiency considerations of the most relevant mechanical and electrical systems, all of which are covered in some depth in subsequent chapters. Incorporation of renewables should generally be a lower priority. It is essential to address all the technical issues related to renewables, particularly the likely energy yield and carbon savings in practice, so that the viability can be assessed in the context of alternative carbon reduction measures.

An essential aspect of the approach for delivering energy efficient buildings is the adoption by the client of a management regime that will be committed to running the building in an optimal way. Some of the key considerations for effective whole-life operation have been outlined, including commissionability and a planned and structured approach to operation and maintenance.

While building services designers can identify a suitable hierarchical approach to energy performance, they must, as a minimum, ensure that their designs comply with the relevant regulatory requirements. The Building Regulations Approved Document in England and Wales Part L has been briefly described, as an example. The requirements for new non-domestic buildings have been outlined in brief, together with the likely implications for specific elements of the design.

Chapter 4

Post occupancy evaluation for optimal energy and environmental performance

4.1 Introduction

This chapter outlines the methods of carrying out a post occupancy evaluation (POE) of a building. It continues from the previous chapter which outlined how to address sustainability at the design stage to outline how to assess whether sustainable design strategies have been implemented and operated successfully. The POE is of practical importance in the improvement of existing buildings and also generally as it can help to inform design decisions for future buildings by highlighting common pitfalls and successes to be avoided/implemented.

With the introduction of Energy Performance Certificate (EPC) regulations and Display Energy Certificates (DEC) for most buildings in the UK and other European countries, the investigation of design and operational energy performance is compulsory (or it will be soon) for most buildings; the investigation of environmental performance and user satisfaction seems to be the next step. As in Chapter 3, this chapter only covers carbon mitigation, and not the many other issues relevant to sustainability in buildings, such as water, drainage, materials, recycling and biodiversity.

4.2 The European Energy Performance of Buildings Directive (EPBD)

In Europe, as elsewhere in the world, there is a strong demand to reduce energy use, both to mitigate CO_2 emissions and to strengthen security in supply. In the case of buildings in European Union member countries, this is managed through the Energy Performance of Buildings Directive (EPBD Directive 2002/91/EC), which requires member states to apply minimum requirements covering the energy performance of new and existing buildings. The EPBD therefore plays a major role in forming building energy policy in the EU. The Directive requires:

- a common methodology for calculating the integrated energy performance of buildings;
- minimum standards on the energy performance of new buildings and existing buildings that are subject to major renovation;
- systems for the energy certification of new and existing buildings and, for public buildings, prominent display of this certification and other relevant information. Certificates must be less than five years old;

- regular inspection of boilers and central air-conditioning systems in buildings and, in addition, an assessment of heating installations in which the boilers are more than 15 years old.

The common calculation methodology must include all aspects that determine energy efficiency and not just the quality of the building's insulation. This integrated approach should take account of aspects such as heating and cooling installations, lighting installations, the position and orientation of the building and heat recovery, etc.

Some countries have based minimum standards on a reference building approach in which a specified minimum improvement over an equivalent 'reference building' is required. However, this has led to anomalies that can result in air conditioning being used even when it is shown to be far more energy intensive than equivalent passively cooled buildings providing the same level of comfort. Some countries have avoided the reference building approach and based requirements on an actual energy target irrespective of the means by which this is achieved. In such cases an allowance or 'fictitious' cooling amount is often factored into the energy design calculation to discourage a low energy solution that subsequently requires air conditioning to meet comfort needs. In other words, if a design is shown to not reasonably fulfil summer thermal comfort requirements, an allowance for subsequent cooling energy must be factored into the energy estimate, even if a cooling system is not included in the initial construction. Evaluation is largely based on approved calculation methods followed by energy monitoring of the actual building once constructed (Liddament 2009).

This chapter does not cover the requirements and methodologies to produce EPCs and DECs required by the implementation of the EPBD as these are regulated by Building Regulations (mainly Part L in the UK) of different countries in Europe.[1]

4.3.1 Case study: the present implementation in the UK

EPCs are now required in the UK for all commercial buildings whenever built, rented or sold. The certificate records how energy efficient a property is as a building and provides A–G ratings. These are similar to the labels now provided with domestic appliances such as refrigerators and washing machines. An EPC is always accompanied by a recommendation report that lists cost-effective and other measures (such as low and zero carbon generating systems) to improve the energy rating. A rating is also given showing what could be achieved if all the recommendations were implemented. EPCs are produced by accredited energy assessors.

DEC show the actual energy usage of a building, the operational rating, and help the public see the energy efficiency of a building. This is based on the energy consumption of the building as recorded by gas, electricity and other meters. The DEC should be clearly displayed at all times and clearly visible to the public. A DEC is always accompanied by an advisory report that lists cost-effective measures to improve the energy rating of the building. Figure 4.1 shows the DEC of one of the buildings at Brunel University for 2011.

At present in the UK, DEC are only required for buildings with a total useful floor area over 1,000m^2, that are occupied by a public authority and institution providing a public service to a large number of persons and therefore visited by those persons.

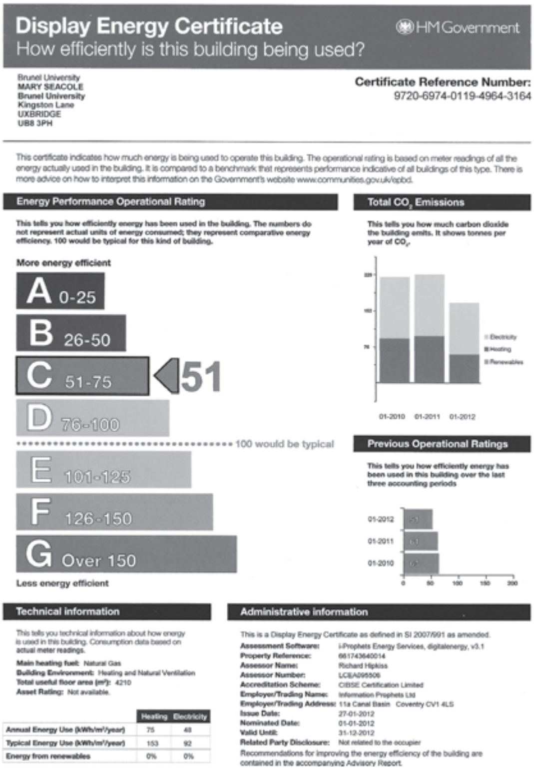


Figure 4.1
Example of a DEC in the UK taken from one of the buildings at Brunel Campus, Uxbridge

Source: courtesy of Brunel University

They are valid for one year. The accompanying advisory report is valid for seven years. The requirement for DEC came into effect on 1 October 2008.

4.3 Why do we need POE?

Energy assessment (already covered by Regulations in Europe as outlined in the previous section and elsewhere) is not the only issue to be addressed by a POE which is wider to include environmental conditions and user satisfaction.

4.3.1 *Environmental assessment tools*

A number of environmental assessment tools have been developed with BREEAM and LEED being the most well known.

> BREEAM (BRE Environmental Assessment Method) was developed by Building Research Establishment (BRE) in the UK in the 1990s. Credits are awarded in nine categories according to performance and combined together using the weighting of each category to produce a single overall score. A building is then awarded a Pass, Good, Very Good, Excellent or Outstanding depending on its overall score. These categories include management, health and well-being, energy, transport, water, materials, waste, land use and ecology and pollution. There are BREEAM schemes for a range of building types.

LEED (Leadership in Energy and Environmental Design) was developed by the US Green Building Council (USGBC) for the US Department of Energy. The first version was launched in August 1998. In LEED version 3 (2009), there are 100 possible base points plus an additional six points for innovation in design and four points for regional priority. Buildings can qualify for four levels of certification which are: Certified (40–49 points), Silver (50–59 points), Gold (60–79 points) and Platinum (80 points and above). The rating system addresses six major areas which are: sustainable sites (16 possible points), water efficiency (10 possible points), energy and atmosphere (35 possible points), materials and resources (14 possible points), indoor environmental quality (15 possible points), innovation in design process (six possible points) and regional priority (four possible points).

Similar to BREEAM, different versions of the rating system are available for various building types. Other countries have been developing environmental assessment tools as follows:

CASBEE (Comprehensive Assessment System for Building Environmental Efficiency) started in Japan in 2001. According to CASBEE website, it is a joint industrial/government/academic project initiated with the support of the Japanese Ministry of Land, Infrastructure, Transport and Tourism (MLIT). There are two spaces involved in CASBEE, internal and external, which are divided by a hypothetical boundary defined by the site boundary and other elements. Therefore, two factors are considered namely:

- Q (Quality): Building Environmental Quality and Performance: evaluates 'improvement in living amenity for the building users within the hypothetically enclosed space'.
- L (Loadings): Building Environmental Loadings: evaluates 'negative aspects of environmental impact which go beyond the hypothetical enclosed space to the outside'.

CASBEE deals with four assessment fields namely: energy efficiency, resource efficiency, local environment and indoor environment.

NABERS (National Australian Building Environmental Rating Scheme) is the Australian Government's initiative to measure and compare the environmental performance of buildings in Australia. NABERS provides rating for buildings based on their measured operational impacts on the environment. NABERS rates the waste and indoor environmental quality for offices as well as the water and energy use of hotels, offices and homes. The higher the NABERS star rating, the better the actual environmental performance of a building. The ratings are from 1 to 5 (poor to exceptional) with an increment of 0.5. The Green Building Council of Australia's Green Star rating is different from NABERS: the focus of Green Star is on the potential of design features in new buildings to reduce a range of environmental impacts, whereas NABERS is focused on the actual environmental impact of existing buildings over the previous twelve months.

GBTool has been under development since 1996 and is used in the Green Building Challenge, which is an international collaborative effort to develop a building environmental assessment tool that exposes and assesses the controversial aspects of building performance and from which participating countries can draw ideas to incorporate into or modify their own tool. It has evolved considerably, and over 25 countries are now involved in the system. The latest version, GBTool 2005, is developed by International Initiative for a Sustainable Built Environment (iiSBE). There are three factor levels when assessing a building using GBTool: the high level 'Issues', the second level 'Categories' and the third level 'Criteria'. The top level consists of seven general performance issues, 29 categories are included in the second level, whereas the third covers 109 criteria. The weighting of the scores at the lower levels is used to derive the assessment scores, i.e. category scores are obtained by aggregating the constituent criteria weighted scores. The weighted scores of issues are then used to obtain the overall score of the building. The weighting value, from the lower levels to the overall building, is a total of 100%.

HK-BEAM (Hong Kong Building Environmental Assessment Method) was first launched in December 1996 with funding from the Real Estate Developers Association of Hong Kong. HK-BEAM is used to measure, improve, certify and label the whole-life environmental sustainability of buildings. It assesses buildings in terms of whole-life site, material, energy, water, indoor environment and innovative aspects. Improvements are identified during assessment and buildings are labelled as Platinum, Gold, Silver Bronze or Unclassified accordingly. It integrates the following aspects such as land use, site impacts and transport, hygiene, health, comfort and amenity, use of materials, recycling and waste, water quality, conservation and recycling, energy efficiency and conservation. The overall grade is based on the level of applicable credits gained as well as on a minimum percentage of indoor environmental quality.

Thus, in the last 10 to 15 years, a number of environmental assessment tools have emerged that are useful for POE assessments. But how did POE start?

4.3.2 History of POE

A literature review on the subject carried out (Pegg 2007) indicates the following:

1 Theory followed on from 'operational research' – post Second World War.
2 Initial POE findings appear in the late 1950s and early 1960s, focused on mass house building projects.
3 Part of original RIBA – Royal Institute of British Architects (1965) Plan of Work (Stage M), later omitted (1973).
4 The field of environmental psychology grew in the 1970s, which led to a desire to understand how buildings affected people.
5 This was coupled with the energy crisis, out of which came a movement for 'green' buildings.
6 Concerns arose as Sick Building Syndrome was observed in a number of deep plan air-conditioned buildings, leading to a wider debate about the purpose of buildings.

7 Probe Studies (UK) a DTI sponsored research project performed POEs on 20 UK low energy buildings, 1995.
8 UK green building effort steps up with revisions to Building Regulations, planning policy and the adoption of BREEAM.
9 Federal Facilities Council (US) reported that they systematically review all new buildings (2003).

A study in the late 1990s found that clients of the UK construction industry were frequently dissatisfied with the completed product, while the industry reported low profitability. One of the reasons for this dissatisfaction is the lack of a natural feedback route for designers (and contractors) to learn how their buildings are working, and what the users really think of the solutions. This process is indicated diagrammatically in Figure 4.2.

Indeed it is not only designers who lack feedback. There is a trend to outsource facilities management in large corporations, this means that the parent organisation is not closely connected to the operations of the building and is not able to improve briefing on subsequent buildings.

However, feedback was recognised as being a useful component of design, and was included as Stage M of the RIBA plan of work (this is a document that describes the responsibilities of architects at each stage of a building project) in 1965. However, it was not sustained, being removed in 1973. This is possibly because architects did not receive fees for reviewing their work.

One reported problem is that benefits are split between the client (current and future), design team and construction team and, therefore, no one believes that they should fully fund the process of POE. Of course other barriers exist, such as the reluctance to discover negative aspects of the design (potentially leading to costs) and the

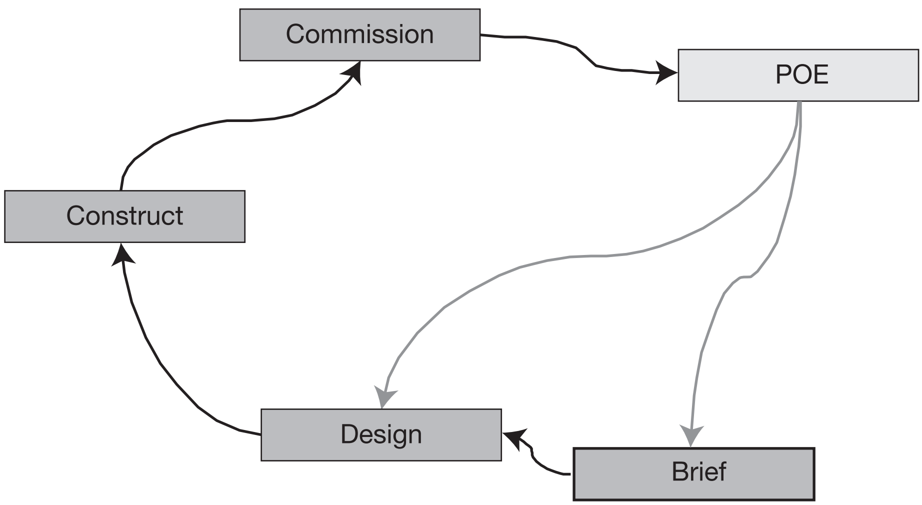


Figure 4.2 The role of POE in the building design and use cycle

fact that a designer appreciates that decisions made within a project are a result of a variety of mitigating factors (personalities, costs, time, etc.) and therefore feels POE can make little difference.

Barriers to POE can be summarised as:

- designers do not get paid for reviewing their work, as the current client rarely benefits;
- decisions are made in a growing team, responsibility is diluted and therefore it can be difficult to use the feedback;
- litigation is becoming more common, and therefore POE can highlight problems that would have been ignored in the past;
- managing knowledge and capturing context in large organisations, and within teams, are difficult (the possibility of information overload);
- problems are more commonly reported than successes, which can demotivate staff;
- there's a danger of only reporting what is easily measurable, rather than what represents performance.

Despite these barriers there are a wealth of benefits reported such as:

- rapid feedback leads to quicker reaction (rather than other research routes);
- is closely linked to design and therefore can become easily actionable;
- improves the ability to predict and therefore minimises risk in the future;
- good results can be marketed effectively;
- decisions can be made more quickly if relevant evidence is available;
- the alternative is to continue to build in ignorance of the outcomes.

In addition, user satisfaction is a very important consideration when operational buildings are investigated. A building with low energy consumption alone does not indicate a successful project. From early on it has been stated that buildings are for, and should go some way to, supporting objectives and activities carried out. We must therefore make some reference to the users and their needs within a building to ensure that a balanced evaluation of a building has taken place.

The link between people and their environment has been the study of extensive research in offices by environmental psychologists. Satisfaction in the built environment is commonly assessed by rating scales of satisfaction for tangible environmental variables, such as acoustics and thermal comfort. It is the purpose of these questionnaires to gauge how satisfactory a building or a space is, with the intention that designers can know what they should improve next time. An example is described in the following section.

4.4 POE methods

A recent literature review on the subject (Pegg 2007) identified the POE methods described in this section. As mentioned before, the purpose of a POE is always to understand more about how a building performs, which suggests that objective POE requires a method, metric and benchmark.

The key elements that these fields have in common are the recognition that the subject concentrates on the interactions between the users and the built environment, and subsequent connection of that information with the building design process. The feedback process can be summarised in Figure 4.3.

Some of the earlier studies looked at attempts to meet housing demands in the 1930s and 1940s to assess the effectiveness of architects' attempts at providing functional spaces around society. These studies found that architects' assumptions about how these societies would function were naïve, and in error. The studies were grounded in the social sciences, using interviews and observation to determine the successes and failures of estates. The work looked at how spaces affected socialisation, and practical living, all compared to explicit assumptions and hypothesis.

Studies in the early 1970s used a variety of techniques to determine the needs and assess the current practice of building comprehensive schools. They viewed the problem from first principles and developed a representative model of how organisations within buildings operate, determining the influence of the environmental systems on the activities of the users. The studies used a variety of methods including examining current design practice, using surveys and taking physical measurements in buildings.

The work identified methodologies and spatial planning guidance that affected future buildings, highlighting some workable concepts for planning a building (such as the POP ratio, a comparison of the actual perimeter of the building, compared to a cylinder of equivalent floor area).

In North America the theoretical foundation of studying buildings after completion was discussed in studies, which viewed the work from an environment–behaviour point of view, and used multi-methods to look at how the building affects the users. The work pointed out the conflicts between airtight 'energy efficient' buildings and health related ventilation problems.

The prevalence of open-plan air-conditioned offices saw much dissatisfaction. Sick Building Syndrome was one of the key problems in these open-plan offices and comprehensive studies were undertaken to provide more knowledge about this effect. Most studies found little direct linkage between a particular building type and HVAC technology, but did find that the ability to exert control over one's environment was associated with symptoms.

The interest in the environment, and specifically energy usage was investigated in a range of POEs of buildings incorporating passive solar features. Known as the Solar

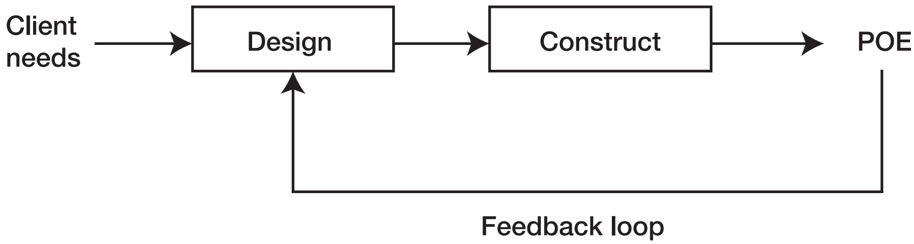


Figure 4.3 Basic concept of feedback within building design

Building Studies carried out in the 1990s, they monitored the energy consumption of a number of building types and passive approaches.

More recently, the Probe studies (see next section) reviewed over 20 buildings previously featured in the *Building Services Journal*, and used techniques to assess the build quality (air pressure test), energy performance (audit) and user satisfaction (questionnaire). Key findings showed that designers' estimates of consumption were often half the actual consumption (due to unrealistic assumptions) and that chronic problems persisted to some extent in most of the buildings.

One will begin to note that the topic of POE is incredibly diverse in methods used and focus of studies. This highlights the numerous activities and objectives that buildings support and the ever-growing list of stakeholders involved in buildings. It is clear that no POE can claim to be truly holistic; however, do we consider a simple building energy audit a POE? It seems that taking some researchers' belief that buildings are constantly designed as users adapt their environment to support their needs, then it appears that we should. This is because the audit is a feedback mechanism leading to a decision based on balancing the cost and benefits of energy efficiency improvements.

Yet, in order to frame the field and tentatively suggest that to become manageable POE should rest alongside design, we suggest that the studies should seek to evaluate the outcomes of design within a recognisable project environment. What is more, we should *also* consider that the outputs should inform future design, with the intention that a body of knowledge is generated, and tested.

While the work should inform future design, it should concentrate on the improvement of building performance from the point of view of the building stakeholders, and seek to develop robust and measurable performance indicators that demonstrate progress.

This consideration has implications for future POE practitioners, as it means that work carried out must attempt to understand and describe the original context of the building design, or disseminate to a field where the context is shared. The idealised process of POE is outlined in Figure 4.4. The figure shows that the outcomes of the design process are a building with high environmental impacts, and moderate 'building performance'. The POE process adds to the 'knowledge' of the design organisation, and feeds into the next project; the cycle is repeated with improved outcomes from the next building.

As is suggested by the nature of the studies highlighted in the previous section, POE studies are diverse in nature. The types of studies carried out vary from single issue studies, using fairly focused methodologies, such as field thermal comfort studies – through to wider focused studies, such as the Sick Building Syndrome studies, which utilise a variety of methods to elicit influencing factors, and finally 'holistic studies' which attempt to cast a wide net to learn about a wide range of performance parameters. There are three types of study:

- *technical* – looking at measurement of physical parameters to describe the environment generated by the interaction of building services, building fabric and human behaviour;
- *behavioural* – looking at the what links the occupants' satisfaction with the physical environment;

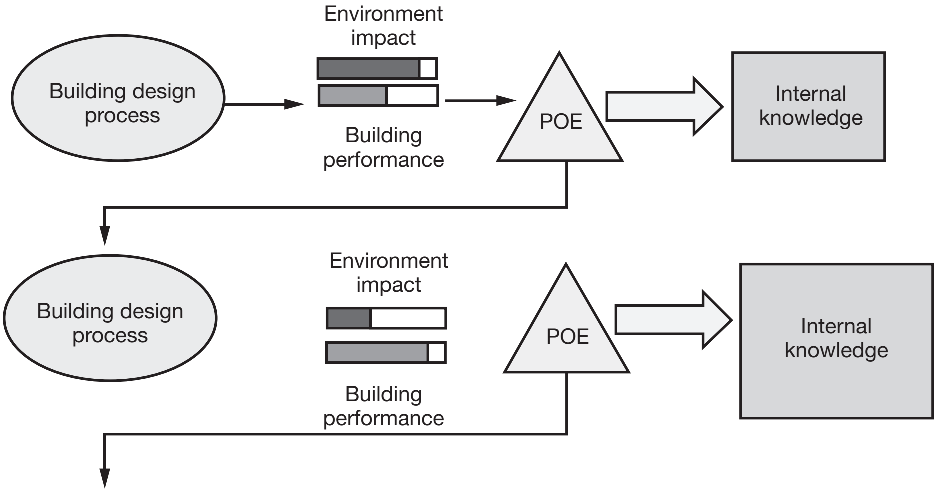


Figure 4.4 Conceptual representation of the POE system in design

- *functional* – determining how the building directly supports the activities carried out within the building.

The question arises, what is possible to measure in a building? Parameters that have established methods of measurement are:

- *user perception about their environment* – usually through questionnaires and comparison with established benchmarks;
- *energy* – usually addressed by prescribed methods in national Regulations in European countries. In the UK, approved methods are included in Part L of the Building Regulations. Most assessments of operational energy have been developed from a method described in CIBSE TM22 (CIBSE 2006b) that uses measurements and an audit to determine the overall energy usage of each system compared to benchmarks. Benchmarks have been published in TM46 (CIBSE 2008b);
- *objective environmental measurements* – usually carried out for thermal comfort, indoor air quality (IAQ), noise, daylight and luminance, airtightness and in some cases thermographic survey. It requires skill in where and when to measure, and most have been covered in corresponding modules of this course;
- *changes to original design* – usually evaluated by inspecting original drawings and carrying out a survey of current use of space and services. Consultation with designers and facilities managers help in the interpretation for the need of such changes.

4.5 A method developed in the UK – PROBE study

In the 1990s, a UK study investigated operational buildings and established a methodology which is followed today. The study was called 'Post occupancy review of building engineering' (PROBE).[2] The methodology had two parts: building investigation, and data analysis.

The building investigation includes the following:

- design and construction
- energy consumption
- occupant questionnaires
- management interviews
- maintainability
- control issues
- review of performance
- changes made.

The data analysis includes the following issues:

- comparison with original design
- energy assessment
- occupant survey analysis
- key messages.

The report includes the following sections:

- study report
- response from design team
- response from building occupier
- publication.

The outcome as mentioned before helped to:

- improve industry practice
- inform further research by identifying
    - common/repeated mistakes
    - specific aspects that lead to good performance.

As an example, some results are presented below of a study on the 'Elizabeth Fry Building', which is a learning resource centre at the University of East Anglia, UK,[3] and one of the buildings investigated. The building was also revisited in 2011 and the results of this investigation were published in the *Building Services Journal* (Bordass and Leaman 2011).

The building was designed on low energy design principles, has four-storey, 3,250m^2 floor area and includes a hollow-core ventilation system. This is an activated thermal mass strategy where hollow-core floors enhanced access to the thermal capacity of the structure to reduce cooling and heating demand. Heating is satisfied by three 24kW domestic condensing boilers.

Energy consumption results are shown in Figure 4.5 in terms of normalised energy consumption and carbon dioxide emissions. Normalisation, usually per treated floor area, makes comparison with other buildings and benchmarks easier. Comparison

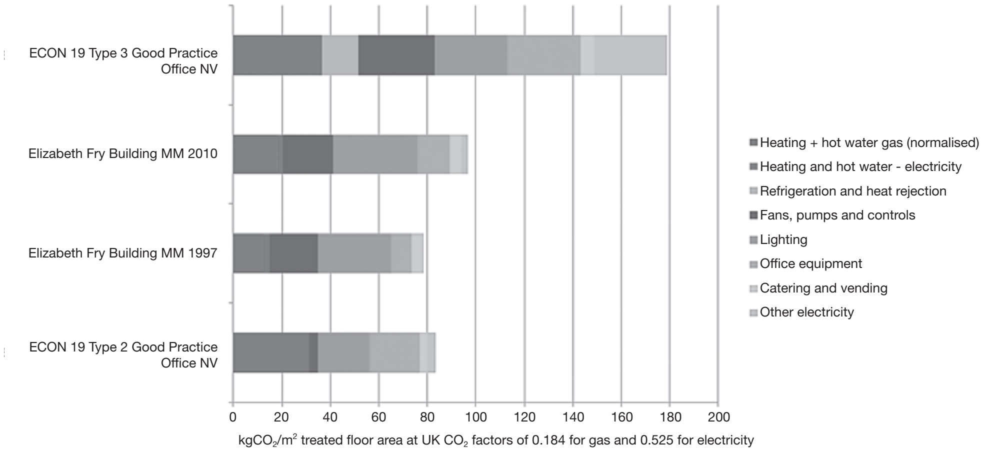


Figure 4.5 Energy consumption results

Source: redrawn from Bordass and Leaman 2011, after *BSJ* March 2012

with benchmarks is important to show the performance of the building in comparison with others. In the UK, publications exist to facilitate this, and in the case of the examined building are identified within Figure 4.5. They show that the building performs very well both in energy consumption and CO_2 emissions. During the 2011 revisit, a slight increase of the annual CO_2 emissions was found of approximately 10kg/m^2 treated floor area and this was mainly attributed in heating and hot water due to the change to constant hot water and the appearance of some additional electric heaters (Bordass and Leaman 2011).

User satisfaction results are shown in Figure 4.6 where it can be seen that occupants are happy with their environmental conditions and mostly with the controls provided.

One important issue at the time of the study was airtightness now regulated by Building Regulations Part F in which airtightness targets for domestic and non-domestic buildings are specified and airtightness testing is mandatory. The building was tested in 1994 (before handover) and also in 1998 as part of the Probe study; the result was an air leakage index of 6.5m/h which placed it at below very airtight buildings in the UK. Tests were repeated in September 2011 and the result was 5.3m/h air leakage index which is better than 1998. This was attributed to changes in the building such as the removal of the catering kitchen and its ventilation plant (Bordass and Leaman 2011).

All investigated parameters were summarised to key design lessons which included:

- energy performance
- ventilated hollow-core slabs
- construction supervision
- controls
- aftercare
- occupant comfort.

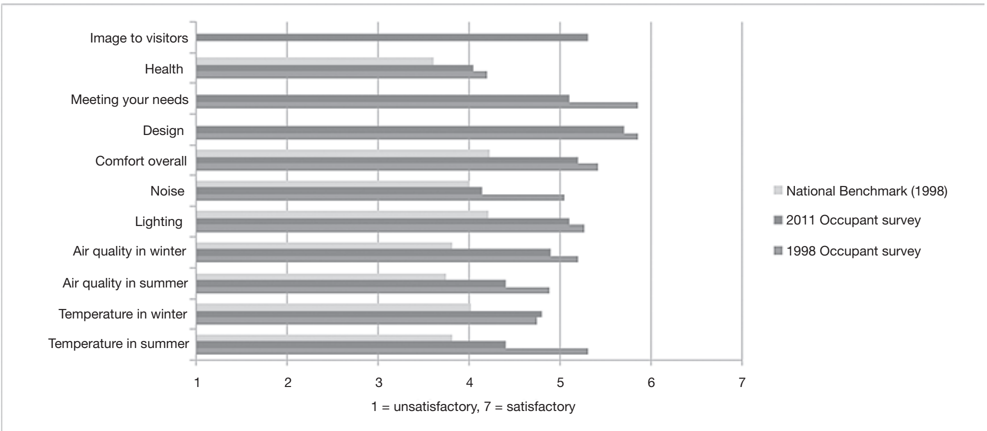


Figure 4.6 User satisfaction results

Source: Redrawn from Bordass and Leaman 2011, after *BSJ* March 2012

4.6 One example from a recent European study

As mentioned before, operational energy studies are now part of regulatory framework in Europe and elsewhere. The next step is to carry out studies which include monitoring of achieved environmental conditions and user satisfaction surveys. Such a study was conducted under the European programme, Intelligent Energy Europe.

One studied building from the UK is Red Kite which is also mentioned in the previous chapter as an example of a low energy design building. The building is situated in a climatic region with moderate heating and cooling load. An external photo of the buildings is shown in Figure 4.7.

Red Kite House is a three-storey office building in south-east England with a total floor area of 2,500m^2. Each floor is mainly an open-plan office area with some meeting and other rooms. The total number of staff is about 250, some of whom are permanently stationed in the building; others spend a proportion of their working time away from the office and are only intermittently present, using a 'hot-desking' arrangement. Occupied weekday hours are between 8.00 and 18.00.

The form of building is designed to ensure that an effective natural ventilation strategy can be achieved and, as a consequence, it has a relatively long, narrow plan on an east–west axis, with a typical depth of 16m. The limited depth ensures good use of natural lighting. A brise soleil (Figure 4.8) is situated at roof level on the south facade and is designed to provide protection from direct solar gain in the summer months but to allow useful heat gains in the heating season. The brise soleil incorporates photovoltaic cells that reduce the building's electricity demand on conventional grid supply. Roof-mounted thermal solar collectors provide hot water for washrooms.

The building is naturally ventilated by automatically controlled high level windows on each floor of the main facades. Larger manually operated windows are also available. The ceiling of each storey is exposed concrete (Figure 4.9). This thermal mass is used in conjunction with night-time ventilation to reduce peak internal temperatures in summer. In addition to the ventilation strategy, described in more detail later,

Figure 4.7 External view of the Red Kite House building

Figure 4.8
The brise soleil incorporating PV cells in Red Kite House

Figure 4.9 Open-plan office showing natural and artificial lighting

the building incorporates a number of other sustainable features including rainwater storage system, which collects surface water from the roof and recycles it for WC flushing, and sustainable drainage measures, e.g. permeable paving, permeable gravel beds around the building, and grass landscaping.

The building achieved an excellent rating based on the UK BREEAM assessment method.

4.6.1 Ventilation strategy

Except for simple mechanical extract ventilation for the toilets and meeting rooms, the building is fully naturally ventilated by openable windows on the north and south facades. High level top-hung lights on each floor are automatically opened by motorised links. Larger top-hung opening lights are provided at a lower level, and these can be manually operated by occupants.

The open-plan arrangement allows free movement of air across the building. Even where partitions are provided, for instance for meeting rooms, these are not carried to the full ceiling height of 3.2m, again allowing crossflow of air.

There are no suspended ceilings and the concrete soffit is exposed on each floor. This provides substantial thermal mass which, combined with night-time ventilation cooling, acts to minimise peak temperatures during the occupied period and obviates the need for air conditioning.

Operation of the high level windows is controlled by local temperature measuring devices. When the temperature rises above a set point, determined by the building management team, the windows open and remain open until either the temperature falls or rain is detected by a roof-mounted sensor.

4.6.2 Evaluation of energy and environmental conditions performance

Energy performance

The monitored energy consumption data for 2006, normalised on unit treated floor area basis yields annual consumptions of 66kWh/m^2 for heating and 127kWh/m^2 for electricity (Figure 4.10).

These may be compared with benchmarks current at the time of construction given in the UK Energy Consumption Guide 19: Energy Use in Offices (ECG19) for naturally ventilated, open-plan offices (see also CIBSE TM41). For typical practice, the benchmarks are 151kWh/m^2 for heating and 81kWh/m^2 for electricity. The good practice values are 79kWh/m^2 for heating and 54kWh/m^2 for electricity. These are shown in Figures 4.11 and 4.12, together with similar benchmarks for a standard air-conditioned building.

Red Kite House has an excellent heating consumption, below the good practice benchmark for naturally ventilated open-plan offices, and substantially lower than for air-conditioned offices. The electricity consumption, however, is higher than both typical and good practice for naturally ventilated open-plan offices. This is likely to be as a result of the Red Kite House's relatively high density of occupation, and the high computer and office appliances not reflected in current benchmarks. It was not possible to check this as sub-metering of the electricity circuits was not available.

Indoor climate

Thermal: Temperature measurements were made at six locations during the period 15 March to 15 September 2006. These provided an initial overall assessment of performance, the results of which are summarised in Table 4.1, indicating the proportion of occupied hours for which the temperature at five locations exceeded 28°C.

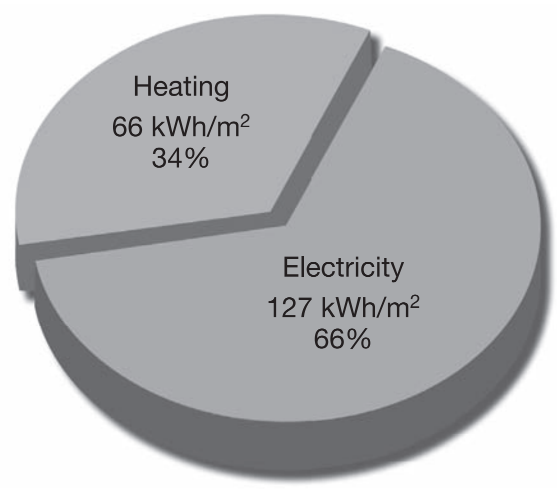


Figure 4.10 Heating and electricity measured energy consumption

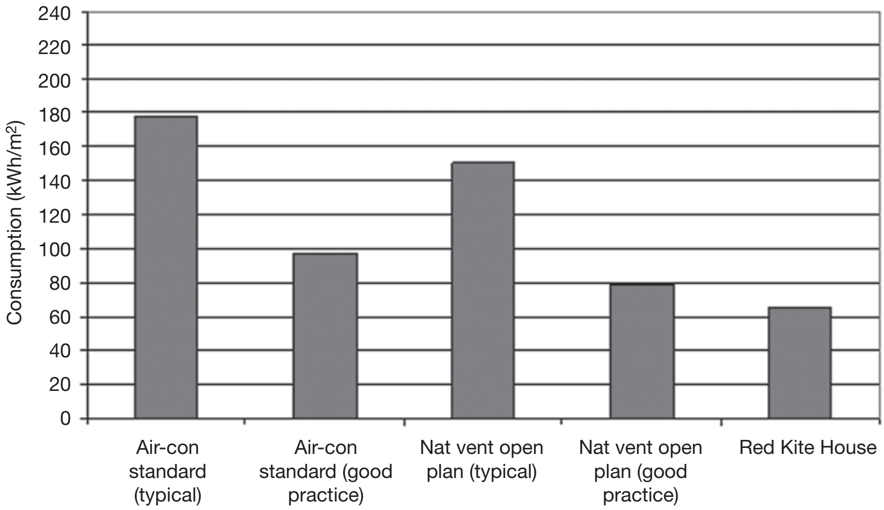


Figure 4.11 Comparison of heating consumption with UK benchmarks for office buildings

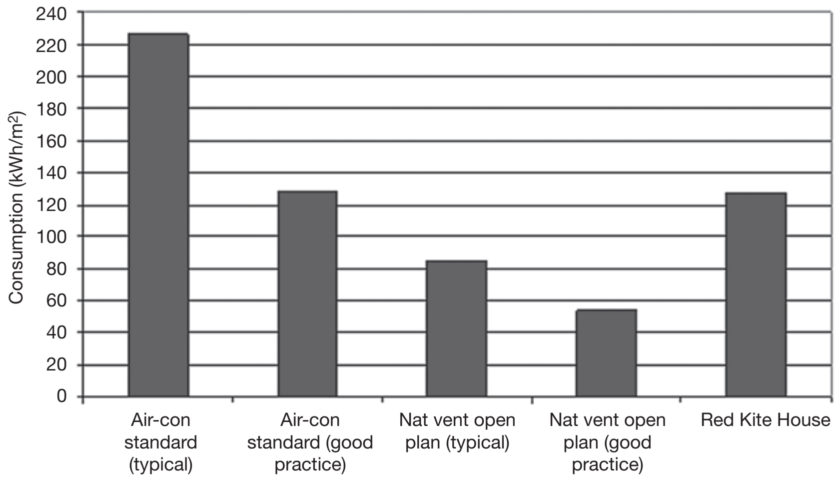


Figure 4.12 Comparison of electricity consumption with UK benchmarks for office buildings

Ventilation: Continuous measurements in two locations in open-plan office areas over a two-week period in June/July 2008 showed low concentrations of carbon dioxide; always less than 800ppm, with 700ppm being exceeded for only three hours. Measurements made in a two-week period in October 2008 yielded slightly higher rates with mean values of 590ppm and 660ppm during office hours and occasional peaks above 1,000ppm. Higher concentrations were measured in December 2008 but these may have been atypical because of relatively low indoor temperatures resulting from a problem with the heating system.

Occupant assessment of performance

About 55% of occupants responded to a questionnaire survey to assess satisfaction with the indoor environment. The results are summarised in Table 4.2.

In general, a significant majority of occupants are satisfied in summer with the overall indoor environment together with specific aspects including thermal comfort, air movement and IAQ. In winter, satisfaction with the thermal environment is reduced although detailed analysis of responses indicates that this appears to relate to a local problem with building operation rather than design. As with many open-plan buildings, there is some dissatisfaction with internally generated noise. Dissatisfaction with external noise in summer is likely to have arisen from a nearby temporary construction site. There is a very high level of satisfaction with the natural and artificial lighting. This is a benefit of the open-plan design of limited depth with windows provided on two opposing facades.

Design lessons

Occupants indicated a high degree of satisfaction with the indoor environment but designers of future buildings using the same principles might consider including monitors within the BEM system to allow windows to be opened if carbon dioxide concentrations reached a set limit. Control algorithms need to be carefully designed where

Table 4.1 Proportion of occupied hours that air temperature exceeds 28°C

Ground floor	*West wing Level 1*	*East wing Level 1*	*East wing (south) Level 2*	*East wing (north) Level 2*
1.81%	2.79%	1.76%	2.30%	1.42%

Source: Bateson 2008

Table 4.2 Summary of occupant assessment of the indoor environment

	Summer %	*Winter %*
Overall indoor environment is acceptable	82	69
Thermal environment is acceptable	77	61
Indoor air quality is acceptable	93	90
Acoustic environment is acceptable	51	65
	Natural %	Artificial %
Lighting is acceptable	97	84

window opening is controlled by several variables (such as temperature, rain, carbon dioxide) to ensure optimal operation.

With the increasing use of computing equipment in offices, in order to manage energy use, it is useful to meter lighting and other building-related electricity consumption separately from other uses.

Key points concerning the design

- night-time natural ventilation in common with a thermal sink provided by exposed concrete ceilings limits peak temperatures in summer;
- the combination of brise soleil and solar PV array both limits unwanted solar gains in summer and provides a useful supply of renewable electricity;
- the deliberately limited building width, combined with open-plan design and orientation provide for efficient natural ventilation and daylighting, both of which increase the satisfaction of occupants.

A simplified subjective easy-to-do environmental checklist suitable for people starting POE studies is included in the Appendix.

4.7 Summary

In this chapter the usefulness of POE studies to complete the design cycle was outlined and some methods and examples of POEs were presented.

- The history of POEs in the last 50 years indicates that valuable lessons can be learnt for better operation of buildings and also for input to future designs.
- Apart from operational energy evaluation (which is now compulsory in many European countries), a POE should include evaluations of environmental conditions to confirm design intentions and fine tune systems, and a user satisfaction evaluation to confirm that the building performs according to occupants' expectations. User satisfaction evaluation could play an important role in future design aspirations.
- Two case studies of low energy buildings with POE evaluations were presented.

Notes

1 Useful general website for up-to-date information on the implementation of the EPBD is found at www.buildup.eu
2 More details can be found at www.usablebuildings.co.uk
3 A report was published in the *Building Services Journal* and can be found in www.usablebuildings.co.uk under PROBE.

Appendix

Environmental building appraisal forms

Stage 1 – First Appraisal: Total Environment

Using the seven point scale provided, rank the following factors associated with the total environment (1 least favourable, 7 most favourable).

Table A1. Sheet 1 (total environment)

Private	*1*	*2*	*3*	*4*	*5*	*6*	*7*
The external environment in which the building is placed							
The visual character of the building							
The social setting							
The approach to the building							
The site itself; space, levels, vegetation							
The building exterior							
The building interior							
The effect of the building on the locality							

Use this space to elaborate on your impressions and define the points on the scale.

Stage 2 – Detailed Appraisal: Organisation of Spaces

Using the seven point scale provided, rank the following factors associated with the organisation and design of spaces within the building (1 least favourable, 7 most favourable).

Table A2. Sheet 2 (organisation and design of spaces)

	1	2	3	4	5	6	7
Consider the distribution of the total space horizontally and/or vertically. This may be determined by: • function • space available • daylighting policy • policy decisions (e.g. prestige) • economic considerations • assumptions about social organisations How appropriate are the decisions which have been made?							
Consider the communication between spaces – the access, ease in locating individuals and comprehending the spatial organisation. How effective is the spatial communication in this building?							
How 'efficient' has the planning been? What is the ratio of usable to service space provided?							
Consider the status of the building within the hierarchy of its type. What is the standard of space provision in relation to people, functions, furniture and equipment accommodated?							
Consider the use of space. Is the space fully used? Does it include provision for expansion/reduction of activities?							
Consider the shape of the space. Is it appropriate, for example to the function, the space available and the daylighting?							
Consider the height of the space, real or apparent, together with the effect of light and colour. How suitable does the height of the space appear to be?							

Stage 2 – Detailed Appraisal: Visual and Lighting Factors

Using the seven point scale provided, rank the following factors associated with the visual environment of the building (1 least favourable, 7 most favourable).

Table A3. Sheet 3 (visual and lighting factors)

Private	*1*	*2*	*3*	*4*	*5*	*6*	*7*
Consider the appearance of the interior of the building, both in natural and artificial light. Consider also the appearance of persons and objects seen in the interior, e.g. modelling, colour rendering. How effective is the visual design in facilitating the performance of visual tasks, e.g. inspection or reading?							
Daylight design. Consider the quantity and consistency/variability of daylight illuminance. Consider also the quality – brightness distribution, glare, reflection, shadow, solar penetration, suitability, character. Consider the view from the windows – distance, interest, obstruction. How effectively has daylighting been used?							
Electric lighting design. Consider the quantity and consistency/variability of electric lighting illuminance. Consider also the quality – brightness distribution, glare, reflection, modelling, shadow, suitability of luminaires and other fittings, installation. Appearance of luminaire when illuminated and when not. How effective has the electric lighting design been?							
Consider the surfaces and finishes: floors, walls and ceilings. How do the quality, condition, colour and texture affect the visual environment?							
Consider the furniture and equipment. How do their suitability, quality, condition, colour, textures and visual organisation affect the visual environment?							

Stage 2 – Detailed Appraisal: Heating and Air Conditioning

Using the seven point scale provided, rank the following factors associated with the heating and air-conditioning environment of the building (1 least favourable, 7 most favourable).

Table A4. Sheet 4 (heating and air conditioning)

Private	*1*	*2*	*3*	*4*	*5*	*6*	*7*
Consider the following air comfort factors: • the air temperature within the building • experience of radiation (ceiling heating, sunlight, losses to windows and cold surfaces) • temperature gradient (cold feet, hot head) • air freshness/stuffiness • air movement – stagnation, draughts • humidity • consistency/variability of thermal conditions • any aesthetic effects of thermal design How effective overall has the design for thermal comfort been?							
Consider the thermal environmental design: • heavy/light construction • opportunities for solar penetration • thermal insulation • treatment of surfaces, inside and outside • designed method of emitting heat: suitability, efficiency • designed methods of controlling the thermal environment: air temperature, ventilation, air movement, humidity How effective overall has the thermal environmental design been?							

Stage 2 – Detailed Appraisal: Acoustics

Using the seven point scale provided, rank the following factors associated with the aural environment of the building (1 least favourable, 7 most favourable).

Table A5. Sheet 5 (aural environment)

Private	*1*	*2*	*3*	*4*	*5*	*6*	*7*
Consider the following aural comfort factors: • subjective impressions of noise levels generally • general quality of sound – live or dead • isolation from external (street) noise • isolation from noise created within the building e.g. in the circulation space • absence of noise in spaces needing quiet How effective overall has the design for aural comfort been?							
Consider the aural environmental design features: • volume and shape of the spaces • sound insulation of partitions (floors and other space divisions) • absorbency/reflectance of surfaces: floors, walls, ceilings, other surfaces. Their effect on noise levels and quality of sound • design of movable furniture: effect on noise levels and quality of sound How effective overall has the aural environmental design been?							

Stage 2 – Detailed Appraisal: Environmental Impact

Using the seven point scale provided, rank the following factors associated with the environmental impact of the building (1 denotes least favourable, 7 most favourable).

Table A6. Sheet 6 (environmental impact)

Private	*1*	*2*	*3*	*4*	*5*	*6*	*7*
Consider any energy efficient design strategies present in the building: • daylighting • energy efficient lighting • natural ventilation • 'free' cooling • heating and cooling control strategies • visible signs of energy consumption information to occupants and visitors							
Consider water usage in the building: • possible rainwater collection or grey water use • water efficient appliances and sanitary facilities • visible signs of water consumption information to occupants and visitors							
Consider the construction materials used for the building: • use of recycled construction materials • use of materials according to their environmental impact							
Consider the employees/visitors and goods transport facilities: • availability to public transport and cycling facilities • use of local suppliers for materials, equipment, etc.							
Consider contribution to pollution and ozone depletion from the building: • low NO_x emissions plant and non-ozone depleting refrigerants • visible signs of regular monitoring of building pollution contribution							
Consider the ecological impact of the building; e.g. protection of pre-existing ecological features such as trees, hedges, water courses, etc.							
How effective do you rate the overall environment impact of the building?							

Stage 3 – Re-appraisal

Summarise the assessments made so far, again using the seven point scale (1 least favourable, 7 most favourable).

Table A7. Sheet 7 (Re-appraisal)

Private	*1*	*2*	*3*	*4*	*5*	*6*	*7*
First impressions of total environment							
Functional requirements							
Space							
Visual environment							
Thermal environment							
Aural environment							
Environmental impact							
Re-assessment rating of total environment							

Use this space to note down any factors which have changed your assessment from the first overall appraisal (sheet 1). Note any environmental factors not considered.

Chapter 5

Energy efficient ventilation

5.1 Introduction

Ventilation is necessary in buildings mainly for the following reasons:

- to provide fresh air for occupants
- to dilute and exhaust pollutants
- to protect the buildings against moisture in certain climatic conditions
- to provide air for fuel burning appliances
- to provide cooling in summer.

Ventilation provision is thus related either to indoor air quality (IAQ) or thermal comfort. Until recently, most regulations and guidelines on ventilation provision were based on IAQ requirements. However, the function of ventilation to improve thermal comfort in certain situations is also being addressed, mainly by guidelines and newer standards.

This chapter first outlines ventilation requirements for various types of buildings and available ventilation strategies. It then introduces some parameters used to measure ventilation efficiency within a single space. It follows an outline of how ventilation rate due to natural forces of wind and buoyancy can be calculated and enhanced by the use of fans. The chapter concludes with a description of ventilation strategies useful to provide thermal comfort in a building thus avoiding the need for artificial cooling in certain circumstances.

5.2 Ventilation requirements

Two standards are usually quoted in relation to ventilation requirements; these are the European Standard EN15251 (2007) (adopted as a British Standard in the UK) and the American Society of Heating, Refrigerating and Air-conditioning Engineers' Standard 62.1 (ASHRAE 2007). The standards include a prescriptive method, where the minimum ventilation rates can be found in a table listing values for different types of space. Before detailing ventilation requirements, it is worth mentioning BS EN13779 (2007) which includes classifications of outdoor and indoor air, useful to know as they impact on ventilation requirements.

EN13779 (2007) divides the outdoor air into three categories (Table 5.1) and IAQ into four categories (Table 5.2). The quality of indoor air is then defined by its level of CO_2 above outdoor levels (Table 5.3). The outdoor CO_2 concentration varies normally between 350 and 420ppm. Internal CO_2 level is a good indicator for the emission of human bio-effluents and is therefore suitable to use as a proxy indicator of IAQ within buildings that are occupied by people.

In addition, pollution from building materials is considered. According to EN15251 (2007) buildings are classified into three categories:

- *very low polluting buildings*: buildings where an extraordinary effort has been made to select low emitting materials and activities with emission of pollutants are prohibited, and no previous emitting sources (e.g. tobacco smoke) were present;
- *low polluting buildings*: buildings where an effort has been made to select low emitting materials, and activities with emission of pollutants are limited or prohibited;
- *not low polluting buildings*: old or new buildings where no effort has been made to select low emitting materials, and activities with emission of pollutants are not prohibited.

Table 5.1 Classification of outdoor air quality (ODA)

Category	*Description*
ODA 1	Pure air which may be only temporarily dusty (e.g. pollen)
ODA 2	Outdoor air with high concentrations of particulate matter and/or gaseous pollutants
ODA 3	Outdoor air with very high concentrations of gaseous pollutants and/or particulates

Source: BS EN13779 2007

Table 5.2 Classification of indoor air quality (IDA)

Category	*Description*
IDA 1	High indoor air quality
IDA 2	Medium indoor air quality
IDA 3	Moderate indoor air quality
IDA 4	Low indoor air quality

Source: BS EN13779 2007

Table 5.3 CO_2 levels in rooms

Category	*CO_2 levels above level of outdoor air in ppm*	
	Typical range	*Default value*
IDA 1	≤ 400	350
IDA 2	400–600	500
IDA 3	600–1,000	800
IDA 4	> 1,000	1,200

Source: BS EN13779 2007

An example of a low polluting building is the following: 'The building is low polluting if the majority of the materials are low polluting. Low polluting materials are natural traditional materials, such as stone and glass, which are known to be safe with respect to emissions, and materials which fulfil the following requirements:

- emission of total volatile organic compounds (TVOC) is below 0.2mg/m²h
- emission of formaldehyde is below 0.05mg/m²h
- emission of ammonia is below 0.03mg/m²h
- emission of carcinogenic compounds (IARC) is below 0.005mg/m²h
- material is not odorous (dissatisfaction with the odour is below 15%)'

(EN15251 2007, Annex C)

Following these definitions and applying the calculation methods described in EN15251 (2007) based on the requirements by people and pollution level by building materials, ventilation rates can be calculated usually in litres per second per square metre of floor area (l/s/m²) or litres per second per person (l/s/p). As an example Table 5.4 gives calculated values for non-residential buildings for three categories of pollution from the building extracted from EN15251 (2007).

A comparison of the requirements according to EN15251 and ASHRAE 62.1 is presented in Table 5.5 (after Olesen 2011). It can be seen that there are big differences between the European recommendations and those listed by ASHRAE. One major reason is that ASHRAE provides for minimum code requirements, where the basis for design is adapted people, while the European recommendations are for unadapted people (visitors).

In the UK, ventilation requirements are specified for various buildings by Part F of the Building Regulations.[1] They mainly cover IAQ requirements while thermal comfort requirements are covered to some extent by Part L of the Building Regulations. Requirements are traditionally divided into domestic and non-domestic buildings. The requirements of the 2010 regulations are presented in Table 5.6.

For the air supply in office buildings, the specified whole building ventilation rate is 10 l/s/p. This can be achieved by natural ventilation (reference is made to CIBSE 2005a), mechanical ventilation or alternative approaches (reference is made to CIBSE 2000a, 2005a, 2005b, 2006a). It can also be provided by other ventilation systems provided that they meet specified moisture and air quality criteria (performance based ventilation).

Table 5.4 Examples of recommended ventilation rates for non-residential buildings for three categories of pollution from building itself

		Airflow for building emissions pollutions ($l/s/m_2$)		
Category	*Airflow per person l/s/pers*	*Very low polluting building*	*Low polluting building*	*Non low polluting building*
I	10	0.5	1	2
II	7	0.35	0.7	1.4
III	4	0.2	0.4	0.8

Source: EN15251 table B.3 p.35

Note: Rates are given per person or per m² floor area

Table 5.5 Comparison of requirements for smoking free spaces in commercial buildings

Type of space	*Occupancy person/m²*	*Category CEN*	*Minimum ventilation rate, i.e. for occupants only l/s/person*		*Additional ventilation for buildings (add only one) l/s/m²*				*Total l/s/m²*	
			ASHRAE R_p	*CEN*	*CEN very low pollution*	*CEN low pollution*	*CEN not low pollution*	*ASHRAE R_p*	*CEN low pollution*	*ASHRAE*
Single office (cellular office)	0.1	I	2.5	10	10	1.0	2.0	0.3	2	0.55
		II		7	7	0.7	1.4		1.4	
		III		4	4	0.4	0.8		0.8	
Conference room	0.5	I	2.5	10	10	1.0	2.0	0.3	6	1.55
		II		7	7	0.7	1.4		4.2	
		III		4	4	0.4	0.8		2.4	

Source: adapted from Olesen 2011: table 1

Note: according to ASHRAE 62.1 and EN15251

Table 5.6 Ventilation requirements for domestic buildings, extract ventilation rates and whole dwelling ventilation rates

Room	*Intermittent extract*		*Continuous extract*		
	Minimum rate		*Minimum high rate*		*Minimum low rate*
Kitchen	30 l/s adjacent to hob; or 60 l/s elsewhere		13 l/s		Total extract rate should be at least the whole dwelling ventilation rate
Utility room	30 l/s		8 l/s		
Bathroom	15 l/s		8 l/s		
Sanitary accommodation	6 l/s		6 l/s		
	Whole dwelling ventilation rates				
	Number of bedrooms in dwelling				
	1	2	3	4	5
Whole dwelling ventilation rate l/s	13	17	21	25	29

Source: Building Regs, Part F, p. 19

For other building types, reference is made to professional publications and standards. CIBSE Guide A (2006a) includes tables with a suggested general air supply rate at 10 l/s/p for most building types. It varies for specific areas such as hospital operating theatres (0.65–1.0m³/s), hotel bathrooms (12 l/s/p), ice rinks (3 ACH – air changes per hour) and sports hall changing rooms (6–10 ACH).

In addition, airtightness specifications for envelope and ducts have been introduced in many countries; these are usually related to energy efficiency measures in buildings but obviously it has a direct effect on ventilation requirements and systems to provide them. For example in the UK, there is a minimum standard of $10m^3/h.m^2$, m^2 of building envelope at 50 pascals (Pa) and all buildings must be tested to comply with this. In addition, ductwork leakage testing should be carried out for systems served by fans with a design flow rate greater than $1m^3/s$. Obviously airtightness specifications will affect the infiltration rate considered in ventilation calculations.

5.3 Ventilation strategies

Ventilation is normally provided by the following means:

- Infiltration (which is determined by external envelope airtightness)
- Purpose ventilation which can be further divided into
    - Natural
    - Mechanical
    - Combination (hybrid or mixed mode ventilation).

Ventilation is controlled in buildings because the health and comfort of the occupant is at risk if low ventilation is provided; but if too much ventilation is provided, especially during the heating season, a high energy penalty will be incurred.

Air infiltration is the process by which air enters into a space through adventitious leakage openings in the building fabric. Infiltration is considered as unwanted ventilation because it cannot be controlled. As mentioned in the previous section, in many countries, there exist stringent regulations on the restriction of infiltration.

Natural ventilation is the process by which outdoor air is provided to a space by natural driving forces of wind and stack effect. These forces are constantly fluctuating; the challenge of natural ventilation design is to use these forces so that the airflow into a space is maintained at the desired rate. Natural ventilation is usually provided by one of the following configurations:

- Single sided ventilation (Figure 5.1)
- Crossflow ventilation (Figure 5.2)
- Stack ventilation (Figure 5.3).

Mechanical ventilation uses fans to supply air to, and exhaust air from, rooms in buildings. Depending on demand, the supply air may be heated, cooled, humidified or dehumidified. The ventilation system may be equipped to recover heat from the exhaust air. The system may also recirculate extract air. Windows may be sealed or operable. During the last decade, major developments have taken place or been further refined, such as various kinds of demand controlled ventilation, systems with improved airflow characteristics at room level (e.g. displacement ventilation), heat recovery systems with efficiencies up to 90%, major developments in fan characteristics (e.g. direct current and inverter drive variable speed fans), low pressure air

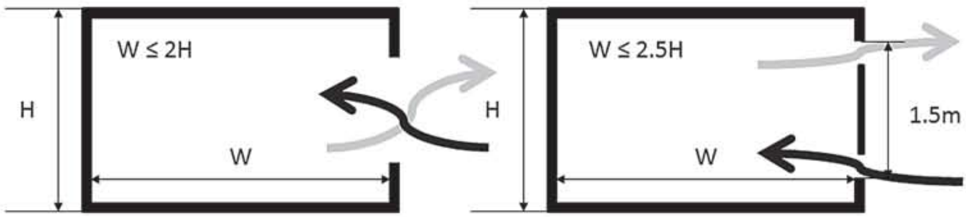


Figure 5.1 Schematic showing the principles of single sided ventilation

Source: redrawn from BRE 1994

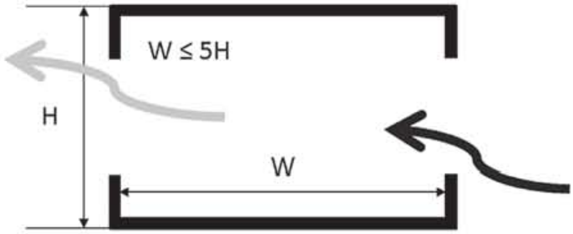


Figure 5.2 Schematic showing the principle of crossflow ventilation

Source: redrawn from BRE 1994

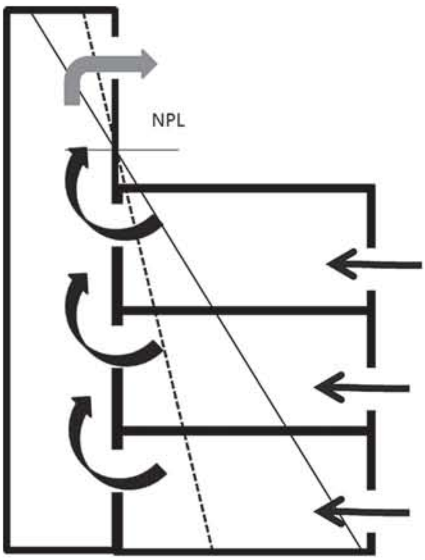


Figure 5.3 Schematic showing the principles of stack ventilation

Source: redrawn from BRE 1994

distribution systems. In mechanically ventilated buildings, the ventilation air may also be conditioned before it is supplied to the rooms via duct systems (and this is discussed in more detail in Chapter 7).

Hybrid ventilation (Heiselberg 2002; RESHYVENT 2004) *or mixed mode ventilation* (CIBSE 2000a) is normally used to improve the reliability of natural ventilation or to increase its range. A hybrid system can include a natural system combined with a full independent mechanical system. Hybrid ventilation techniques include:

- natural and mechanical: two fully autonomous systems in which the control strategy either switches between the two systems or uses one system for some tasks and the other system for other tasks;
- fan assisted natural ventilation: this is based on a natural system combined with an extract or supply fan;
- stack and wind assisted mechanical ventilation: this is a predominantly mechanical system, in which natural driving forces are used to add to the driving pressure.

Within a single space, there exist two extreme modes of air circulation and these are termed *mixing and displacement ventilation.*

Mixing ventilation assumes that the air in the space is fully mixed; this means that the concentration of contaminants is the same throughout the space and equal to that in the exhaust. Ventilation requirements presented in the previous section include this assumption of a fully mixed ventilation strategy and this is shown schematically in Figure 5.4. In reality, however, the room air is seldom fully mixed. Figure 5.5, (a) and (b) illustrate an extreme case where there is a short circuit in the ventilation system. The contamination release in the room in both figures is the same, and also the concentration in the exhaust. The mean concentration in the room, however, differs because of the position of the contamination source.

Displacement ventilation is an alternative strategy to mixing ventilation. The principle is based on air density differences where the room air separates into two layers: an upper polluted zone and a lower clean zone (Skistad 2002). This is achieved by supplying cool air at a low velocity in the lower zone, and extracting the air in the upper zone.

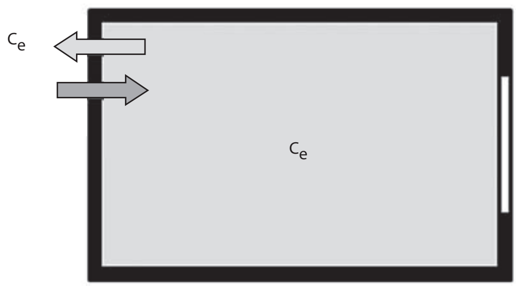


Figure 5.4 Fully mixed flow in a single space results in the mean contaminant concentration in the space and in the exhaust being identical

Source: adapted from Mundt 2004

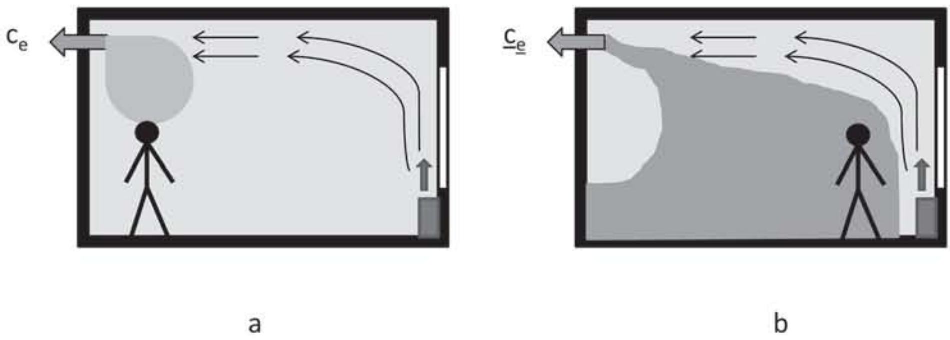


Figure 5.5 Diagram shows a different situation of ventilation effectiveness in a single space depending on the location of contaminant sources

Source: adapted from Mundt 2004

For displacement ventilation systems, the selection of design supply air temperature is an important task (Schild 2004). If it is too low the draught risk increases in the occupied zone. Figure 5.6 shows a simplified chart for temperature changes in the room with displacement ventilation. The temperature difference between extract air and room air at floor level is about the same as the temperature difference between room air at floor level and supply air.

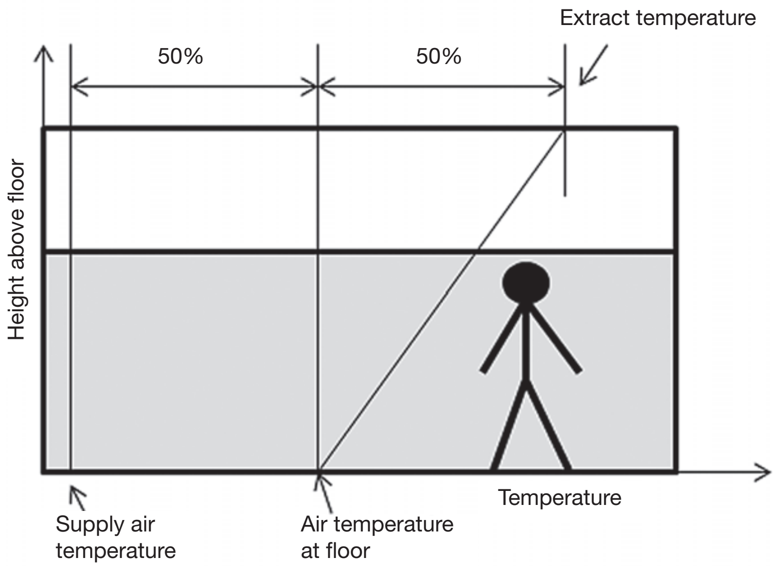


Figure 5.6 Average temperature differences with displacement flow patterns

Source: Skistad *et al.* 2002

The advantages of the displacement ventilation air distribution system can be seen in Figure 5.7. Due to vertical temperature distribution, the supply air temperature in the cooling situation can be higher than that of mixing airflow pattern. With a higher supply of air temperature, free cooling with outdoor air can be used for longer periods, and when mechanical cooling is used the coefficient of performance of the compressor cycle is better with a higher temperature of evaporator. The vertical temperature difference also leads to a higher extract air temperature with displacement system, which is an advantage when heat recovery from ventilation air is applied.

In summary, the advantages of the displacement flow pattern for air distribution are:

- for a given air quality, there are indications that displacement ventilation needs less supply air;
- displacement ventilation has more potential for free cooling, and needs less cooling energy than mixing ventilation. This is most pronounced in rooms with high ceilings;
- diffusers for displacement ventilation need less pressure drop than diffusers for mixing ventilation, and thus less fan power.

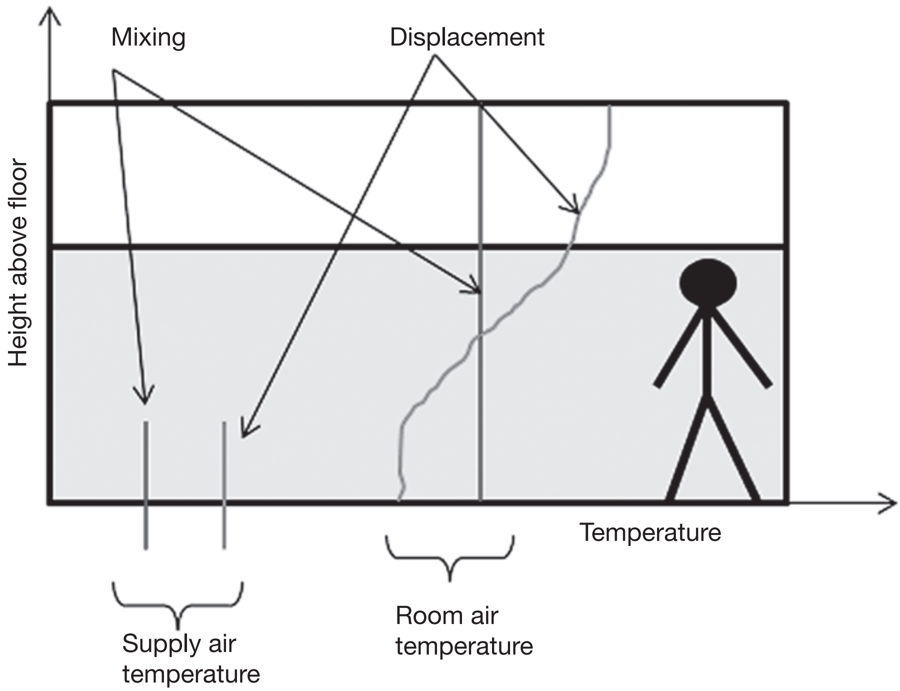


Figure 5.7 Temperature distributions in missing and displacement flow patterns

Source: Skistad *et al*. 2002

5.4 Ventilation efficiency

In many cases, the circulation of air within a single space would be between mixing and displacement ventilation. For this reason indices have been developed to measure the ability of the ventilation system to remove contaminants. The following definitions have appeared in the ventilation literature since 1980s (Liddament 1993; Sutcliffe 1990) and the descriptions that follow have been adapted from Mundt (2004).

5.4.1 Air change efficiency

At the design stage when the use of the space is unknown, the ventilation should be designed to give a rapid air exchange in the room. The air change efficiency is a measure of this. In order to explain this, the concept of *age of air* is introduced first, which measures how old the air is in a space. Thus the local mean age of air at a given point is a measure of the air quality at that point. In a fully mixed situation the local mean age of air will be the same in the whole room. If there is a shortcut from supply to exhaust, the local mean age of air will be low in the short circuited zone, and high in the stagnant zone. This is shown diagrammatically in Figure 5.8 where another concept, *nominal time constant* is also introduced; this is the local mean age of air at the exhaust, defined as:

$$\tau_n = \frac{V}{q_v} \tag{5.1}$$

where

τ_n = the nominal time constant of ventilation h
V = the room volume, m^3
q_v = the supply airflow, m^3/h

From the definition, the nominal time constant depends on the airflow rate and volume of the room, and is independent of the ventilation pattern.

Figure 5.8 illustrates how nominal time constant and *local mean age of air* are related. 'The local mean age of air of a small volume in the room is the average time from the time that the molecules in the room enter the room. The local mean age is thus given by the time at which the concentration of original molecules falls to zero at point P. The local mean age increases linearly from zero at the entrance to the nominal time constant to the exit. The average room mean age of air is therefore half of the nominal time constant in the case of piston flow'.

Air change efficiency can then be defined as the shortest possible air change time (which is the nominal time constant) over the actual air change time.

$$\textit{Air change efficiency} = \frac{\textit{nominal time constant}}{\textit{actual air change time}} \tag{5.2}$$

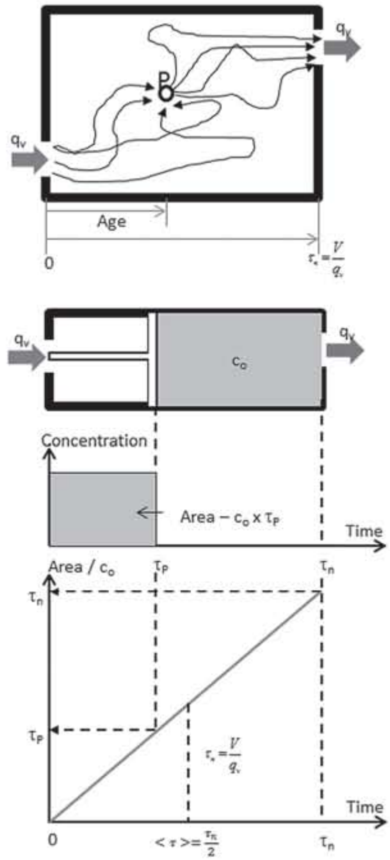


Figure 5.8
Relationship of age of air and nominal time constant for an ideal piston flow in a space

Source: adapted from Mundt 2004

The definition of the air change efficiency can also be explained as the ratio between the lowest possible mean age of air (nominal time constant over 2) and the room mean age of air.

$$\textit{Air change efficiency} = \frac{\textit{nominal time constant}}{2 \times \textit{mean age of air}} \tag{5.3}$$

The range of air change efficiency for four broad classifications of ventilation pattern in one space is summarised in Table 5.7.

Table 5.7 Air change efficiency for different flow conditions in one space

Flow pattern	*Air change efficiency*
Ideal piston flow	100%
Displacement flow	50–100%
Fully mixed flow	50%
Short circuit flow	<50%

5.4.2 Contaminant removal effectiveness

In many cases we are interested to know the ability of a ventilation system to remove contaminant and this can be done by comparing the concentration in the exhaust with the mean concentration in the room. This measure is called *contaminant removal effectiveness*:

$$\textit{Contaminant removal effectiveness} = \frac{\textit{concentration in the exhaust}}{\textit{mean concentration in the room}} \tag{5.4}$$

A satisfactory result is achieved when the concentration of contaminants in the space is low compared with the concentration in the exhaust air. The concentration in the exhaust is dependent on the release rate of the contaminant and the ventilation flow rate, and is independent of the ventilation arrangements. The exhaust concentration can also be compared to local values of the concentration of contaminants; these indices are called *local air quality indices*. This index is used in large spaces with local pollution sources with a focus on the specific location of breathing zones of occupants or workers. These can be calculated using computational fluid dynamics (CFD) models or tracer gas measurements.

5.5 Calculating ventilation rate due to natural driving forces

When the ventilation strategy for a building is for natural or mixed mode, it is necessary to calculate the airflow provided by natural forces. This is difficult to carry out accurately considering the number of possible air paths into the building and the variability of external driving forces of wind and temperature. There exists guidance on how to carry out quick calculations at the feasibility stage and detailed computer simulation tools, either stand-alone (for ventilation calculations only) or integrated within thermal simulation models.

In the following section, the process of feasibility stage calculation methods is described, based on publications such as CIBSE Guide B (2005b), BS5924 (1991) and CIBSE AM10 (2005a).

5.5.1 Flow through purpose designed openings

For a given applied pressure, the nature of airflow is dependent on the dimensions and geometry of the opening itself. For well-defined, purpose-provided openings such as vents, airflow is usually assumed to be turbulent and is often approximated by the orifice equation given by:

$$Q = C_d A \left[\frac{2}{\rho}\Delta P\right]^{½} \quad (\mathrm{m^3/s}) \tag{5.5}$$

Where:

Q = airflow rate (m^3/s)
C_d = discharge coefficient
ρ = air density (kg/m^3)
ΔP = pressure difference across opening (Pa)
A = area of opening (m^2)

In this instance the area, A, is the total net physical openable area. This is usually much less than the dimension of the vent itself because a significant part of the vent area is taken up with an insect screen or loose filling. In this equation, A represents the area of a single opening which is equivalent in resistance to all the resistances between the inlet and the outlet (CIBSE 2005a). If there are multiple resistances, the resistance need to be summed in series, using:

$$\frac{1}{A^2} = \sum_{i=1}^{i=j} \frac{1}{A_i^2} \tag{5.6}$$

Where A_i is the area of the 'i'th element in the path

In cases of openings on opposite walls, using the orifice equation (5.5), the total opening area A on each facade can be calculated from the area (A_E) between the two facades, as follows (BS EN5925 1991):

$$\frac{1}{A_E^2} = \frac{1}{A_1} + \frac{1}{A_2} \tag{5.7}$$

The discharge coefficient

The discharge coefficient is dependent on the opening geometry and also on the direction of approaching flow (e.g. wind direction). For a flat-plate orifice in which the air stream is directed at right angles to the opening, it typically has a value of approximately 0.61–0.65. Such a range is widely used in preliminary design calculations. However, for practical components the actual value will be dependent on the component itself as well as wind direction. For more detailed analysis, therefore, the component should be tested to obtain its actual flow characteristics.

5.5.2 Estimating wind induced pressure

In general it is observed that relative to the static pressure of the free wind, the time averaged pressure acting at any point on the surface of a building may be represented by the equation:

$$P_w = \frac{\rho}{2} C_p v^2 \tag{5.8}$$

Where:

P_w = wind induced pressure (Pa)
ρ = air density (kg/m^3)
C_p = wind pressure coefficient
v = wind velocity at a datum level (usually building height) (m/s)

Terrain and shielding

Since the strength of the wind close to the Earth's surface is influenced by the roughness of the underlying terrain and the height above ground, a reference level for wind velocity must be specified for use in the wind pressure calculation. When calculating the wind impact on ventilation, the wind velocity is commonly expressed as the measured speed at building height. As a general rule, 'on-site' wind data are rarely available and therefore data taken from the nearest meteorological station must usually be applied. Before such data can be used, however, it is essential that such measurements are corrected to account for any difference between measurement height and building height, and intervening terrain roughness must also be taken into account. By nature of the square term in Equation 5.8, wind pressure is very sensitive to the wind velocity and, as a consequence, the arbitrary use of raw wind data will invariably give rise to misleading results. This is, perhaps, one of the most common causes of error in the calculation of air infiltration rates and wind induced airflow rates.

Suitable correction for the effects of these parameters may be achieved by using a power law wind profile equation of the form:

$$\frac{v}{v_m} = \alpha z^{\gamma} \tag{5.9}$$

Where:

z = datum height (m)
v = Mean wind speed at datum height (i.e. height of building) (m/s)
v_m = mean wind speed at meteorological station (m/s)
α and γ are coefficients according to terrain roughness (see Table 5.8)

This equation and the associated coefficients are taken from BS EN5925 (1991). Example coefficients are given in Table 5.8.

Such an approach is generally acceptable for winds measured between roof height and a recording height of 10m. It is inappropriate for the reduction of wind speeds measured in the upper atmosphere. Alternative methods of wind correction are also used based on a log law profile.

Table 5.8 Terrain coefficients for use with Equation 5.8

Terrain coefficient	a	γ
Open, flat	0.68	0.17
Country with scattered windbreaks	0.52	0.20
Urban	0.35	0.25
City	0.21	0.33

Pressure coefficient

The pressure coefficient, C_p, is an empirically derived parameter which is a function of the pattern of flow around the building. It is normally assumed to be independent of wind speed but varies according to wind direction and position on the building surface. It is also significantly affected by neighbouring obstructions with the result that similar buildings subjected to different surroundings may be expected to exhibit markedly different pressure coefficient patterns.

Accurate evaluation of this parameter is one of the most difficult aspects of natural ventilation and air infiltration modelling and, as yet, is not possible by theoretical means alone. Although pressure coefficients can be determined by direct measurements of buildings, most information comes from the results of wind loading tests made on scale models of isolated buildings in wind tunnels.

Purpose designed tests for specific buildings and shielding conditions may be performed, but this is an expensive exercise and is therefore rarely possible.

For low buildings of up to typically three storeys, pressure coefficients may be expressed as an average value for each face of the building and for each 45° sector, or even 30° sector in wind direction.

For taller buildings, the spatial distribution of wind pressure takes on much greater significance, since the strength of the wind can vary considerably over the height range. In these instances spatial dependent data are essential. Solutions include scale wind tunnel modelling and the use of CFD to predict the surrounding pressure field.

Representative pressure coefficients for open and urban environments are shown in Table 5.9.

5.5.3 Stack effect

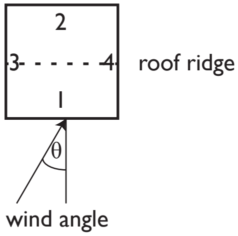
Assuming a uniform air temperature, the pressure of an air mass at any height z above a convenient datum level, z_o, (for example ground or floor level) is given by:

$$p_z = p_o - \rho g z \quad \text{(Pa)} \tag{5.10}$$

Where:

p_z = pressure at required height (Pa)
p_o = pressure at datum level z_o (Pa)
g = acceleration due to gravity (m/s^2)
z = height above datum (m)

Table 5.9a Example of pressure coefficients for low-rise buildings in open terrain



		OPEN TERRAIN/SHIELDING							
		Wind angle							
Location		0	45	90	135	180	225	270	315
Face 1		0.7	0.35	−0.5	−0.4	−0.2	−0.4	−0.5	0.35
Face 2		−0.2	−0.4	−0.5	0.35	0.7	0.35	−0.5	−0.4
Face 3		−0.5	0.35	0.7	0.35	−0.5	−0.4	−0.2	−0.4
Face 4		−0.5	−0.4	−0.2	−0.4	−0.5	0.35	0.7	0.35
Roof (<10° pitch)	Front	−0.8	−0.7	−0.6	−0.5	−0.4	−0.5	−0.6	−0.7
	Rear	−0.4	−0.5	−0.6	−0.7	−0.8	−0.7	−0.6	−0.5
Roof (11–30° pitch)	Front	−0.4	−0.5	−0.6	−0.5	−0.4	−0.5	−0.6	−0.5
	Rear	−0.4	−0.5	−0.6	−0.5	−0.4	−0.5	−0.6	−0.5
Roof (>30° pitch)	Front	0.3	−0.5	−0.6	−0.4	−0.5	−0.4	−0.6	−0.4
	Rear	−0.5	−0.4	−0.6	−0.4	0.3	−0.4	−0.6	−0.4

Table 5.9b Example of pressure coefficients for low-rise urban buildings

		URBAN							
		Wind angle							
Location		0	45	90	135	180	225	270	315
Face 1		0.2	0.05	−0.25	−0.2	−0.25	−0.3	−0.25	0.05
Face 2		−0.25	−0.3	−0.25	0.05	0.2	0.05	−0.25	−0.3
Face 3		−0.25	0.05	0.2	0.05	−0.25	−0.3	−0.25	−0.3
Face 4		−0.25	−0.3	−0.25	−0.3	−0.25	0.05	0.2	0.05
Roof (<10° pitch)	Front	−0.5	−0.5	−0.4	−0.5	−0.5	−0.5	−0.4	−0.5
	Rear	−0.5	−0.5	−0.4	−0.5	−0.5	−0.5	−0.4	−0.5
Roof (11–30° pitch)	Front	−0.3	−0.4	−0.5	−0.4	−0.3	−0.4	−0.5	−0.4
	Rear	−0.3	−0.4	−0.5	−0.4	−0.3	−0.4	−0.5	−0.4
Roof (>30° pitch)	Front	0.25	−0.3	−0.5	−0.3	−0.4	−0.3	−0.5	−0.3
	Rear	−0.4	−0.3	−0.5	−0.3	0.25	−0.3	−0.5	−0.3

The resultant pressure gradient is therefore:

$$\frac{dp}{dz} = -\rho g \tag{5.11}$$

Which becomes, by consideration of the ideal gas law, equations:

$$\frac{dp}{dz} = -\rho_o g \frac{273}{\theta} \tag{5.12}$$

Where:

ρ_o = air density at 273K (kg/m^3) = 1.293 (kg/m^3)
θ = absolute temperature of the air mass (K)

Thus the pressure gradient is inversely proportional to the absolute temperature of the air mass. For two openings, on opposite walls as illustrated in CIBSE AM10 (2005a: figure A6.1), the stack pressure difference can be calculated by:

$$p_s = -\rho_o g 273(h_2 - h_1)\left[\frac{1}{\theta_e} - \frac{1}{\theta_i}\right] \text{ (Pa)} \tag{5.13}$$

Where:

θ_e = absolute temperature of the outdoor air (K)
θ_i = absolute temperature of the indoor air (K)

Stack pressures are often comparable with wind induced pressures and many ventilation designs concentrate on developing the stack pressure to drive ventilation airflow.

5.5.4 Combining wind with stack pressure

The total pressure, p_{t_i}, acting at an opening, i, due to the combined impact of wind and stack effect, is given by:

$$p_{t_i} = p_{w_i} + P_{s_i} \tag{5.14}$$

It is important to understand that summing the pressures due to stack and wind effect at each opening is not the same as summing the flow rates determined by calculating the flow rates due to wind and stack pressure separately.

5.5.5 Calculating the natural ventilation rate

The calculation of naturally induced airflow through the building requires the following steps:

- calculate wind pressure for each path;
- calculate stack pressure for each path;
- determine the total pressure (add wind+stack) for each path;
- apply the general flow equation to each path;
- determine an internal pressure for the space such that the total airflow into a space is balanced by the total airflow out of the space.

This final step is the central component of ventilation calculations. Except for very simple networks, the calculation is not direct and the process of 'iteration' is required. It is this element that makes ventilation calculation approaches so difficult to follow.

Taking all the flow paths, the conservation of mass requires a flow balance between the ingoing and outgoing airflow. This is expressed by:

$$\sum_{\mathrm{i}=1}^{j} \rho_i Q_i = 0 \quad \text{(kg/s)} \tag{5.15}$$

Where:

ρ_i = density of air flowing through flow path i (kg/m^3)
Q_i = volume airflow rate through flow path i (m^3/s)

This method of calculating airflow rate for single zones is relatively easy to incorporate in thermal models and the algorithm on how it can be done is included in CIBSE Guide A (1999).

For multi-zone network models, achieving a solution becomes more complex. Unlike the 'single zone' approach, where there was only one internal pressure to determine, there are now many values. This adds considerably to the complexity of the numerical solution method.

As mentioned before, multi-zone ventilation models are incorporated in most thermal and energy simulation models to consider the energy impact of natural ventilation paths. In addition, there exist multi-zone models focusing on ventilation and contaminant distribution in buildings such as CONTAMN (2011).

5.6 Fans

Fans are used in hybrid ventilation design to increase airflow rate when natural driving forces are not enough to achieve the required ventilation rate. Their properties depend on the design, the size and the rotating speed; this will affect their energy consumption.

When a fan is connected to a duct system the fan type and size are selected according to the airflow and the resistance of the duct system and components such as filters, dampers and heating/cooling coils. The fan must work against this resistance to move the air at the desired flow rate and to the desired position in the building.

When a fan is connected to a duct system the flow in the system stabilises at the flow rate with which the pressure generated by the fan is equal to the pressure drop in the complete system. The fan must work against the resistance of losses in the duct system to move the air at the desired flow rate and to the desired position.

5.6.1 Power demand of fans

Power input to the airflow is the product of airflow and pressure rise:

$$P = \Delta p q_v \tag{5.16}$$

Where

P = the input power of fan into the airflow, W
Δp = the total pressure difference across the fan, Pa
q_v = the airflow through the fan, m^3/s

The power demand to run the fan, however, is much greater due to losses in the fan impellor, the fan drive and the motor. Often all these efficiencies are lumped into the total efficiency of the fan. The electrical power required to run the fan can be calculated from the equation:

$$P = \Delta p q_v / \eta_{tot} \tag{5.17}$$

Where

η_{tot} is the total efficiency of fan including fan itself, motor (including speed control etc.), drives and losses in the built-in situation.

The power demand is thus affected by the airflow, the pressure difference and the efficiency. The fans are designed for one velocity airflow, where the flow has lowest losses and the efficiency has its maximum value. If the flow is smaller or larger, the efficiency is decreased.

If the rotation speed of a fan increases, the airflow changes in relation to rotating speed, pressure proportional to the second power of the speed and power demand to the third power of the fan speed.

$$\frac{q_{v1}}{q_{v2}} = \frac{n_1}{n_2} \tag{5.18}$$

$$\frac{\Delta p_1}{\Delta p_2} = \left(\frac{n_1}{n_2}\right)^2 \tag{5.19}$$

$$\frac{P_1}{P_2} = \left(\frac{n_1}{n_2}\right)^3 \tag{5.20}$$

Where

n = fan speed, 1/min

Therefore, variable speed fans have become popular for energy efficiency reasons.

5.6.2 Specific power of fans

The term 'specific power' of each fan is used to define the overall efficiency of the air moving system.

$$P_{SFP} = \frac{P}{q_v} = \frac{\Delta p}{\eta_{tot}} \tag{5.21}$$

Where

P_{SFP} = the specific fan power in W/m^3/s
P = the input power of the motor for the fan, W
q_v = the nominal airflow through the fan in m^3/s
Δp = the total pressure difference across the fan, Pa
η_{tot} = the total efficiency of fan, motor and drive in the built-in situation.

In the air-handling system the coefficient is valid for the nominal airflow with clean filter conditions and all bypass closed. It is related to an air density of 1.2 kg/m^3.

In many countries, the allowed specific power of the fan is stipulated in the regulations and guidelines to help with energy efficiency measures. For example in the UK (CIBSE 2004a), a specific fan power of 2–3W/m^3/s is recommended for office buildings.

5.7 Ventilation for cooling

Increasingly, ventilation is used to provide internal thermal comfort in buildings; i.e. controlling temperature inside buildings and thus avoiding overheating. In this case, ventilation rates required are quite different (usually much higher) than ventilation rates required for IAQ purposes. In many cases, ventilation is provided by natural means although hybrid strategies and coupling with internal thermal mass are increasingly popular. In some cases, mechanical ventilation is used for providing thermal comfort, although this option is usually energy consuming because of the energy required by the fans. Ventilation for controlling internal temperatures is location and building operation dependent. In very broad terms the following climatic classifications might apply:

Climatic regions with high cooling load

In such climates, ventilation strategies are usually designed to provide some cooling to reduce reliance on active air-conditioning systems. Such ventilation strategies would most likely be implemented in climates with a hot cooling season and winters requiring no or very little heating. Ventilation strategies for thermal comfort (cooling) would usually be combined with other passive and/or active cooling methods in addition to passive and/or active heating methods.

Climatic regions with high heating load

These ventilation strategies are mainly designed to provide IAQ. They would most likely be implemented in climates with a cold heating season and a summer requiring none or very little cooling. Ventilation strategies for IAQ (heating) would, in most cases, be efficient mechanical ventilation strategies, perhaps combined with passive cooling strategies for the summer.

Climatic regions with moderate heating and cooling loads

In these climates, ventilation strategies are designed to provide thermal comfort in the summer. Such ventilation strategies might also be implemented in climates where extra high moisture levels might impose an additional load. Natural ventilation strategies might be able to satisfy cooling load requirements for a range of buildings with moderate internal heat gains.

Therefore, outside air, if colder than thermal comfort temperature, can be used to cool an indoor space. Levermore (2002) gives the heat transfer equation as:

$$\Phi_v = \tfrac{1}{3} NV(\theta_f - \theta_o)\,(1 - e^{-x}) \tag{5.22}$$

Where:

Φ_v = heat transfer by ventilation (W)
N = air change rate (h^{-1})
V = room volume (m^3)
θ_f = surface temperature of the internal surfaces of the building fabric (°C)
θ_o = outdoor air temperature (°C)

And exponent x is given by:

$$x = \frac{4.8A}{\tfrac{1}{3}NV} \qquad (5.23)$$

where A is the area of opening (m^2).

If free cooling through external air is provided with mechanical ventilation, the electrical energy consumption of fans should be considered when calculating energy efficiency improvements.

In addition to free cooling as described above, ventilative cooling can be purposely provided with two methods.

5.7.1 Ground coupled ventilation

Ground coupled air systems (sometimes called earth-to-air heat exchangers – ETAHE) are mainly used for preconditioning outdoor air during the summer but can also be used during winter to preheat the air. An ETAHE draws ventilation air through ducts buried underground, as shown in simplified diagram in Figure 5.9.

A typical ideal operation of the system is shown in Figure 5.10.

Figure 5.11 shows an operational building from Portugal where an ETAHE is used as part of the low energy design of the building.

Most existing ETAHEs are installed in mechanically ventilated buildings, in which electrical fans provide the airflow driving forces. In such systems, an ETAHE can be a single duct or multiple parallel ducts made of prefabricated metal, PVC, or concrete pipes with diameters at a magnitude of 10cm. In case of the parallel pipe systems, the distance between the pipes should be kept approximately 1m from each other in order to minimise the thermal interaction. The size of an ETAHE depends on the designed airflow rate and the available space. A maximum air velocity of 2m/s is normally recommended for smaller systems, and larger systems can be designed for air velocity up to 5m/s. Due to the high velocity and small duct size, large amount of energy has to be spent on the mechanical ventilation systems to deliver air through the ETAHEs (Perino 2008).

The cooling potential of the systems depends on the ground temperature distribution. It is generally recommended a depth of 2–4m for the pipes but this depends on the location and the condition of the soil (Zimmerman and Remund 2001).

The energy saving potential of an ETAHE has attracted many simulation studies since the 1980s. The main efforts have been on the development of simulation methods. However, some simplified tools for the prediction of outlet temperature and sizing of ETAHE systems have also appeared. These methods are usually based on statistical analysis of simulation results and are not independent of external conditions (Grosso and Raimondo 2008; Santamouris 2006; Santamouris and Asimakopoulos 1996; Warwick *et al*. 2009).[2] Many thermal simulation models include modules to consider ETAHE systems during the design.

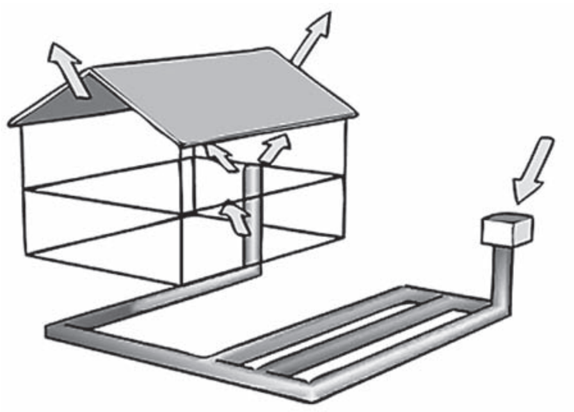


Figure 5.9 Indicative diagram of an ETAHE system

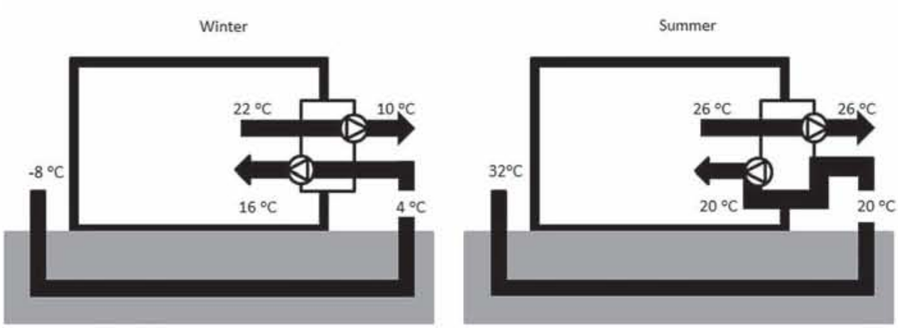


Figure 5.10 ETAHE system schematic, for winter and summer incorporating a heat exchanger for winter

Source: adapted from Hollmuller 2011

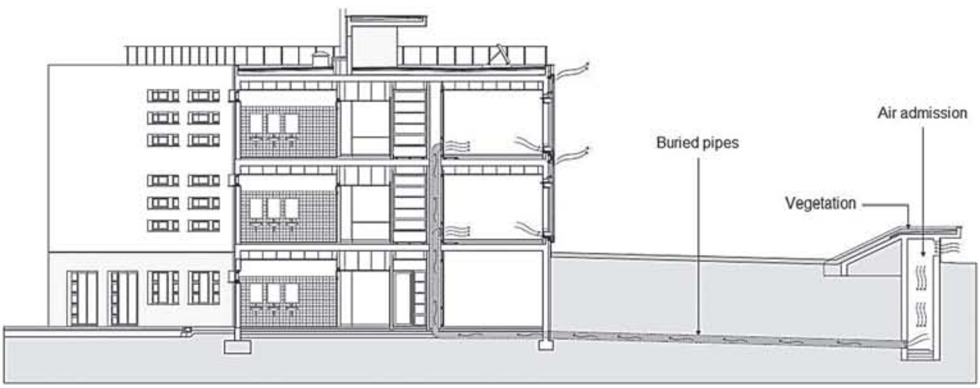


Figure 5.11 The SOLAR XII building in Portugal in which ETAHE is used as part of the low energy cooling strategy

Source: courtesy of the AdVent Project

5.7.2 Night cooling

Night cooling is a low energy cooling strategy whereas the building is ventilated during the night. It works by using natural or mechanical ventilation to cool the surfaces of the building fabric at night so that they can absorb heat during the day. Night-time ventilation is suitable for areas with a high diurnal temperature range and where night-time temperature is not so cold to create discomfort. Figure 5.12 shows temperature measurements to demonstrate the effect of natural night ventilation in practice (Kolokotroni 1998). It shows that night ventilation reduces air and surface temperatures, and delays the peak internal temperature until later in the day.

Night ventilation is effective where a building includes an exposed internal thermal mass so that heat can be absorbed during the day. Night ventilation can affect internal conditions during the day in four ways:

- reduces peak air temperatures
- reduces air temperatures throughout the day, and in particular during the morning hours
- reduces slab temperature
- creates a time lag between external and internal temperatures.

Parameters directly affecting the cooling potential of night ventilation are:

- day ventilation rate
- night ventilation rate

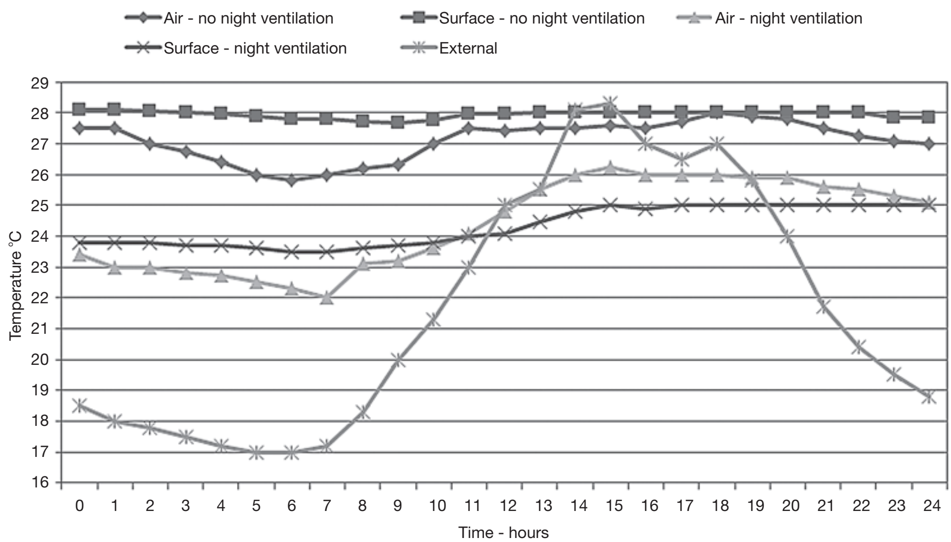


Figure 5.12 Measured hourly temperatures in an exposed thermal mass office with and without night ventilation

Source: adapted from Kolokotroni 1998

- exposed internal thermal mass
- internal heat gains
- weather (temperature and solar gains).

Figure 5.13 presents the effect of day and night ventilation and the exposed thermal mass on the maximum internal temperatures for a library in south-east England. It can be seen that, for example, a 2.5°C reduction could be achieved for the maximum day temperature in a construction with exposed thermal mass to which night ventilation is provided at a rate of 5 ACH (Kolokotroni 2001).

Night ventilation systems are classified as direct or indirect as a function of the procedure by which heat is transferred between the thermal storage mass and the conditioned space (Santamouris 2004). In direct systems the cool air is circulated inside the building zones and heat is transferred in the exposed opaque elements of the building. The reduced temperature mass of the building contributes to reduce the next day's indoor temperature through convective and radiative processes. Circulation of the air can be achieved by natural or mechanical ventilation. In direct systems, the mass of the building has to be exposed and the use of coverings or false floors or ceilings has to be avoided.

In indirect systems, the cool air is circulated during the night, through a thermal storage medium where heat is stored and then recovered during the day period. In general, the storage medium is a slab covered by a false ceiling or floor while the circulation of the air is always forced, Figure 5.14. ETAHE systems as described in Section 5.7.1 can be classified as indirect night cooling systems. Direct and indirect

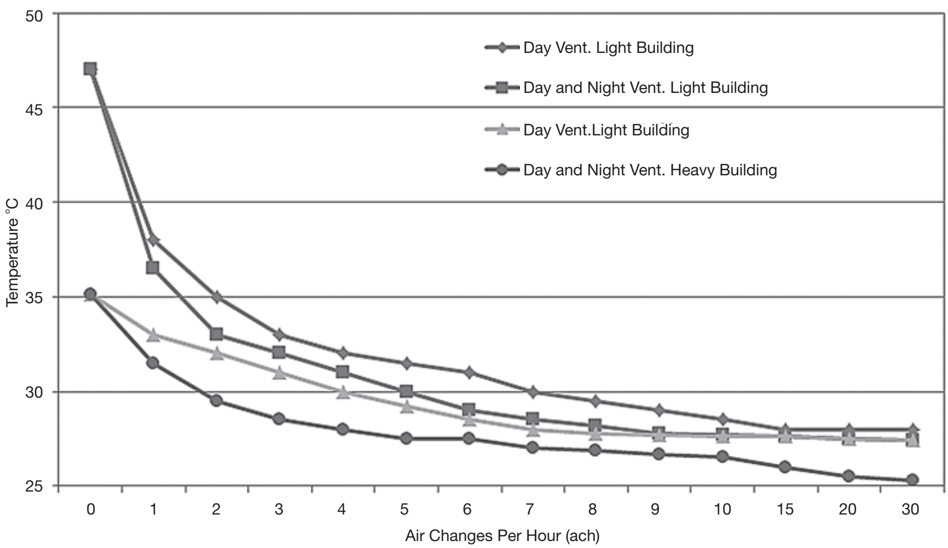


Figure 5.13 Predicted maximum temperatures for library buildings as a function of ventilation rate and exposed thermal mass

Source: adapted from Kolokotroni 2001

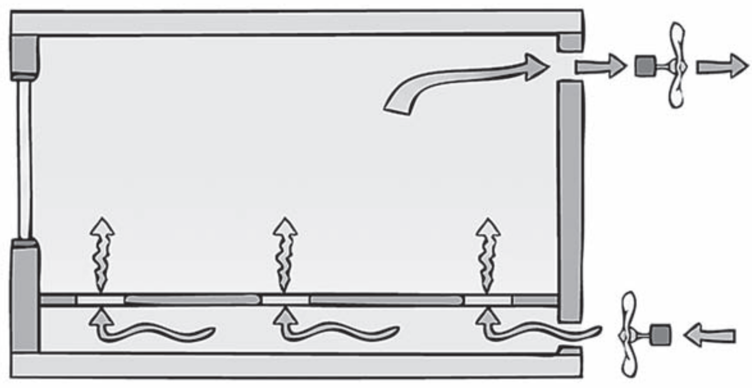


Figure 5.14 Indicative diagram of an indirect night cooling system

Source: author's compilation with Warwick

systems are used many times in a combined way. Their combination has been successfully demonstrated in the past and they are now mature technologies, for example in the Schwerzenbacherhof Office and Industrial Building Schwerzenbach, Switzerland (Zimmerman and Anderson 1998).

Although it is a powerful strategy for cooling, however, it presents important limitations. Moisture and condensation control is necessary, particularly in humid areas. Pollution and acoustic problems (especially in urban areas) as well as problems of privacy are associated with the use of natural ventilation techniques. Another important limitation is associated with climatic conditions within cities. The increase of the ambient temperature, especially during the night because of the urban heat island phenomenon, as well as the marked decrease of wind speed in urban canyons might considerably reduce the cooling potential of night cooling strategies.

5.7.3 Developments based on traditional systems and strategies

Finally it should be mentioned that in the drive for energy efficiency and low energy heating/cooling methods for buildings, traditional ventilation components and strategies are explored, developed for modern buildings, and reach the market successfully. As an example, the windcatcher ventilation component and the passive downdraught evaporative cooling system are described briefly:

Windcatcher

The windcatcher system is a passive ventilation system which uses both buoyancy and wind driven forces to provide ventilation in a space. A diagram of the component is shown in Figure 5.15. Windcatcher systems have been employed in buildings in the Middle East for many centuries, and they are known by different names in different parts of the region. Modern day variants have been used increasingly in locations where a strong wind driving force is available.

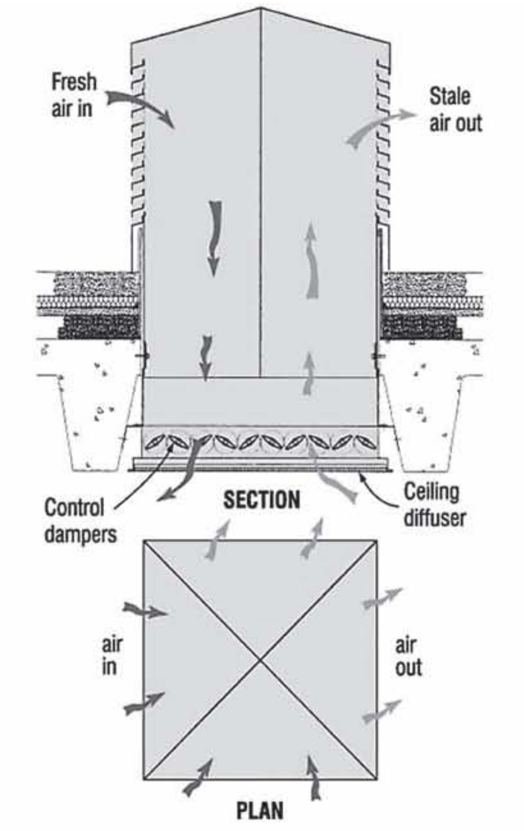


Figure 5.15
Modern windcatcher design

Source: courtesy of Monodraught, UK

The modern wind tower of a windcatcher consists of a vertical stack which, in cross section is divided into quadrants. This normally penetrates and terminates at ceiling level in a space. Wind directed at the windward facing quadrant (or quadrants) is driven down the stack to ventilate the space below. Simultaneously stale air is sucked out of the space driven by the negative pressures generated by the wind on the leeward facing quadrant or quadrants. Dampers located in ceiling mounted diffusers control the rate of airflow.

The advantages of the components are that air is drawn in at high level where pollutant concentration is usually lower than at street level; they can be integrated with a hybrid fan to ensure reliable operation under low wind speed conditions; and they have the possibility to supply air into deep plan spaces.

PDEC

The passive downdraught evaporative cooling (PDEC) system has again been traditionally developed in hot dry climates. In the past, evaporative cooling was achieved through water-filled porous pots within the supply air stream, or the use of a pool of water at the base of the supply stack. In modern systems, water sprayed high into the supply air stream cools the air stream and increases the supply air density thereby augmenting the buoyancy induced pressure differences that drive airflow.

Modern applications can be found in moderate climates, for example, the School of Slavonic and East European Studies (SSEES) building of University College London (Cook and Short 2005).

5.8 Summary

In this chapter the principles of energy efficient ventilation were outlined; ventilation can be provided through natural or mechanical means or a combination of the two (hybrid or mixed mode ventilation). It was stated that ventilation provision has a dual purpose: first to provide satisfactory indoor air quality; and second (depending on external climate and type/use of the building) thermal comfort. These two functions of ventilation must be considered separately to provide ventilation in an energy efficient manner.

This chapter first outlined ventilation requirements for various types of buildings and available ventilation strategies. It then introduced some parameters used to measure ventilation efficiency within a single space. It followed an outline of how ventilation rate due to natural forces of wind and buoyancy can be calculated and enhanced by the use of fans. The chapter concluded with a description of ventilation strategies useful to provide thermal comfort in a building thus avoiding the need for artificial cooling in certain circumstances.

- Ventilation requirements for various types of buildings are presented according to regulations and guidelines of professional institutions.
- Ventilation strategies are outlined and parameters used to measure ventilation efficiency within a single space are outlined.
- Calculations of ventilation rates due to natural forces of wind and buoyancy are presented. These calculations are useful for the initial design stage in a building when the ventilation strategy is not decided yet.
- Fan characteristics related to energy efficiency are presented.
- Ventilation strategies useful to provide thermal comfort in a building are presented. These include; ventilative cooling, ground coupled ventilation, night ventilation, windcatchers and natural evaporative cooling.

Notes

1 Building Regulations are available online from http://www.planningportal.gov.uk/buildingregulations/approveddocuments/ (accessed 11 January 2013).
2 WKM is a computer program developed to size ETAHEs. Online at http://www.igjzh.com/huber/wkm/wkm.htm (accessed 11 January 2013).

Chapter 6

Air-conditioning systems

6.1 Introduction

Designers of building services systems are frequently called upon to select the most appropriate air-conditioning system for a specific application. To carry out the selection process correctly, they must have a good knowledge of the various air-conditioning systems available on the market, their characteristics and applications. They must also be aware of the implications of selecting a particular system on the capital and running costs. Other important criteria in the selection process include spatial requirements, maintainability, reliability, flexibility and environmental impacts. All these factors are interrelated and so the designer should understand their relative importance for each design job. Other important selection criteria include the specific requirements of the client in terms of aesthetics, maximisation of rental income and the saleability of the property.

In this chapter we consider the different types of air-conditioning systems and their applications.

6.2 Classification of air-conditioning systems

Air-conditioning systems can be classified into a number of broad categories as follows:

Central systems or unitary systems. Central systems employ one or more air-handling units (AHUs) which are served by heating and cooling equipment located outside the conditioned area. In unitary systems, all the components required for conditioning the supply air are housed in a single package. Cooling is provided by a direct expansion coil housed in the package.

Single zone or multi-zone systems. A single zone system serves only one zone in the building. The spaces in this zone have similar load characteristics and the supply conditions are controlled from a single sensing point within the zone. In a multi-zone system terminal devices are used to control the supply conditions to individual zones. Each zone is controlled from its one sensing and control unit.

Constant air volume (CAV) and variable air volume (VAV) systems. In CAV systems, the supply air volume to each zone is maintained constant. Variations in the load at part-load conditions are met by varying the temperature of the supply air. In VAV systems the supply air temperature is maintained constant. Variations in load are catered for by varying the supply air volume flow rate.

6.3 Unitary systems

Unitary systems are the simplest air-conditioning equipment. They are factory assembled units with all the components contained in a small number of enclosures. The units can provide cooling only or can be configured to provide both cooling and heating by using the vapour compression cycle in reverse, i.e. heat pump cycle. A simpler method of providing heating is to use electric resistance heaters with a non-reversible vapour compression cooling system.

The simplest types of unitary systems are through the wall units in which all components are contained in one enclosure, and split systems. Split air-conditioning systems consist of an outdoor and an indoor unit. The outdoor unit contains the compressor, the condenser/fan assembly and the expansion valve. The indoor unit contains the evaporator and the supply fan. The outdoor and indoor units are connected by refrigerant piping. The supply fan recirculates air from the conditioned space. A fixed quantity of fresh air may also be provided through an opening on the wall. Split systems are available in larger capacities than room units.

Advantages

- simple to install
- lower cost than central systems in providing individual space control.

Disadvantages

- no humidification capability
- higher energy usage than central systems for the air conditioning of large buildings
- limited air distribution capability within the conditioned space.

Applications

- small buildings
- commercial premises such as banks
- hotel apartments.

6.3.1 Multi-split and variable refrigerant volume (VRV) systems

In multi-split systems one external unit serves a number of indoor units. The systems can be single zone, where all indoor units are controlled by a single thermostat or multi-zone where each unit is controlled by its own thermostat and can provide individual space temperature control. A limitation, however, is that if cooling is required in one area it is not possible to provide heating in a different area served by the same system because the compressors of the outdoor unit will function in only the cooling or the heating mode. This limitation can be overcome by the variable volume system (VRV).

With VRV systems each indoor unit may provide cooling or heating independently of the other units. Where one area of the building requires heating and another cooling, heat removed from the area that requires cooling can be upgraded and used in the area that requires heating, thus improving the overall efficiency of the system.

Ventilation air to the spaces, if desired, can be provided by separate heat recovery units. With these systems an equal quantity of outside air and exhaust air are drawn through a heat recovery heat exchanger so that the exhaust air is used to heat or cool the ventilation air.

Advantages

- lower cost than central systems for single zone air conditioning
- VRV units provide individual zone control.

Disadvantages

- no humidification capability
- units sited in indoor spaces may create noise problems
- multiple units sited indoors may occupy valuable rentable space.

Applications

- office and other commercial buildings
- multi-tenanted buildings – each tenant served from a separate multi-split or VRV system
- renovation work – retrofit applications.

6.3.2 Packaged systems

These are larger capacity single zone systems, up to 100kW. They can be used to serve a single space or a number of spaces within a zone by siting the system centrally and distributing the supply air to the individual spaces through a duct distribution system. Each zone is served by its own packaged unit.

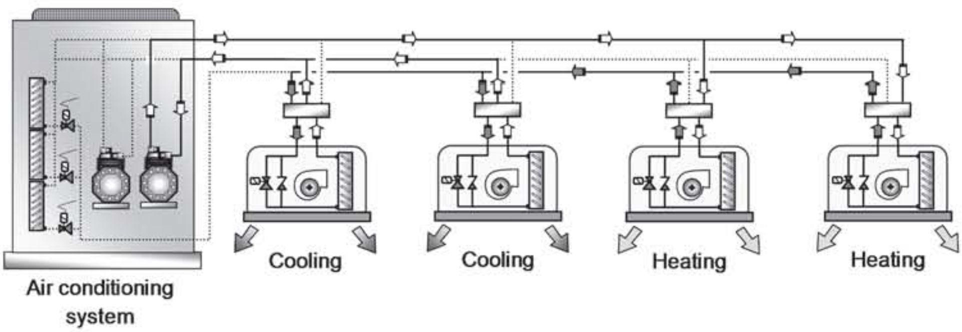


Figure 6.1 Schematic of a VRV system (Daikin air conditioning)

Packaged systems can be mounted indoors in basements, utility rooms, attic or crawl spaces, outdoors on the ground, or rooftop. Unlike through the wall and split systems, packaged units are supplied with fans capable of operating with ductwork. A packaged air-conditioning system is shown in Figure 6.2.

Advantages

- lower cost than central systems for single zone air conditioning
- can provide individual air distribution in the conditioned spaces
- can provide ventilation air at all times
- units are available with complete and self contained control systems
- can provide individual zone control.

Disadvantages

- no humidification capability
- air-cooled units should have access to outdoor air
- units sited in indoor spaces may create noise problems
- multiple units sited indoors may occupy valuable rentable space.

Applications

- office and other commercial buildings to provide floor by floor air conditioning
- multi-tenanted buildings – each tenant served from a separate packaged system
- open-plan spaces to provide central air distribution
- renovation work – retrofit applications.

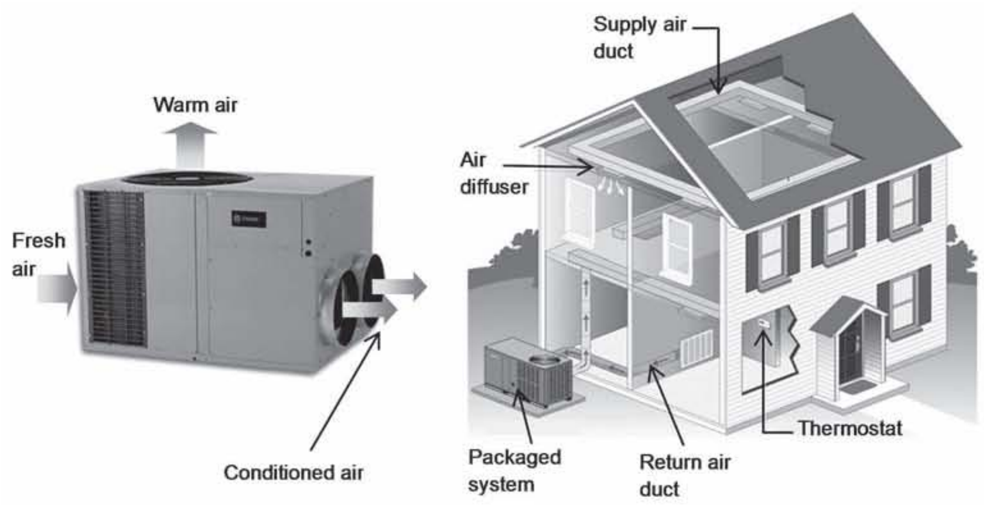


Figure 6.2 Packaged air-conditioning system

Source: Goodmanmfg.com

6.4 Central air-conditioning systems

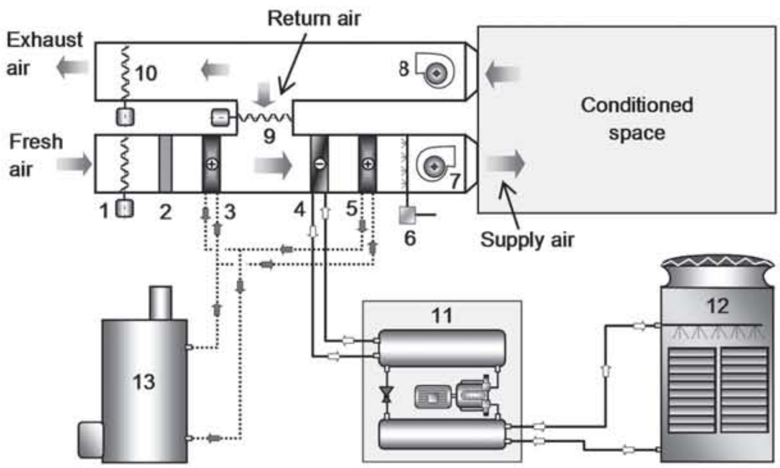
Central systems employ one or more AHUs which are served by heating and cooling equipment located outside the conditioned area.

Applications

Central air-conditioning systems can be used:

- for the conditioning of spaces which have uniform load. These are usually large open spaces with small external loads and high internal loads such as theatres, department stores and the public spaces of commercial buildings;
- for precise control of the conditions within a small space. Such spaces can be precision laboratories or manufacturing units and operating theatres requiring cleanliness and accurate control of temperature, humidity and air distribution;
- as a source of conditioned air for other systems. Some multi-zone systems utilise the plant in individual zones to offset part of the sensible load. The latent load and the remainder of the sensible load are handled by the central system which either conditions fresh air or a mixture of fresh and recirculated air. This arrangement reduces the amount of air handled by the central plant and as a consequence the size of the ductwork is reduced. Such systems can be used in multi-storey buildings where space is at a premium.

Figure 6.3 shows the main components of a central single zone air-conditioning system. The majority of these components are described in detail in Chapter 7.



1. Outdoor (fresh) air damper; 2. Filter; 3. Pre-heater; 4. Cooling coil;
5. Re-heater; 6. Steam humidifier; 7. Supply fan; 8. Return fan;
9. Return air damper; 10. Exhaust air damper; 11. Chiller; 12. Cooling tower;
13. Boiler

Figure 6.3 Main components of a central air-conditioning system

6.5 All-air central air-conditioning systems

6.5.1 Introduction

In all-air central air-conditioning systems, the only medium providing both sensible and latent cooling in the conditioned space is air. All cooling and humidification/dehumidification is provided in the central plant and the cold air is distributed to the various zones within the building. Heating may be provided either at the central plant or within the air stream in individual zones.

All-air systems may be classified into two major categories: a) constant volume variable temperature systems; and b) variable volume constant temperature systems.

The above systems may also be classified as: *single duct systems*, and *dual duct systems*. Single duct systems employ a common duct distribution system and all the heating and cooling coils are arranged in a series flow path within the air-handling unit (AHU). Dual duct systems employ two duct distribution systems with one duct conveying the hot air stream and the other duct the cold air stream.

Advantages

- quiet operation and centralised maintenance – all mechanical equipment is located remotely from the conditioned spaces. This facilitates noise isolation and allows for easy maintenance;
- design simplicity – wide choice of zoneability, and humidity control and simultaneous availability of heating and cooling if required. Wide flexibility in the design of air distribution within the conditioned spaces and minimum interference from furniture, windows, curtains etc;
- economy of operation – outdoor air can be used directly in marginal weather conditions to provide 'free cooling', reducing the need for refrigeration;
- adaptability to heat recovery – they can easily be adapted to accommodate heat recovery equipment.

Disadvantages

- duct clearance – the requirement for clearance either at the ceiling or floor levels and clearance for duct risers reduces the usable space, which may be critical especially in high rise buildings;
- complicated balancing – multi-zone systems with a large number of air outlets are very difficult to balance to achieve the design flow rates;
- coordination at the design stage – they require greater coordination between the architect and the mechanical and structural designers at the design stage to provide easy access to terminal devices.

Applications

All-air systems are applied to buildings with a large number of zones that require individual control of space conditions. Such buildings include: department stores, supermarkets, common areas in hotels, office buildings, theatres, cinemas and hospitals. They can also be used in specialised applications where there is a need for close control of temperature and humidity; these include clean rooms, hospital operating theatres, computer rooms and textile factories.

6.5.2 Constant air volume, variable temperature system (CAV)

In the constant volume variable temperature system, the supply volume to the conditioned spaces remains constant and the heating and cooling loads are satisfied by varying the supply temperature of the air. The supply temperature can be varied by a number of methods, the most common being: a) control of the cooling capacity of the cooling coil; b) air reheat control; c) terminal reheat system.

Cooling coil capacity control

In direct expansion coils, the control of cooling capacity can be achieved by a number of ways such as: on–off control of single or multiple reciprocating compressors arranged in parallel, cylinder unloading of reciprocating compressors, hot gas bypass, control of the inlet guide vanes in the case of centrifugal compressors, and variable speed control. Variable speed control is the most efficient and currently the most commonly used method in medium to large capacity systems.

Control of the capacity of chilled water coils can be achieved through modulation of the water flow through the coil. The flow control can be achieved either by a two-way valve or by a three-way diverting valve and a space thermostat as shown in Figure 6.4. Two-way valves are used in variable flow pumping systems and three-way diverting valves in constant flow systems.

When a diverting valve is used, a regulating valve is placed in the bypass line and set at the same pressure drop as the coil and the isolating valves to balance the flow.

At part-load conditions, as the load on the space falls, the space thermostat, T, sends a signal to the controller which progressively reduces the mass flow of chilled water through the coil, thus maintaining a constant space temperature. With this

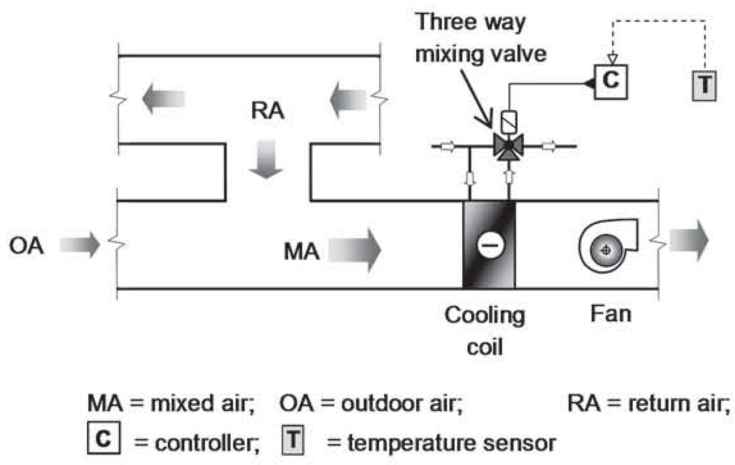


Figure 6.4 Chilled water flow control

method of control, the off-coil temperature and the relative humidity of the air in the space will vary with load whereas the space and return air dry-bulb temperatures will remain constant.

Reheat control

This is the best method of control in terms of maintaining the design space temperature and relative humidity at part-load conditions. The system is illustrated in Figure 6.5. It employs a humidistat, a thermostat, a controller, and heating and cooling coils. The controller compares the signals from the humidistat and the thermostat and if the humidistat signal is higher, the coil control valve is modulated accordingly to control the space humidity. If in the process the temperature falls below the set point, then the controller energises the heating coil control valve to raise the space temperature to the design value. If the temperature rises above the set point, the signal from the thermostat is used to control the cooling coil valve in sequence with heating to reduce the space temperature. The term ‘sequence control’ is used to indicate that either the heating coil or the cooling coil is used at a particular time, but not both.

The space humidity may also be controlled by a dry-bulb temperature sensor placed in the duct immediately after the cooling coil. This sensor controls the flow in the cooling coil to maintain the off-coil temperature constant. Although the apparatus dew point and the moisture content of the air leaving the coil will vary, the variation is very small. This method of control is therefore considered to provide a constant off-coil air dew point temperature and moisture content, which is known as dew point control.

Terminal reheat system

The terminal reheat system can be used to provide temperature and humidity control to zones or spaces that have unequal loadings and require high ventilation rates. Applications include hospitals, office buildings, schools and laboratories. A schematic diagram of the system is shown in Figure 6.6.

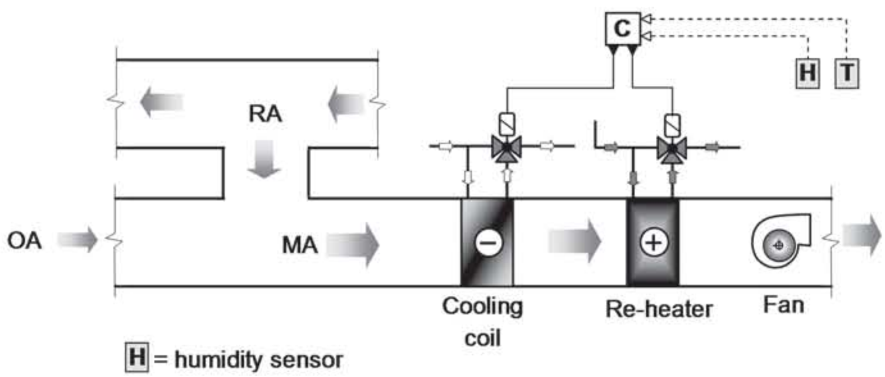


Figure 6.5 Cooling and dehumidification with reheat

The cooling coil, with a preheater coil if required, is placed in the central plant, and heating coils are inserted in the duct system in individual zones. Heating may be provided by steam, hot water or electricity. The central plant provides cooling to satisfy the design cooling and dehumidification loads of the building. The temperatures in the various zones or spaces are controlled by reheating the air stream of the particular zone to the required temperature. The reheaters can also be used to provide winter heating as required.

The main disadvantage of terminal reheat systems is their high operating costs because they provide simultaneous cooling and heating of the supply air.

To save energy, a load analyser control system can be employed which allows the off-coil temperature to rise in response to a reduction in demand from the greatest cooling load.

6.5.3 Variable air volume system (VAV)

Variable volume systems satisfy the cooling and heating loads of a building by varying the supply air volume to the conditioned spaces. In their simplest form, VAV systems consist of a central plant which conditions the air and a supply fan which delivers the air to zone terminal devices. The terminal devices regulate the air flow to the conditioned spaces. Terminal devices are available in various configurations, the simplest being a thermostatically controlled damper. The ratio of the minimum air volume flow to the design flow at the central plant is termed the system turn down ratio, whereas the ratio of the minimum flow to the design flow at the terminal device is termed the terminal turn down ratio.

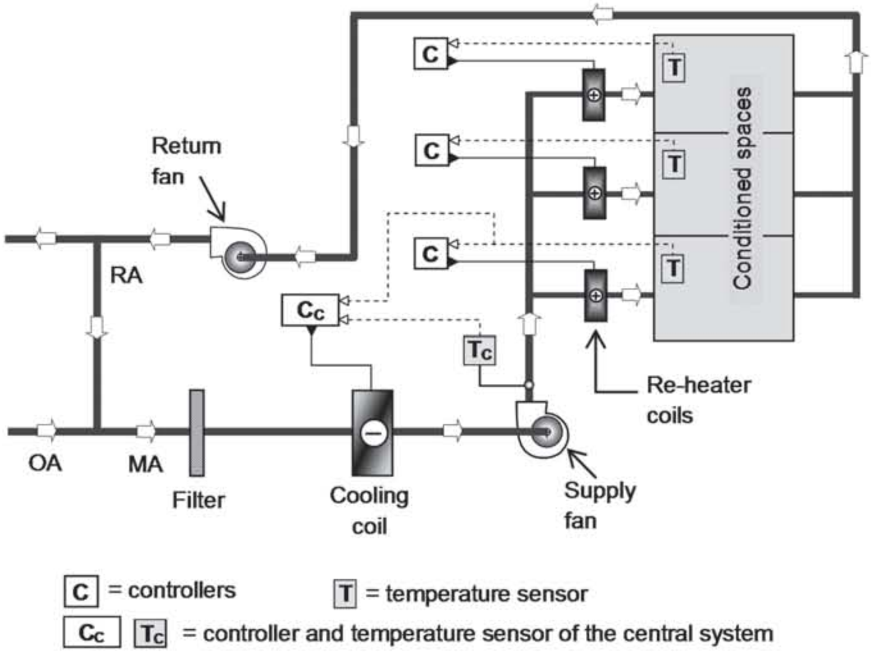


Figure 6.6 Schematic diagram of a terminal reheat system

Advantages

- *Low operating cost.* The fan power and refrigeration power follow the reduction in air flow at reduced loads producing savings on the operating cost of the system. In intermediate seasons all outdoor air can be used for ‘free cooling’, saving in refrigeration power. Also, heating and cooling cannot occur simultaneously, resulting in savings in chiller and boiler running costs.
- *Low capital cost.* The system has lower capital cost than other systems providing individual space control, because it employs single runs of duct and simple control at the terminal devices. The system can also exploit diversity in heat gains and thus it is possible to size the equipment on the simultaneous heat gain rather than the individual maximum heat gains, resulting in lower capacity equipment.
- *Simple individual space control and simple operation.* The system provides individual space temperature control through a thermostat and a flow control terminal device. Changeover of operation from summer cooling to winter heating simply involves stopping the refrigeration equipment and starting the heating equipment at the central plant.
- *Centralised equipment.* All major equipment is centralised allowing for easy maintenance.

Disadvantages

The traditional VAV system has a number of disadvantages which can be overcome to a greater or lesser extent by employing more sophisticated equipment and control systems. These include:

- *Reduced space air movement at reduced loads.* This problem may be overcome by using special terminal devices and introducing design modifications to the basic VAV system.
- *Reduced dehumidification capacity at reduced loads.* At low sensible loads, if the latent gains remain relatively constant, the relative humidity in the space may rise to unacceptable levels.
- *Reduced ventilation capacity at low loads*, if a fixed percentage of outdoor air is used. This problem may be overcome by using a flow sensor in the outdoor air duct to control the mixing dampers.

Applications

Constant temperature variable volume systems are suitable for applications where there is a relatively constant load throughout the year such as the interior spaces of office buildings and department stores. These systems can also be used to provide summer cooling in perimeter zones of buildings which are served from a separate wet distribution heating system. Such buildings include hotels, hospitals, department stores and office buildings.

Variations to the traditional VAV system

- *VAV reheat systems*. These systems are used to provide heating to buildings which have low heat losses and do not employ a separate perimeter heating system. The reheat units are located in the perimeter area of all floors plus the perimeter and interior areas of the top floor of multi-storey buildings as shown in Figure 6.7(a). Typical applications of VAV reheat systems include perimeter zones of office buildings, schools and laboratories as well as interior conference rooms.

A typical VAV reheat terminal unit consists of a single chamber box in a single duct air delivery system as shown in Figure 6.7(b). The unit contains a maximum volume flow regulator, a damper, minimum position stops and a hot water or electric reheat coil. Under normal cooling operation, the VAV terminal unit damper modulates between full supply and minimum supply in response to the room thermostat. As less cooling is required the unit modulates to minimum supply which corresponds to between 30% and 50% design air flow. When the room temperature drops below the corresponding minimum set position of the damper, the reheat coil is activated. If hot water is used, then for economy of operation its supply temperature is reset from outside air temperature.

- *Baseboard heating VAV systems*. Baseboard heating VAV systems employ a separate baseboard heating system in the perimeter zones of the building. If the heat loss from the skin of the building particularly from glazed areas is high, i.e. above 70 W/m^2, then cold downward draughts are created. To prevent uncomfortable conditions near the windows, these draughts must be reduced. The best way of achieving this is to supply heat below the windows to create a counteracting convection current to offset the downward flow of cold air from the window surface, as shown in Figure 6.8.

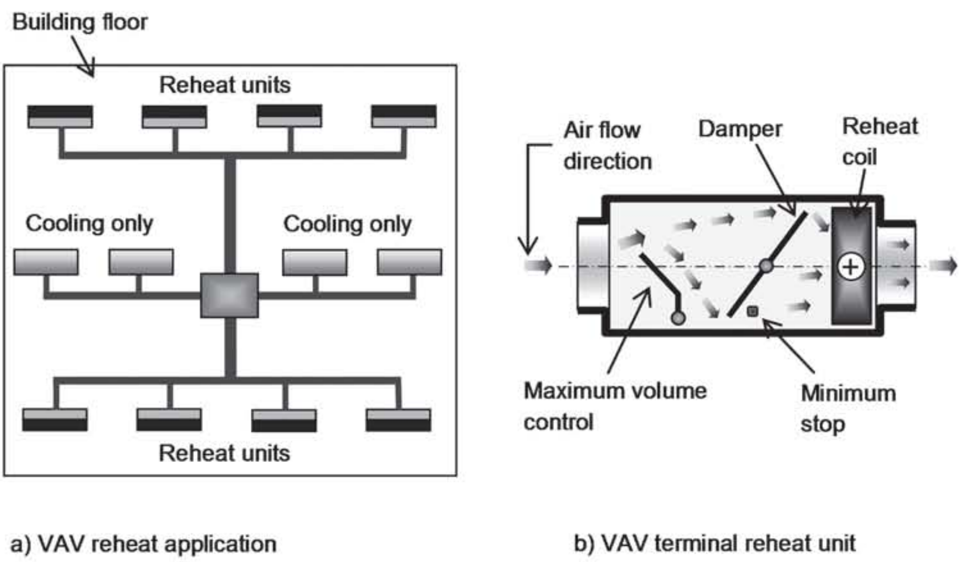


Figure 6.7 VAV reheat system

Convector heaters are preferred to radiators as they emit a considerably larger portion of their heating capacity in the form of convective heat. The cold down-draught is more efficiently counteracted and the air temperature is raised directly as the heating capacity of the unit is increased.

In baseboard heating VAV systems, the VAV system is used to offset the space cooling load in the interior and perimeter zones all year round. The transmission loss in the perimeter zones is counteracted by supplying heat through the baseboard heating system.

- *Combination of CAV and VAV systems.* This system, also known as the skin air VAV system, employs two AHUs. The constant volume AHU, which is used to offset the transmission losses or gains of the perimeter zone, and the VAV system, which is used to offset the solar load of the perimeter zone, and the internal loads of the interior and perimeter zones. In the perimeter zones the air from the VAV air-handling unit is mixed with the air from the CAV air-handling unit before being discharged to the space.
- *Fan powered VAV systems.* As mentioned above, VAV diffusers provide good air distribution and can maintain the coanda effect at turn down ratios down to 40% of design flow. Lower turn down ratios will cause the air pattern to de-stabilise and the air will begin to dump. Increasing the air flow will not automatically restore the coanda effect due to hysteresis in the system. The air flow will have to be increased to approximately 60% before the coanda effect is restored, with the associated problem of creating draughts in the conditioned space.

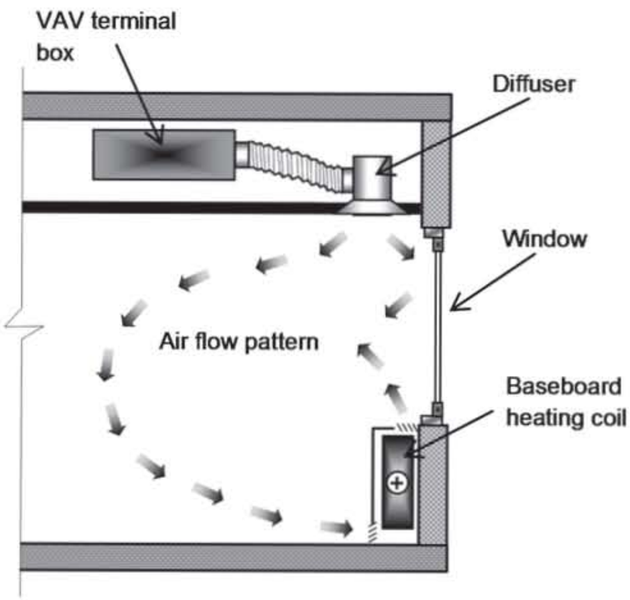


Figure 6.8 Baseboard heating VAV system

The conflicting requirements of variable volume flow at the central plant and good air distribution in the conditioned spaces can be resolved by introducing a fan into the VAV terminal to boost the air flow. The fan mixes the cooler primary air with recirculated room air and provides a near constant volume air to the room. A general system arrangement is shown in Figure 6.9.

Fan assisted VAV terminal units are available in different configurations. The units may also include heating coils for perimeter zone reheat where necessary.

6.5.4 *Dual duct system*

The dual duct system is an all-air system in which the central plant supplies warm air in one duct, and cold air through a second duct. The air is supplied to individual spaces through mixing boxes which mix warm and cold air from the two ducts in appropriate proportions to maintain the required space temperature.

Advantages

- *Individual temperature control*. Because of the availability of warm and cold air to all spaces, the terminal units can provide individual temperature control to each space independently from the other spaces.
- *Rapid temperature response*. Because of the simultaneous availability of warm and cold air, terminal units can provide a rapid response to load variations in the space.
- *Simple operation and control*. The system does not require changeover from summer to winter operation. The space thermostat controls the mixing box to supply a higher proportion of warm or cold air as required.

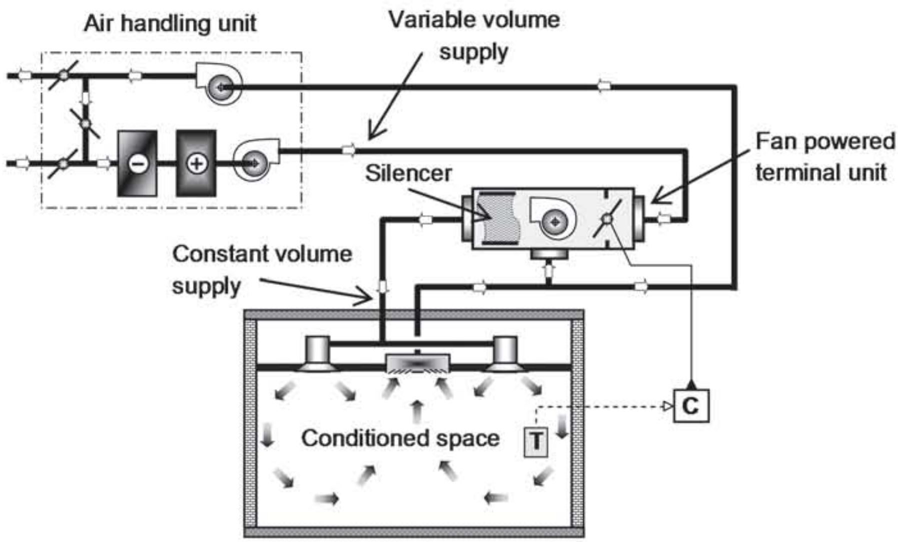


Figure 6.9 Fan powered VAV system arrangement

Disadvantages

- *High capital cost*. This arises from the large area of ducting as two duct runs are required compared with the single duct runs of other all-air systems.
- *High energy use*. The simultaneous provision of cold and warm air to all the terminals results in high energy usage.
- *Large space requirement*. Large ceiling voids are required to accommodate the ductwork which reduces the amount of rentable space. This is particularly important in high rise buildings.

Applications

The dual duct system is used in buildings with highly variable sensible loads and where automatic temperature control with fast response to changes in load is required for individual spaces. Main applications include high specification multi-room buildings such as office buildings, hospitals and laboratories. Particularly, the dual duct system can be employed for the air conditioning of perimeter zones with a separate single duct system employed for the internal zones of a building.

6.6 Air and water central air-conditioning systems

6.6.1 Introduction

In air and water air-conditioning systems, both air and water are distributed to the conditioned spaces to provide heating and cooling. Because of the higher heat carrying capacity of water compared to air (higher specific heat and density), lower quantities of water are needed to transfer or remove the same amount of heat energy from the conditioned spaces than air. This reduces the space requirement for pipe distribution compared to ductwork distribution.

The combination of air and water – with water normally satisfying the sensible load, and the air normally satisfying ventilation and humidity control requirements – enables considerable reduction of the space required for fluid flow distribution in the building, while maintaining some of the performance capabilities of all-air systems. The reduced air requirement combined with high velocity distribution can minimise the space requirement of air and water systems. The pumping power required to circulate water in the conditioned spaces is less than the fan power requirement in all-air systems resulting in lower running costs.

The most commonly used air and water systems are: a) *induction systems*, and b) *primary air fan coil systems*.

In all-water systems, the load is satisfied entirely through the distribution of water to the conditioned spaces. Air is not conditioned centrally but may be drawn directly into the space from the outside through an opening on the wall for ventilation purposes. All-water systems do not provide humidity control and they cannot be classified as 'full' air-conditioning systems. The most common types of all-water systems are: a) space ventilation fan coil system, and b) the unitary heat pump (Versatemp system).

6.6.2 Air and water system characteristics and applications

Air and water systems consist of a central air-conditioning plant, a duct distribution system and a room unit. The central plant provides constant volume air to the room unit. This air stream is usually referred to as primary air. The room unit draws air from the room, passes it through a coil where it is either cooled or heated, as required, before it is discharged back to the room. The room air recirculated by the room unit is usually termed the secondary air.

The primary air quantity is very small and is designed to satisfy:

a the ventilation requirements of the space or spaces in the building;
b part of the sensible cooling requirements to supplement the cooling provided by the coil of the room units;
c the maximum cooling load at changeover from summer to winter cycle;
d the latent load of the building.

The primary air is cooled and dehumidified in the summer, heated and humidified in the winter at the central plant. Return air from the building can be recirculated but the recirculated quantity is very small and thus it may not be economic if the capital cost of the return ducts is considered.

When 100% outdoor air is used and the outdoor temperature is likely to fall below freezing, a preheater is necessary. The use of a re-heater at the central plant depends on the design of the system.

The water side consists of piping and a pump which circulates water through the coil in the room units. The water is either cooled by the chiller serving the cooling coil of the central plant, or heated by a boiler or an alternative water heating system.

Advantages

- *Low space requirements.* The use of water as thermal energy distribution medium reduces the space required for fluid flow distribution in the building.
- *Reduced size of central air-handling system.* The lower air requirement reduces the size of the air-handling equipment at the central plant.
- *Individual space temperature control.* Individual room temperature control can be provided by adjusting the thermostat, which controls the flow of water in the room unit.
- *Energy savings.* Using water as the main source of transmission of cooling and heating to the various spaces in the building reduces the power requirement for fluid flow distribution.
- *No cross contamination for 100% outdoor air systems.* If the outdoor air is used only for ventilation and humidity control purposes then recirculation of air from the building is not required. Recirculation is achieved within the conditioned room by the fan of the room unit and so cross contamination is avoided.

Disadvantages

- *Difficult control during intermediate season operation.* Because of the low quantities of air supplied by the central plant, the control of space conditions during intermediate weather conditions is difficult if space demand alternates between heating and cooling. Correct timing of changeover of the plant from cooling to heating and vice versa requires careful consideration and considerable experience.

- *Limited control of humidity*. Humidity control is provided at the central plant or at individual zones serving a number of spaces. Individual space humidity control is not provided and so humidity in individual spaces is allowed to vary within limits acceptable for thermal comfort.
- *Risk of condensation requiring careful design*. Because of the low quantities of air supplied by the central plant, to satisfy dehumidification requirements the air must be supplied at a low dew point temperature. To avoid condensation of the coils of the room units the surface temperature of the coil should be maintained above the dew point temperature of the supply air.
- *Low ventilation capability*. Because of the low quantity of supply air, the system is unsuitable for use in applications requiring high ventilation rates such as laboratories. In these applications, all-air systems or air and water systems with supplementary ventilation are used.

Applications

Air and water systems are mainly used in applications with highly variable sensible loads and a fairly constant latent load and where accurate control of humidity is not very important. Such applications include the perimeter zones of buildings, such as hospitals, schools, office buildings and hotels. The low space requirements for fluid flow distribution makes air and water systems particularly suited to high rise building applications where usable space is a very important design criterion.

6.6.3 Air and water induction system

In air and water induction systems, primary air (usually 100% outdoor air) is conditioned at the central plant and is distributed at high velocity to the room induction units. The primary air flows through nozzles in the induction unit and the reduction of pressure, which results from the increase in velocity induces secondary air from the room that flows through the coil(s) in the unit. The secondary air is either heated or cooled depending on the temperature of the water flowing through the coil(s) in the unit. The primary air is then mixed with the secondary air in the mixing chamber of the unit and the mixture is accordingly discharged to the conditioned space.

Design considerations

Air and water induction unit systems are normally designed for 100% outdoor air. The cooling coil of the central plant, usually referred to as the primary coil, is designed to provide all the dehumidification requirements of the system. The coil in the induction unit, usually referred to as the secondary coil, is designed to provide only sensible cooling or sensible cooling and heating depending on the design of the system. Ordinarily no latent cooling is accomplished at the secondary coil. A drain pan, however, is usually provided in case condensation occurs at abnormal operating conditions.

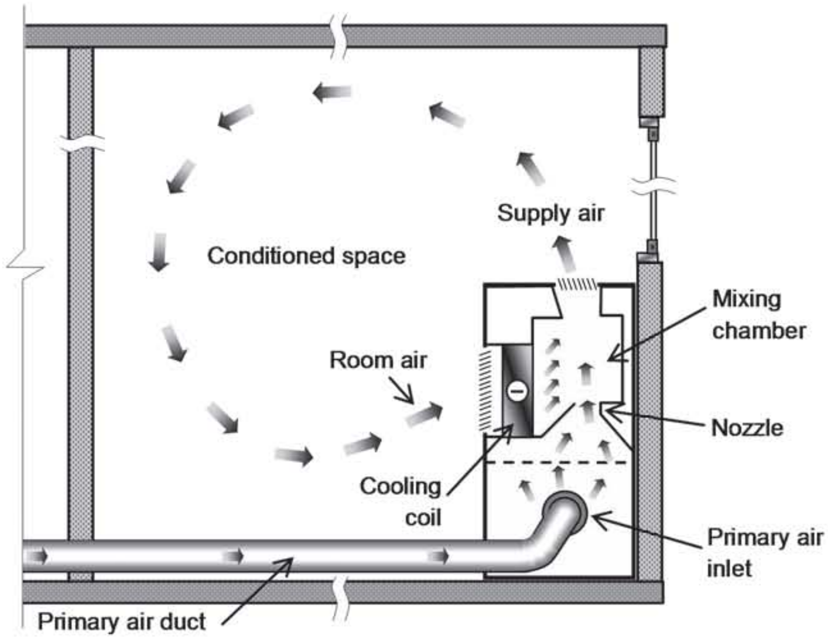


Figure 6.10 Air and water induction unit

The volume of secondary air induced depends on the induction ratio of the unit. The induction ratio is defined is the ratio of the secondary air induced to the primary air volume flow rate.

A wide variety of air and water induction system configurations exist. They can be classified into two broad categories: a) non-changeover systems, and b) changeover systems.

Both non-changeover and changeover systems may employ two-pipe, three-pipe or four-pipe induction unit configurations.

Non-changeover induction systems

Non-changeover systems are used in mild winter climates or for building zones with large winter solar loads. A schematic diagram of the system is shown in Figure 6.11.

The system provides chilled water to the secondary coils all the year round. During summer operation the system provides cold and dehumidified primary air to the induction units. As the outdoor temperature drops in winter, the primary air is reheated accordingly to meet the increased heating load of the building.

Changeover induction systems

The changeover induction system is suitable for severe climates with sharply defined seasons. During summer operation, the system supplies cold primary air and chilled secondary water to the induction units. As the outdoor temperature falls, the primary

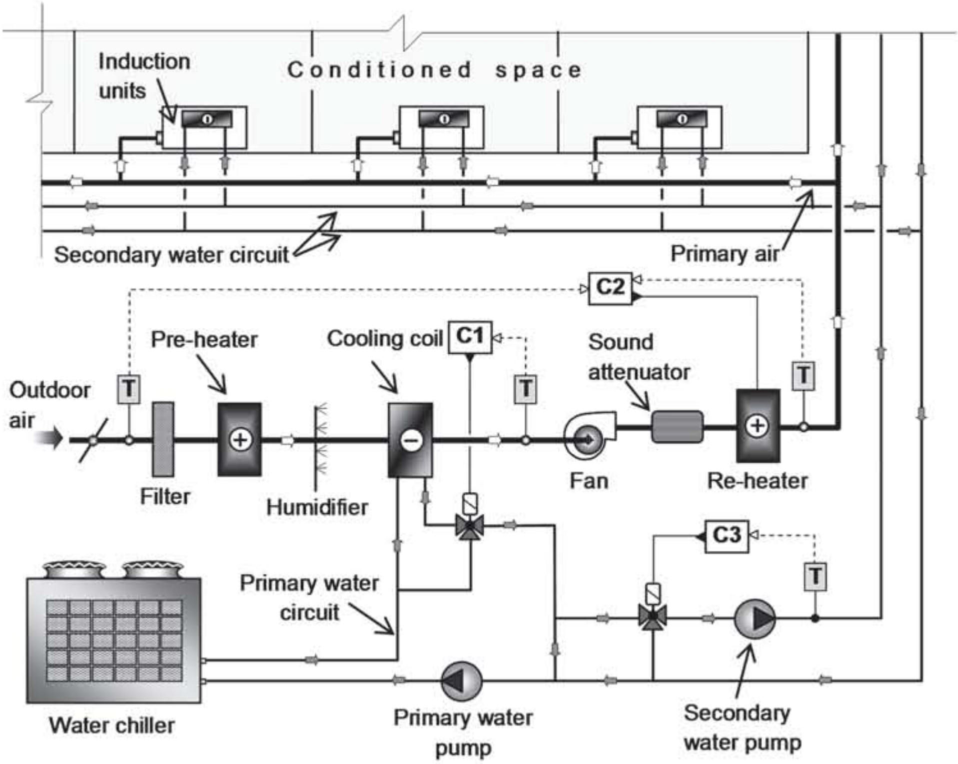


Figure 6.11 Schematic diagram of a two-pipe air and water induction system

Notes: C = controller; T = temperature sensors

air is progressively reheated to offset transmission losses and prevent rooms with low cooling loads from becoming too cold. In intermediate seasons, the water in the secondary coils remains cold.

As the outdoor temperature drops further, the changeover temperature is reached and the secondary water is now supplied hot to overcome the higher transmission losses. Because changeover in intermediate seasons may be troublesome due to wide oscillations in outdoor temperature above and below the changeover temperature, changeover to hot water is limited to times of protracted cold weather.

The changeover induction system may be of a two-pipe, three-pipe or four-pipe configuration:

- *Two-pipe system*. In this configuration, the induction unit employs one coil with one water supply and one water return pipe. In summer and intermediate weather conditions, the coil is supplied with cold water whereas in winter weather conditions the coil is supplied with hot water.
- *Three-pipe system*. In a three-pipe configuration, the terminal unit employs one coil with one hot water supply, one cold water supply and a common return

pipe. With this system terminal units can be supplied with either hot or cold water simultaneously. This configuration is rarely used because of its high energy consumption due to mixing of the hot and cold return water streams.

- *Four-pipe system*. This configuration normally has two secondary coils one cold and one hot, with one hot water supply, one hot water return, one cold water supply and one cold water return pipe. The primary air is supplied cold to the induction units all the year round. In intermediate seasons, both cold and hot water is available to the induction units which can be operated independently at any level from maximum cooling to maximum heating. The four-pipe configuration has several advantages over the two-pipe configuration which include:
  - simplicity of operation and control
  - flexibility and quick response to changes in load
  - lower operating costs
  - no need for summer–winter changeover.

The main disadvantage of the four-pipe system is its higher capital cost.

6.6.4 Primary air fan coil system

The primary air fan coil system is very similar to the induction system. The only difference is in the terminal unit, where the induction unit is replaced by the fan coil unit. The fan coil unit basically consists of a filter, a finned tube coil and a centrifugal fan. Sometimes two coils are used, a hot water coil and a cold water coil. The fan runs continuously and recirculates air from the space through the coil which is supplied with either hot or cold water. The primary air can be supplied directly to the space or through the fan coil unit. When the air is supplied directly to the space, low velocity distribution can be used, resulting in savings in fan power. The supply temperature, however, should be maintained high enough to avoid cold draughts in the conditioned space.

When the primary air is supplied through the fan coil unit, two configurations are possible. The primary air may mix with the secondary air at the supply outlet of the unit after the secondary air has passed through the coil. Alternatively, the primary air may mix with the secondary air before the coil with the mixed stream, passing through the coil before it is discharged to the space. With the second configuration, the primary air supply may vary during capacity control of multiple units because the primary air flow to each unit is dependent to a certain extent on the operation of the fan in the unit.

Fan coil units may be of the horizontal or vertical type as shown in Figure 6.12. Horizontal fan coil units are usually ceiling mounted while the vertical fan coil units are normally installed under the window sill. Vertical units, installed under the window sill, prevent cold draughts from the cold window surfaces by discharging warm air in the opposite direction, which raises the inner surface temperature of the window. For places having mild winter climates, where cold window draughts are not a problem, horizontal ceiling mounted units are preferred because they occupy less floor space.

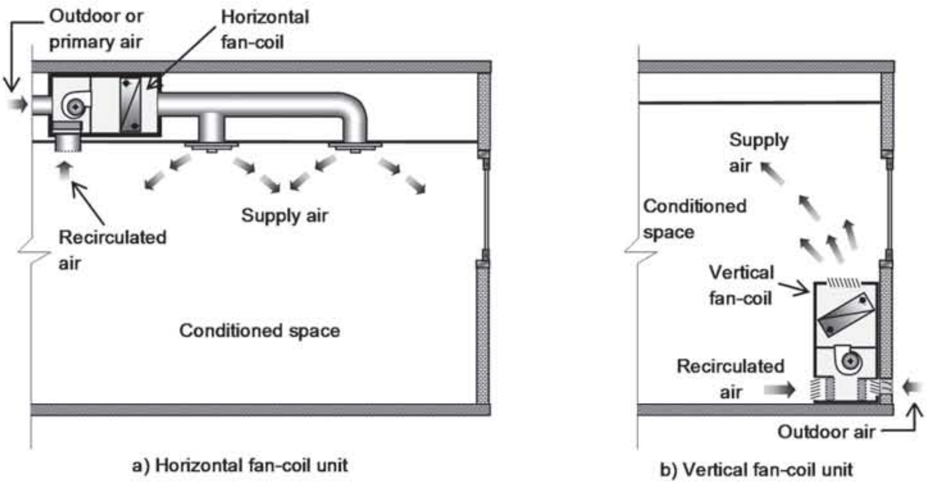


Figure 6.12 Schematic diagram of vertical and horizontal fan coil units

- *System control.* For a two-pipe fan coil unit, control is achieved by a thermostat which actuates a two-way valve to control the water flow to the coil. The thermostat may be of the summer–winter mode of operation type. For a four-pipe system in which two coils are used, each coil is controlled by a two-way valve. In the summer, as the space temperature drops, the thermostat progressively reduces the chilled water flow to the cooling coil until the valve is completely shut off. A further drop in temperature will cause the thermostat to actuate the two-way valve of the hot water coil. The hot water flow through the valve will increase in response to the decrease in the space temperature. The capacity of the fan coil unit can also be controlled by air bypass over the coil and by modulating the fan speed.

Advantages

The primary air fan coil system has the general advantages of air and water systems over all-air systems. Its greatest advantage over other air and water systems is its flexibility in design and layout.

Disadvantages

The system suffers from the general disadvantages of air and water air-conditioning systems. An additional disadvantage over the induction system is the fan power consumption of the induction unit and fan generated noise in the unit.

Applications

The primary air fan coil system is generally used for the perimeter areas of multi-room and multi-storey buildings such as office buildings, hotels, schools and hospitals. The system can also be designed to cater for interior spaces.

6.7 All-water air-conditioning systems

The most common types of all-water air-conditioning systems are: a) *the space ventilation fan coil system*, and b) *the unitary heat pump*.

Neither of these systems is considered to be a 'full' air-conditioning system since they do not provide humidity control to the conditioned space.

6.7.1 Space ventilation fan coil system

The space ventilation fan coil system is supplied by chilled or hot water which satisfies the total load of the space. Ventilation is provided by outdoor air which is induced into the fan coil unit through an opening on the external wall.

Advantages

- *Lower capital cost*. The system does not require a central AHU to condition the air and no ductwork to distribute the air to the spaces.
- *Lower space requirement*. The absence of air distribution ductwork reduces the space required for fluid flow distribution in the building.
- *Lower running cost*. The absence of a central air distribution fan reduces the total fan power consumption.
- *Greater flexibility*. The absence of primary air distribution ductwork increases flexibility in the positioning of the fan coil units.

Disadvantages

- *Sufficient outdoor air ventilation is not guaranteed*. The amount of outdoor ventilation air induced into the fan coil unit depends to a large extent on outdoor weather conditions and is influenced by wind pressure and direction.
- *Condensation on the coil of the fan coil unit*. The coil of the fan coil unit will provide a degree of dehumidification in the summer. The moisture content of the outdoor air will also vary and for certain conditions condensation will take place on the coil of the unit. This increases design provisions for condensate collection and disposal and danger of bacterial growth in the unit exists.
- *Increased noise and dirt from the outdoor* air. The opening on the wall will increase the transmission of outdoor noise and dirt into the space. Better filtration and more frequent cleaning and replacing of the filters will be required than in the case of the primary air fan coil unit.

Because of the difficulties with ventilation and maintenance, the primary air fan coil system is usually preferred over the space ventilation fan coil system.

6.7.2 Reverse cycle unitary heat pump system

This system utilises water-to-air, reversible, unitary heat pump units which can be arranged in modular configuration around the building. The heat pumps operate on the reversible refrigeration cycle and consist of a compressor, a finned refrigerant-air coil, an expansion device, a refrigerant-water coil and a reversing valve. The refrigerant-water coil is connected to a two-pipe water distribution system which is maintained at approximately a constant temperature. The water provides the heat source and the heat sink for the heat pumps. The water circuit includes a closed cooling tower and a boiler. A schematic diagram of the system is shown in Figure 6.13.

Each individual heat pump unit is controlled by a space thermostat. If the thermostat calls for heat, the heap pump operates in the heating mode of operation with the refrigerant-water coil acting as the evaporator, extracting heat from the water, and the refrigerant-air heat exchanger rejecting heat to the space. When the thermostat calls for cooling, the cycle is reversed and the refrigerant-air coil acts as the evaporator removing heat from the space. The refrigerant-water coil acts as the condenser rejecting the heat to the circulating water.

If half of the heat pumps in the system operate in the heating mode and half in the cooling mode, the system is in thermal equilibrium. The water is maintained at a temperature of about 27°C and no heat is added to or removed from the system. If more units operate in the cooling mode than in the heating mode, there will be excess heat generated by the system and this heat is rejected to another system or to the ambient air through the closed loop cooling tower. If more units operate in the heating cycle than in the cooling cycle, additional heat will be required by the system and this is provided by a boiler.

Outside air for ventilation may be provided by a central plant or alternatively it may be drawn directly from the outside into each heat pump unit.

Advantages

- *Economy of operation in applications with simultaneous heating and cooling requirements.* Heat rejected from some units is used as a heat source for other units, improving the overall coefficient of performance of the heat pumps.

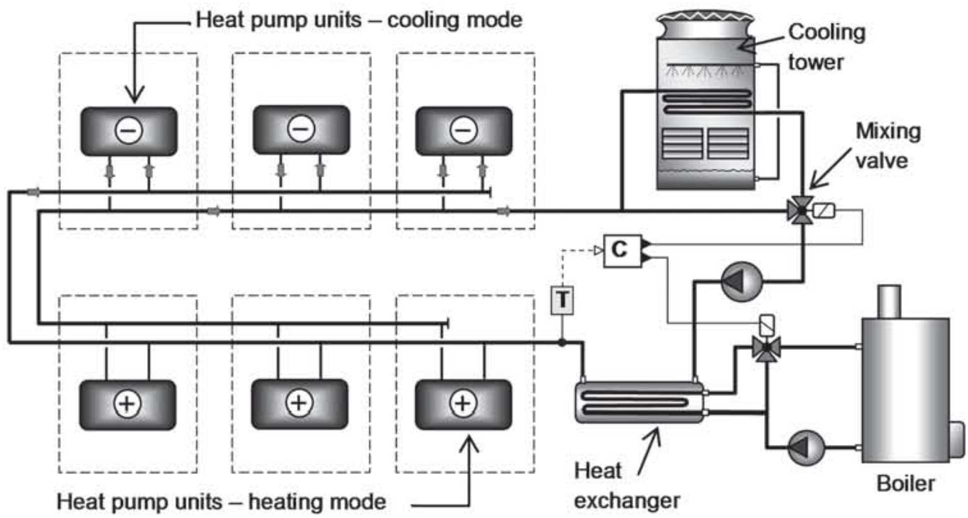


Figure 6.13 Reverse cycle heat pump system

- *Flexibility in design and operation*. The system does not require zoning due to the simultaneous availability of heating and cooling. Each unit can be controlled independently to provide cooling, heating or air circulation.

Disadvantages

- *Poor control of humidity*. The heat pump units do not provide active humidity control although a degree of humidification and dehumidification can be provided if primary air is conditioned in an air-handling unit.
- *Noise problems*. The compressors of the heat pump units are located in the conditioned space and compressor and fan generated noise may be a problem.
- *High maintenance costs*. The heat pump units within the conditioned space will require more frequent maintenance than other terminal units.

Applications

The unitary heat pump system is suitable for perimeter areas of buildings with diverse heat gains, so that for the major part of the year some of the areas will require cooling while an almost equal number will require heating, resulting in an overall load balance. Such buildings include office buildings, hotels and hospitals.

6.8 Chilled ceilings and beams

Chilled ceilings and beams are, in their basic form, static cooling and heating devices that, in recent years, emerged as alternatives to traditional air-conditioning systems. Chilled ceilings are primarily radiant devices, which consist of copper pipes attached on the back of ceiling panels (tiles). When combined with ventilation, chilled ceilings can create a comfortable environment in which heat is dissipated by radiation without causing draughts or noise. The cooling capability of chilled ceilings is relatively low, between 45 and 65 W/m^2. Where larger cooling capacities are required, for example to cater for solar loads in perimeter glazed areas of the building, chilled ceilings can be used in combination with chilled beams.

Chilled beams employ water that flows in ceiling mounted radiators. The cold surface of the radiator cools the surrounding air, creating a continuous cycle in which the cooler air drops into the occupied space and is replaced by rising warmer room air. There are two main categories of chilled beam systems available: a) *passive chilled beams*; b) *active chilled beams*.

6.8.1 Chilled ceilings

In their simplest form, chilled ceilings can be formed by embedding pipes carrying chilled water into the underside of concrete floor slabs. Although this approach can provide relatively high cooling capacity, it also introduces a number of complexities such as difficult control and risk of condensation on the underside of the slab. In order to prevent the ceiling from running wet a suspended variation is usually employed. This normally consists of chilled water pipes attached on the back of metal ceiling panels suspended from the ceiling. The option is also available to supply primary ventilation air through the suspended ceiling, as shown in Figure 6.14.

Due to the circulation of water the surface temperature of the chilled ceiling is reduced a few degrees below room temperature. This together with the ventilation air increases the convective heat transfer effect of the system. Chilled ceilings can also be used to provide heating through the radiant effect.

6.8.2 Chilled beams

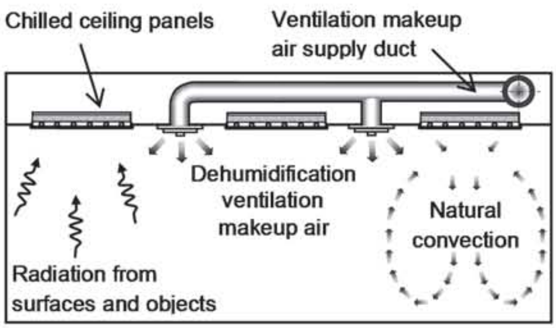
A chilled beam system consists of a central air-conditioning plant, a duct distribution system, and terminal devices in the conditioned space (room units). The central plant provides constant volume air to the room unit which as in the case of induction and fan coil systems is referred to as primary air. In the case of the active chilled beam, the room air is recirculated through the pipe or coil of the chilled beam. This room air is usually termed secondary air.

The primary air quantity is very small and is designed to satisfy some or all of the following requirements:

- the ventilation requirements of the space
- part of the sensible cooling requirements to supplement the cooling provided by the chilled beam
- the latent load of the space.

The main concern with chilled beams is condensation. Since the air surrounding the chilled beam is sensibly cooled, its ability to hold moisture is reduced. Therefore, if the surrounding air is cooled to dew point temperature the moisture will condense and will drop into the occupied space as there is no possibility to drain the condensate from the terminal device. Consequently, for a chilled beam design to be successful, the following should be considered:

a) Chilled ceiling panel
(source: www.troxtechnik)



b) Chilled ceiling panel arrangement with ventilation
(source: http://eneri-source.wikispaces.com)

Figure 6.14 Example of a chilled ceiling system

- the latent load of the occupied space
- the operating temperature of the chilled beam
- the required ventilation rate.

A way of avoiding this problem is to always maintain the temperature of the chilled water supply at a value above the room dew point temperature. This can be done by floating the chilled water supply temperature in response to the room moisture content as well as automatically controlling openable windows to limit infiltration of outdoor air during periods of high external absolute humidity.

Advantages

- smaller air-handling unit and less ductwork compared to all-air air-conditioning systems
- lower fan energy consumption than all-air and primary air fan coil systems
- low noise levels
- lower maintenance costs compared to HVAC terminal units that have moving air side parts and dampers.

Disadvantages

- lower cooling capability than conventional air-conditioning systems (all-air or fan coil systems)
- cost of active beams higher than conventional terminal devices
- limited ability to handle high latent loads and risk of condensation that requires careful humidity control
- slow response to varying cooling loads.

Passive chilled beams

In the passive chilled beam, chilled water circulates through pipework or the heat exchanger of the beam. This cools the air close to the beam which becomes denser and descends, permeating through openings (perforations) on the face panel of the beam. Warmer room air rises to replace the cooler air that has moved downwards and this creates air circulation around the beam as shown in Figure 6.15. The face panel that is cooled by the air stream also acts as a radiant panel exchanging thermal energy with the building structure. The combination of natural convection and radiation increases the cooling capacity of the system compared to chilled ceilings. Heating to the space is normally provided by a separate perimeter heating system.

Active chilled beams

An active chilled beam system is an air-water system that can satisfy higher cooling loads than a passive chilled beam. The system utilises primary air from the central plant to induce and recirculate room air through the heat exchanger of the unit in a similar way to the induction system. As a result, the system operates with forced convection compared to free convection for the passive beam, increasing the heat

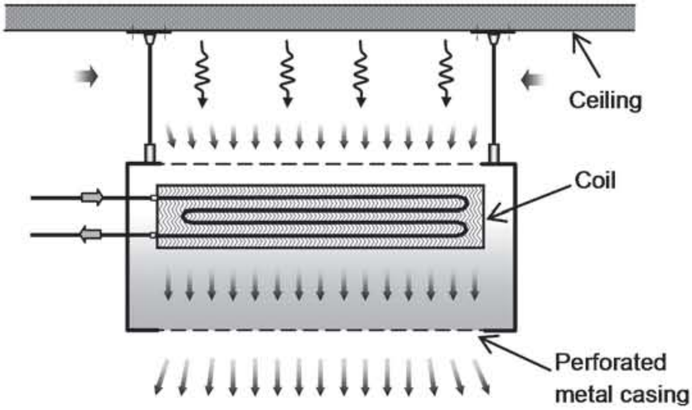


Figure 6.15 Passive chilled beam

Source: Chilled Beam Technology, http://www.chilled-beams.co.uk/

transfer rate and cooling capability of the system. Due to this induction effect, the active chilled beam is also able to provide relatively high heating capacities which are capable of meeting heating load requirements in temperate climates.

The operation of the active chilled beam can be explained by referring to Figure 6.16. Primary air is delivered from the central plant into the primary air plenum. The air then flows through nozzles into the mixing chamber and this creates a low pressure area at the nozzle outlet. This low pressure induces air from the room to flow through the coil and mix with the primary air in the mixing chamber. The mixed air then is accelerated as it passes through the beam diffuser and is discharged to the room.

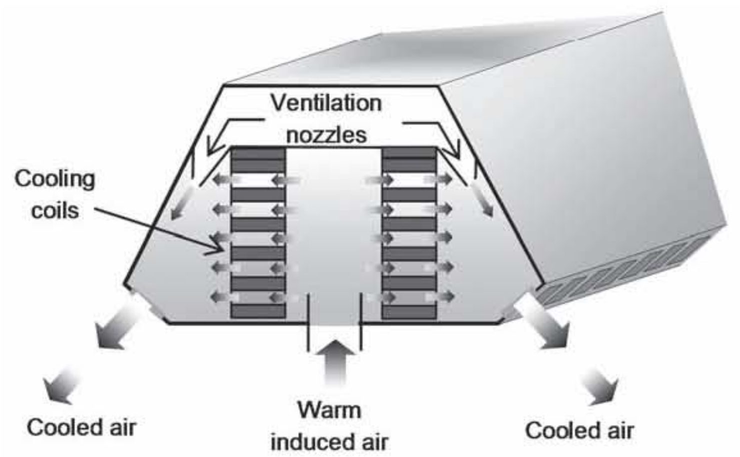


Figure 6.16 Typical construction of an active chilled beam

Source: Energdesignresources.com

6.9 Air-conditioning system selection and evaluation

The main air-conditioning system selection criteria are:

- capital cost
- comfort criteria
- energy use and running costs
- maintenance, reliability and equipment life
- appearance and room noise level
- environmental issues
- flexibility
- space used for central plant and distribution.

This list is not ordered in terms of importance and system selection should be based on a carefully designed evaluation methodology. This is a method of ranking priorities and using weighting factors, to compare alternative systems against a set of criteria.

6.9.1 Capital cost

The capital cost of air-conditioning installations varies considerably depending on the level of complexity of the design and the thermal performance of the building.

One method that can be used to compare the capital cost of various system options is to use cost indices rather than absolute costs. These can be generally derived from job records of installations carried out over recent years. These comparisons are general and approximate and will only be appropriate if the building under consideration is similar to the building used to obtain the cost data. Relative cost ratios taken from three different air-conditioning systems are given in Table 6.1. The cost ratios include the heating, cooling and air distribution equipment of each system but do not include allowance for associated plant room and distribution space costs which will be higher for the 'all-air' systems compared with the 'air-water' systems.

Approximate costs of air-conditioning systems are given in several price books which are updated regularly. Typical figures for common air-conditioning systems for office buildings in the UK quoted for 2006 are given in Table 6.2 (Harris 2006)

Table 6.1 Relative system cost ratio from three sources

System Type	*Relative cost ratio*		
	Source 1	*Source 2*	*Source 3*
VAV	1.0	1.1	1.05
Versatemp heat pump system	0.95	–	1.15
Induction system	1.05	1.15	1.1
Fan coil system	0.97	1.1	–
Dual duct system	1.2	1.35	–

The costs allow for all plant and equipment, distribution ductwork, pipework for heating, chilled and cooling water, automatic controls, fire protection systems and all associated electrical work.

Cost data can vary from one source to another but for reasonable estimates in the UK it is recommended to use the latest edition of *Spon's Mechanical and Electrical Services Price Book* (Langdon 2009). Example costs for office building air-conditioning systems are given in Table 6.3.

6.9.2 Energy and running costs

The accurate calculation of energy demand for an air-conditioning system is complex due to the requirement to model the transient response of the building and the dynamic operation of the HVAC system and its controls. At the early design stage this is even more difficult because the building and the systems under consideration would only be at the outline design stage.

Many consultancy practices use computer programs at the outline design stage to carry out energy analyses. These analyses make many assumptions in the input data but the results can be useful when comparing the performance of the different systems under consideration.

6.9.3 Maintenance, reliability and equipment life

The requirements for maintenance of building services systems should be considered at the outline design stage of a project. When considering the system options, the maintenance requirements of each of the systems should be included in the analysis.

The maintenance requirements of a system are important because they not only affect the running cost of a building but also the reliability of the system. The cause of many problems with building services systems, which result in complaints and dissatisfaction of the building occupants, are due to a lack of correct maintenance rather than faults in the design or installation. The maintenance requirements of any system will depend fundamentally on the quality, and therefore the cost of the plant and equipment, and on the particular design and specification.

Table 6.2 Typical capital costs of different systems in the UK at 2006 prices

System type	*Capital cost £/m²*	*System type*	*Capital cost £/m²*
Variable refrigerant flow (VRF/VRV) with heat recovery	90–190	Variable air volume	215–260
2-pipe fan coil system	155–200	Chilled ceiling	145–185
4-pipe fan coil system – ceiling	190–230	Chilled ceiling with displacement ventilation	190–260
Reversible close loop heat pump system	145–175	Displacement ventilation	100–180
Passive chilled beam	170–240	Active chilled beam	190–250

Source: Harris 2006

Table 6.3 Cost data for office building air-conditioning systems

Comfort cooling (for buildings up to 3,000m²)	*Shell and core £/m² GIA**	*Fit out £/m² NIA⁺*
2-pipe fan coil systems for buildings up to 3,000m²	55–70	95–105
2-pipe fan coil systems for buildings between 3,000m² and 15,000m²	50–65	85–95
2-pipe variable refrigerant volume (VRV) system for buildings up to 3,000m²	40–50	65–75
Full air conditioning		
4-pipe fan coil systems for buildings up to 3,000m²	80–95	135–155
4-pipe fan coil systems for buildings between 3,000m² and 15,000m²	70–85	115–135
3-pipe variable refrigerant volume systems for buildings up to 3,000m²	65–75	115–125
Ventilated (active) chilled beams for buildings between 3,000m² and 15,000m²	70–85	135–145
Chilled beam exposed services for buildings between 3,000m² and 15,000m²	70–85	225–245
Concealed passive chilled beams for buildings between 3,000m² and 15,000m²	70–85	125–135
Chilled ceilings for buildings between 3,000m² and 15,000m²	70–85	215–225
Chilled ceilings/perimeter beams for buildings between 3,000m² and 15,000m²	70–85	235–255
Displacement systems for buildings between 3,000m² and 15,000m²	80–95	–

Source: Langdon 2009

Notes: * = Gross internal area; ⁺ = Net internal area

6.9.4 Appearance and room noise level

The appearance of the system within the occupied areas is one aspect to be considered in system analysis. Generally, it is possible to design all systems to supply and extract air through the ceiling with the terminal units located within the ceiling void, in which case room appearance is not normally an important factor. If under-sill perimeter units and enclosures are an option, then the loss of floor space at the perimeter is a very important factor.

Room noise levels for various systems cannot be generalised and depend on the particular equipment selections. In induction unit systems the high velocity primary air passes through an attenuator, the pressure at the nozzles required to induce secondary air causes some noise generation. This necessitates careful selection of the units to meet the required room noise levels. Reverse cycle heat pumps can be a cause of complaint in private offices with double glazing as the on/off operation of the unit makes the noise more intrusive.

VAV system terminal units include attenuators to reduce the noise generated by the volume control damper and the air velocity generated noise within the high velocity supply ductwork; thus they do not inherently have any design problems with regard to room noise levels. The design of the primary supply ductwork must avoid high pressure differences between terminal units as the noise level of the unit increases as the upstream duct static pressure is increased.

Fan coil units do not normally pose a design problem in terms of selection to achieve the required room noise levels. They are usually selected for low fan speed operation. Noise problems only normally occur if there is a fault on the fan, its bearings or mountings.

Chilled beam/ceiling systems do affect the room appearance more than the other systems as it is necessary that the design of the ceiling is closely integrated with that of the cooling system. In the case of a chilled beam system, this requires that the ceiling has at least 30% open area.

6.9.5 Environmental issues

There is growing awareness of environmental issues related to air-conditioned buildings. These are primarily concerned with energy consumption and the indirect emissions of CO_2 at power stations, direct emissions from the leakage of HCFC and HFC refrigerants and the problem of 'Sick Building Syndrome'. Wet cooling towers and the risk of legionnaires' disease is also a factor.

The concern regarding energy consumption of air-conditioning systems is due to the perceived view that an air-conditioned building is inefficient in energy terms. However, this may not necessarily be entirely correct as in many cases high comfort standards and good energy efficiency can be achieved with properly designed and operated air-conditioned buildings.

When considering the energy used by a system, it is useful to know the relative CO_2 emission factors of the final forms of energy, normally electricity and natural gas in the UK. In the UK the emission factor for electricity can be taken as 0.537 $kgCO_2$/kWh and for natural gas 0.185 $kgCO_2$/kWh (MTP 2009).

Sick Building Syndrome is a complex problem which does not have easily identifiable causes but of the many studies which have been undertaken it can be concluded that the risk is greater within air-conditioned buildings. One of the main contributing factors in this has been found to be the inadequate provision of outside air. The indoor air quality within an air-conditioned building is improved if the rate of outside air ventilation is increased. Generally, air-water systems are designed with ductwork sized to provide the minimum recommended outdoor air quantities which give about 1.5–2.0 air changes per hour within the occupied space. All-air systems with full fresh air capacity operate, on average throughout the year, with typically twice this quantity and therefore offer a higher standard of outdoor air ventilation.

Many of the environmental considerations associated with the built environment are taken into account by the BREEAM environmental assessment method for new office building designs devised by the Building Research Establishment (BRE) (BREEAM 2012). This assessment includes many factors relating to the building services systems and their energy consumption amongst other parameters. The methodology involves the allocation of credits and weighting factors for many aspects that influence the environmental impact of the building during its lifetime. Manipulation of the credits and weightings leads to an overall percentage score which can be used to benchmark the performance of the building against other BREEAM rated buildings. The BREEAM rating benchmarks for new buildings using the 2011 version of BREEAM are shown in Table 6.4.

Table 6.4 BREEAM rating benchmarks

BREEAM rating	*% score*
Outstanding	≥85
Excellent	≥70
Very good	≥55
Good	≥45
Pass	≥30
Unclassified	<30

Source: BREEAM 2012

Notes: Each BREEAM rating level broadly represents performance equivalent to:

- Outstanding: less than top 1% of UK new non-domestic buildings (innovator)
- Excellent: top 10% of UK new non-domestic buildings (best practice)
- Very good: Top 25% of UK new non-domestic buildings (advanced good practice)
- Good: top 50% of UK new non-domestic buildings (intermediate good practice)
- Pass: top 75% of UK new non-domestic buildings (standard good practice).
- Unclassified: represents performance that is non-compliant with BREEAM, in terms of failing to meet either the BREEAM minimum standards of performance for key environmental issues or the overall threshold score required for formal BREEAM certification.

6.9.6 Flexibility

Flexibility requires that systems are designed for change and can be adapted to suit changes that occur. The flexibility of an air-conditioning system and the electrical services distribution system has an influence on the longer-term usefulness of a building. If the difficulty and expense of altering the existing systems are too great it often means that the systems are not adapted correctly to suit new office layouts. This can result in operational problems and complaints of discomfort from the occupants.

Two types of flexibility are required for an air-conditioning system. One is to allow for modifications to partitioned office locations that can occur quite regularly in some buildings. The other is the flexibility to provide additional cooling to areas, which may have a higher than design cooling load.

To provide flexibility for partitioning rearrangement, air inlets are usually associated with the planning grid and light fittings and should not be located on possible partitioning lines. Connections between the air inlets and terminal units can be made in flexible ducting so that relocation of inlets is relatively simple.

Air-water systems can be designed to provide additional cooling to areas of high cooling demand by means of over-sizing the chilled water distribution pipework within the ceiling void. This allows the tenant to replace a terminal unit with a larger model and increase the chilled water flow to meet the load required for a specific area. These systems can therefore be designed to incorporate good flexibility to provide additional cooling.

With an all-air system it is not as easy to provide additional cooling capacity if required by a tenant to a specific area. Some additional capacity can be provided by over-sizing the air-handling plant and distribution ductwork but this is an expensive measure and requires an increase in services plant and riser space.

A very difficult design decision regarding flexibility is the question of providing individual room control to individual offices that have demountable partitioning and will be subject to modification. The cost of the air-conditioning system can be greatly increased if a large number of terminal units are provided to give individual temperature control to each partitioned office. In designing for an owner/occupier or designing the fit-out where it is possible to determine the partitioning arrangement, it would be appropriate to design the system with sufficient terminal units to provide individual temperature control. In most designs where the partitioning layout is not known, a compromise is to use one terminal unit to serve two offices and controlled from averaging thermostats. Many systems are designed so that terminal units can be added if required or modified to provide individual temperature control.

6.9.7 *Space used for plant and distribution*

The space required for the main plant and distribution of an air-conditioning system can have a large influence on the selection of the system. This includes the effect the system selection has on the horizontal service zone and hence the overall height of the building.

In general, all-air systems require greater plant, distribution and horizontal service zones than air-water systems. This is because the space required for the transportation of energy by ducted air is larger than that required when piped water is used. Figure 6.17 illustrates the difference in space required to provide equal amounts of cooling using a circular duct and a chilled water pipe, in both cases the space shown includes the thermal insulation required.

In the case of the all-air system, all the cooling required is provided by the supply of air. In the case of an air-water system the majority of the cooling load is provided by the provision of chilled water and only a small part of the total cooling load is dealt with by the provision of the fresh air supply. The all-air system therefore has considerably larger AHUs and distribution ducts than an air-water system. The all-air system typically has four times the total air capacity of the air-water system, but the distribution space is not four times the area. This is because the ductwork for an all-air system such as a VAV system is sized on medium velocity design criteria, whereas for an air-water system such as a fan coil system the ductwork is sized on conventional low design velocities.

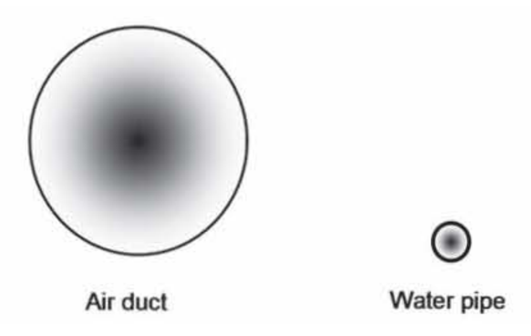


Figure 6.17 Comparison of air duct and water pipe for the same rate of energy transfer

6.9.8 Evaluation methodology

A standard evaluation methodology consists of establishing criteria by which each of the systems under consideration will be evaluated. A weighting factor is assigned to each of the criteria, which establishes its priority and importance relative to the other criteria. The weighting factors are selected and distributed such that their summation equals 100. An example of an evaluation matrix for three different systems is shown in Table 6.5. The evaluation of each alternative involves three steps. First, for each of the three systems a rating is given for each criterion, between 1 and 10 (10 being the best). Second, for each of the criteria, the rating is multiplied by the weighting factor. Third, the summation of these products is tabulated to yield a total value. The highest total value provides an indication of the most appropriate system for the project.

An example of an evaluation matrix of a single system, in this case a chilled beam with displacement ventilation, is shown in Table 6.6.

Table 6.5 Example of an evaluation matrix

Weighting factor (WF)	*Capital cost (20%)*	*Space required (20%)*	*Maintenance required (15%)*	*Energy cost (15%)*	*Flexibility (10%)*	*Acoustics and Comfort (10%)*	*Environmental issues (10%)*	*Total value*
	Rating values (R)							
Scheme 1	7	8	5	6	8	3	4	615
Scheme 2	8	10	4	8	7	8	7	760
Scheme 3	10	10	10	9	8	9	8	935

Notes:
Weighting factors (WF) are distributed by priority; their summation equals 100.
(R) indicates the rating value of each alternative; between 1 and 10, 10 being the highest.
Total value = (WF x R) e.g. For scheme 1, Total value = (20 x 7) + (20 x 8) +(15 x 5) + (15 x 6) + (10 x 8) + (10 x 3) + (10 x 4) = 615.

Table 6.6 Example of a chilled beam system with displacement ventilation

Item	*Weight*	*Poor 2**	*Mediocre 4*	*Good 6*	*Very good 8*	*Excellent 10*	*Score*
Maximum office space	18	o	o	x	o	o	108
Flexible office layout	16	o	o	x	o	o	96
Capital cost	15	o	x	o	o	o	60
Maintenance	12	o	o	o	o	x	120
Control	10	o	x	o	o	o	40
Energy consumption	9	o	o	o	x	o	72
Construction time	6	o	x	o	o	o	24
Acoustics	5	o	o	o	o	x	50
Indoor air quality	4	o	o	o	o	x	40
Building height	3	o	o	x	o	o	18
Minimum plant space	2	o	x	o	o	o	8
Total score	100						636

Note: *score out of 10. The score provides an indication of how good the system is in respect to the performance criteria

6.10 Summary

In this chapter the main types of air-conditioning systems and their principal classification have been considered. The principles of operation of these systems have been described as well as their advantages, disadvantages and applications. The chapter also presents the main criteria for system selection and methodologies that can be used for the evaluation of system alternatives for a particular application.

Unitary and packaged air-conditioning systems are normally used in small buildings to provide heating and cooling and in certain cases limited ventilation but do not normally provide ‘full’ hygrothermal control of the indoor environment and effective ventilation.

Central air-conditioning systems which are normally classified as all-air and air and water systems are used for large buildings and where good control of the indoor environment is required with relatively low energy consumption. All-air systems are normally employed where very good control of indoor conditions is required and where spaces experience large and varying latent loads. Such buildings include restaurants, theatres, dance halls, etc. Air and water systems are used where accurate humidity control is not very important, space is at a premium as is the case for multi-storey buildings and where spaces experience fast and wide variation of sensible loads, such as the perimeter areas of buildings.

The most important criteria for air-conditioning system selection are: capital cost; energy use and running costs; maintenance, reliability and equipment life; appearance and room noise level; environmental issues; flexibility; space used for central plant; and distribution.

For selecting the most suitable system for a particular application, it is appropriate to use an evaluation methodology to rate each system against the most important criteria for the project.

Chapter 7

Cooling, heating and thermal energy distribution systems in buildings

7.1 Introduction

Air conditioning, as well as other thermal environment control systems for buildings, rely on a number of major technologies and equipment for the generation of the required cooling and heating energy, and the distribution of this energy to the various air-handling plant and the conditioned spaces. This chapter describes the various major cooling and heating technologies and equipment employed for this purpose, their important characteristics and selection criteria.

The most commonly used equipment for cooling is vapour compression and sorption refrigeration systems. While producing cooling at the evaporator, both these systems reject heat at the condenser. This heat can either be upgraded to a higher temperature for water heating using heat pump systems or is rejected to the ambient air.

Depending on the type of thermal control systems employed in a building, the cooling or heating energy is distributed to the conditioned spaces through air or water in ducting and piping systems respectively. This chapter describes the main cooling, heating and thermal energy distribution systems for buildings.

7.2 Refrigeration equipment

The cooling and dehumidification in air-conditioning systems is provided in most cases either by chilled water or direct expansion refrigerant (DX) coils. Both chilled water and DX coils are served by refrigeration plant. The most common types of refrigeration plant in air-conditioning applications are (a) vapour compression, and (b) absorption systems.

7.2.1 Vapour compression systems

Thermodynamic systems operating on the vapour compression cycle consist of four basic components: a compressor, a condenser, an evaporator and an expansion device. The components form an elementary system as shown in Figure 7.1. The working fluid, the refrigerant, flows round the system and transfers heat from the evaporator side to the condenser side. The compressor is the key component, its main function being to pump the refrigerant vapour from a relatively low suction pressure to a higher head pressure. The high pressure high temperature vapour is then passed through the condenser where, becoming liquid, it releases heat to the heat-receiving medium, for example water or

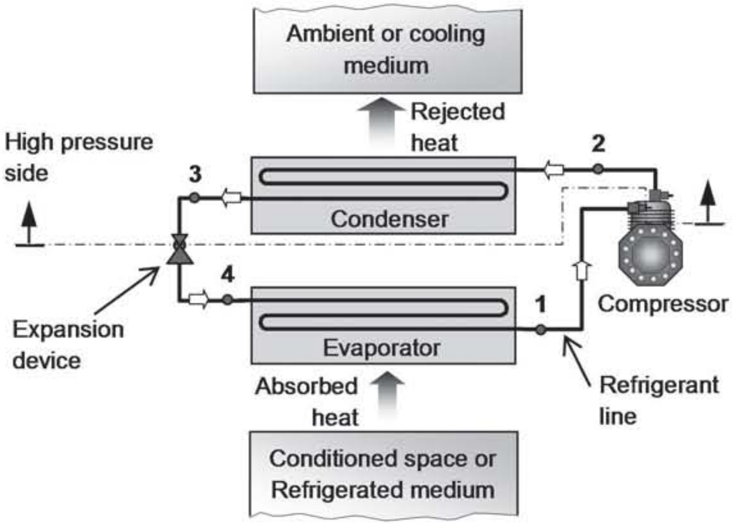


Figure 7.1 Schematic diagram of a simple vapour compression cycle

air. The refrigerant exits the condenser as a high pressure high temperature liquid and passes through the expansion device which lowers the pressure from the high pressure condenser side to the low pressure evaporator side of the system.

The drop in pressure is accompanied by a drop in temperature so that the refrigerant enters the evaporator as a low pressure, low temperature mixture of liquid and vapour. Finally, the refrigerant passes through the evaporator where it draws heat from the heat source area, the supply air in the case of air-conditioning systems, it changes state to a vapour and enters the compressor for the repetition of the cycle.

Refrigerants. These are the working fluids in refrigeration systems. They absorb heat by evaporating at a low temperature and pressure and reject heat by condensing at a higher temperature and pressure. Refrigerant selection for refrigeration systems is important because it affects the performance and environmental impacts of the system. The suitability of a fluid for use as a refrigerant in a vapour compression refrigeration system depends primarily on its thermodynamic properties alongside cost, safety and environmental issues. The properties of refrigerants are usually displayed on a pressure/enthalpy diagram known as the Mollier diagram.

Figure 7.2 shows the pressure/enthalpy diagram for a simple saturated vapour compression cycle.

The thermodynamic processes involved are as follows:
process 1–2 isentropic compression. The compressor work is given by:

$$w = h_2 - h_1 \tag{7.1}$$

process 2–3 constant pressure heat rejection. The condenser duty can be calculated from:

$$q_c = h_3 - h_2 \tag{7.2}$$

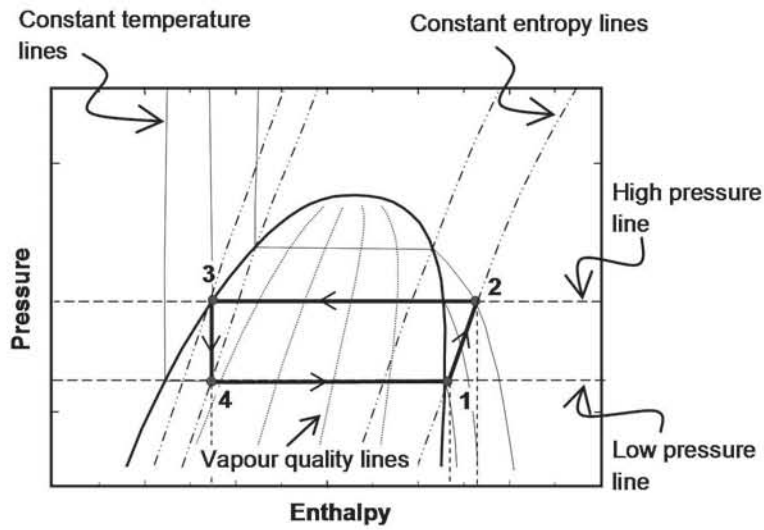


Figure 7.2 Pressure/enthalpy diagram

process 3–4 isenthalpic expansion $h_3 = h_4$
process 4–1 constant pressure heat addition or refrigeration effect. The refrigeration effect is given by:

$$q_e = h_1 - h_4 \tag{7.3}$$

It can be seen from the above that a vapour compression system transfers thermal energy from a region of low temperature to a region of higher temperature. The term 'refrigerator' is used for a machine whose main function is to extract heat from a space or a process requiring cooling, whereas the term 'heat pump' is used for a machine whose main function is to supply heat at an elevated temperature to a space or process requiring heating.

The performance of refrigeration and heat pump systems is expressed as the ratio of useful heat transferred to work input and is usually called the coefficient of performance (COP).

For a refrigeration system,

$$COP_{ref} = \frac{h_1 - h_4}{h_2 - h_1} \tag{7.4}$$

and for a heat pump system,

$$COP_{hp} = \frac{h_2 - h_3}{h_2 - h_1} \tag{7.5}$$

the cooling capacity of the refrigeration system can be calculated by multiplying the refrigeration effect by the refrigerant flow rate in the system:

$$Q_e = \dot{m}_r\,(h_1 - h_4)\ \text{(kW)} \tag{7.6}$$

The heat rejection in the condenser is given by:

$$Q_c = \dot{m}_r\,(h_2 - h_3)\ \text{(kW)} \tag{7.7}$$

The work input to the compressor can be calculated from:

$$W = \dot{m}_r\,(h_2 - h_1)\ \text{(kW)} \tag{7.8}$$

Both the cooling and heating COPs of the vapour compression cycle vary considerably with variations in the evaporating and condensing temperatures. An increase in the condensing temperature with the evaporating temperature constant, causes a reduction in both the cooling and heating COPs. On the other hand, an increase in the evaporating temperature with the condensing temperature constant, causes an increase in both the cooling and heating COPs.

In practical refrigeration cycles, the refrigerant vapour entering the compressor should be superheated to ensure that no liquid refrigerant is carried to the compressor. The cycle is also designed for a small degree of subcooling of the refrigerant liquid at the condenser outlet to reduce flashing of the liquid during expansion. The degree of superheat of the refrigerant at the evaporator outlet is usually controlled by the expansion device. The most widely used expansion device is the thermostatic valve. Electronic refrigerant flow control devices, which have been introduced in the last few years, are slowly gaining wider acceptance by the refrigeration industry.

Refrigerant superheating at the compressor inlet and subcooling at the expansion valve inlet can be achieved outside the evaporator and condenser respectively by introducing a heat exchanger to transfer heat from the refrigerant liquid leaving the condenser to the vapour leaving the evaporator. Liquid/suction heat exchangers enable maximum utilisation of the heat transfer surface of the condenser and evaporator.

Compressors. The compressor is the heart of the refrigeration system. Its function is to pump the refrigerant round the circuit and provide the required pressure differential between the low pressure evaporator side of the system and the high pressure condenser side of the system. The types of compressor are normally used in refrigeration systems are: (a) reciprocating; (b) rotary; and (c) centrifugal.

The reciprocating and rotary compressors are positive displacement machines because the increase in pressure of the refrigerant vapour is provided by a mechanical mechanism through a reduction of the volume of the compression chamber. In the centrifugal compressor, compression is achieved by force action created by a rotating impeller.

Depending on the method of sealing against the atmosphere, refrigeration compressors can be classified as: (a) hermetic; (b) semi-hermetic; and (c) open type.

The hermetic compressor is a completely sealed unit with the motor and the other mechanical parts enclosed in a welded steel casing. The semi-hermetic compressor represents an integral unit, with the motor and compressor housed in a bolted rather than welded casing to permit servicing. The open compressor is driven by an external prime mover coupled to the crankshaft which protrudes from the crankcase through shaft seals. This allows the flexibility of selecting the most suitable drive for a particular application.

Compressor performance is usually given in the form of curves obtained from compressor calorimeter measurements. These curves or maps, which are usually available from the manufacturers, provide compressor power input and refrigeration capacity as a function of evaporating temperature for a range of condenser temperatures. Each set of maps is usually generated for fixed values of condenser subcooling and evaporator superheat. A typical compressor performance map is shown in Figure 7.3.

The reciprocating compressor is the most popular type of compressor and is widely used in the smaller capacity range up to 180kW for domestic, commercial and industrial refrigeration applications.

The helical screw rotary compressor usually consists of two helical grooved rotors enclosed in a stationary housing fitted with suction and discharge ports. Compression is achieved by internal volume reduction through rotary motion of grooved rotors. Helical screw compressors are popular in medium to high capacity refrigeration applications, up to 2,000kW.

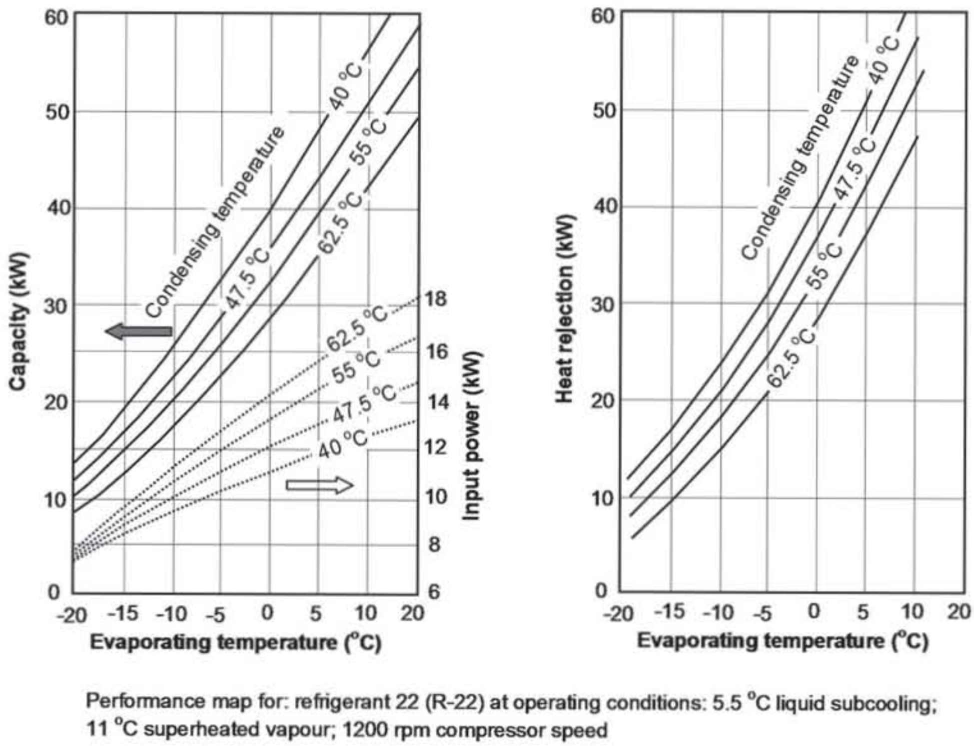


Figure 7.3 A typical compressor performance map

Centrifugal compressors consist basically of an impeller with radial vanes rotated by a shaft and housed in a cast-iron casing. The pressure of the refrigerant is increased through a continuous exchange of angular momentum between a steadily flowing refrigerant gas and the impeller. Centrifugal compressors are high speed machines and are available in the capacity range between 180kW and 3.5MW.

7.2.2 Absorption refrigeration equipment

Absorption refrigeration systems are similar to vapour compression systems. Both employ a volatile refrigerant, such as water or ammonia, which vaporises under low pressure in the evaporator by absorbing heat from the fluid being cooled, and condenses under high pressure in the condenser, rejecting latent heat to the heat rejection medium. The principal difference between vapour compression and absorption systems is in the compression process. In absorption systems, the compression process is performed by a group of components which are the absorber, the generator and a circulation pump. In addition, whereas the energy input to the vapour compression cycle is in the form of mechanical work, the energy input in the absorption cycle is in the form of thermal energy supplied directly to the generator.

Figure 7.4 shows a schematic diagram of an absorption refrigeration system. High pressure liquid refrigerant from the condenser passes into the evaporator through an expansion device which reduces the pressure of the refrigerant to the low evaporator pressure. The liquid refrigerant vaporises in the evaporator by absorbing heat from the fluid to be cooled. The refrigerant vapour then passes to the absorber where it is absorbed by a refrigerant-absorbent solution. The solution, rich in refrigerant, is then pumped to the generator where it receives heat and

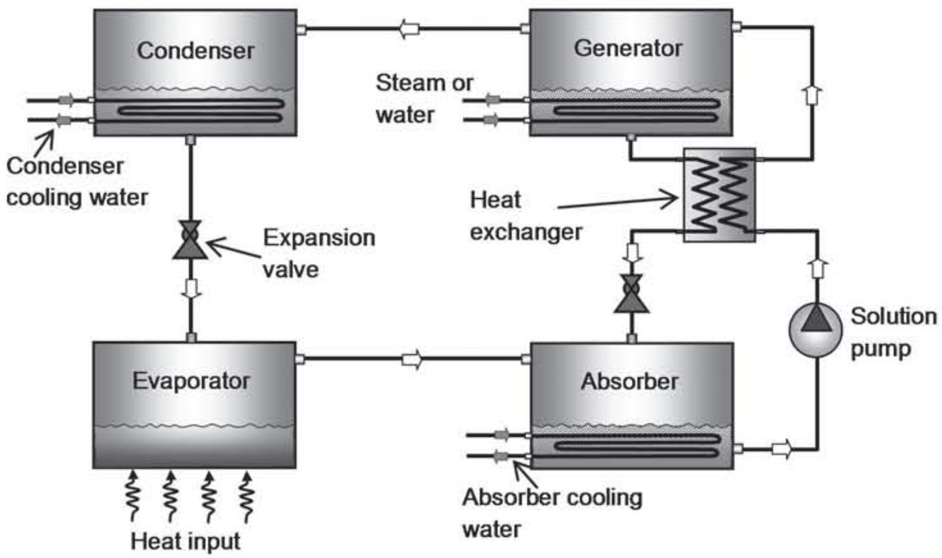


Figure 7.4 Schematic diagram of absorption system

separates into pure, or almost pure, refrigerant and an absorbent solution weak in refrigerant. The refrigerant then enters the condenser where it rejects its latent heat to the heat rejection fluid, whereas the weak solution returns to the absorber through a heat exchanger and an expansion device to absorb more refrigerant and carry it to the generator. The heat exchanger transfers heat from the weak solution to the strong solution and thus reduces the energy requirements of the generator. This improves the COP of the system.

The operating range and COP of absorption systems are to a large extent dependent upon the refrigerant-absorbent fluid pair. Of the many combinations of fluid pairs that have been tried, only the lithium bromide-water and the ammonia-water pairs are commercially used in air-conditioning applications.

Absorption refrigeration systems have much lower COPs than vapour compression systems. Their main advantage, however, is that they can utilise rejected thermal energy from other plants or processes to drive the generator, reducing considerably the energy consumption of the system in situations where high temperature reject heat is available

7.3 Heat rejection equipment

The heat generated by the refrigeration plant can be used to satisfy some of the heat requirements of the building. If excess heat is present then this heat is rejected to the atmosphere or to alternative sink media such as lake or sea water. The main types of heat rejection equipment are: (a) air-cooled condensers; (b) evaporative condensers; (c) water-cooled condensers; and (d) cooling towers.

7.3.1 Air-cooled condensers

Air-cooled condensers consist of a casing which houses a finned refrigerant-to-air coil and a fan-motor assembly. The refrigerant enters the condenser as a superheated gas and is cooled by the air which is drawn through the coil by the fan. The air being at a lower temperature than the refrigerant first de-superheats and then condenses the refrigerant. The refrigerant exits the condenser as a high temperature high pressure liquid. A schematic diagram of an air-cooled condenser is shown in Figure 7.5(a).

The heat rejection rate from the condenser is a function of the heat transfer area, the air and refrigerant flow rates and the temperature difference between the air and the condensing refrigerant. For given condenser size and fluid flow rates, higher ambient temperatures lead to higher condensing temperatures, which result in increased compressor power consumption.

Air-cooled condensers are used mainly in relatively small refrigeration systems where the compressor can be sited close to the condenser to avoid long runs of piping containing high pressure refrigerant. For capacities of approximately 100kW and above, the installed cost of air-cooled condensers is higher than the installed cost of the other heat rejection methods. However, air-cooled condensers have lower maintenance costs than the other heat rejection methods. Other advantages such as the absence of make up water or drainage facilities make air-cooled condensers popular in the capacity range up to 300kW.

7.3.2 Evaporative condensers

Evaporative condensers consist of a refrigerant-to-air coil, a fan-motor assembly, a sump containing water and a circulating pump with a water distribution system. These components are contained in a housing as shown in Figure 7.5(b). The water is distributed over the coil, effecting both sensible and latent heat transfer on the air side. This permits a smaller size unit for a given heat rejection rate than the air-cooled condenser which effects only sensible heat transfer on the air side. The evaporative condenser has a common disadvantage with the air-cooled condenser in that it has to be sited close to the compressor to avoid long runs of high pressure refrigerant piping.

Evaporative condensers generally have lower installed and operating costs than air-cooled condensers in the capacity range between 150 and 500kW. The use of eliminators is necessary with evaporative condensers to prevent carry over of water droplets which may be contaminated.

7.3.3 Water-cooled condensers

Water-cooled condensers are usually shell-and-tube type coils with the refrigerant flowing through the shell and the condenser water through the tubes. The condenser water can be drawn from a river, lake or even the sea. Before such solution is adopted, however, the cost of filtration and the maintenance requirements must be considered very carefully. The use of river and lake water may also be subject to the local water authority's approval.

Water-cooled condensers are most frequently used in combination with cooling towers. The use of a cooling tower enables the condenser to be sited close to the other refrigeration components. The cooling tower can be sited away from the condenser and the water transferred to the tower through water piping. A single cooling tower can serve a number of condensers located in different parts of the building. Water-cooled condensers in conjunction with cooling towers become economically competitive in capacities above 400kW.

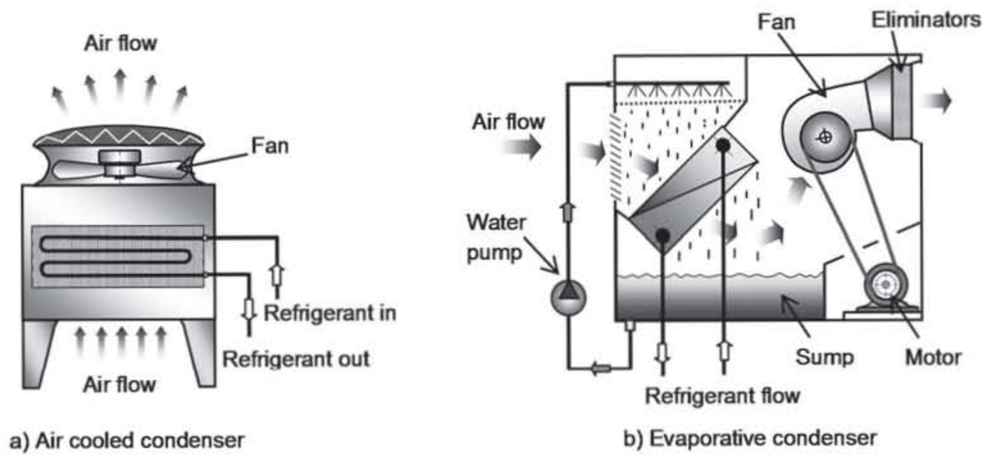


Figure 7.5 Air-cooled and evaporative condensers

7.3.4 Cooling towers

Cooling towers reject heat to the atmosphere by a combination of heat and mass transfer. They cool the water from the water-cooled condenser or condensers of the refrigeration plant by exposing it to the atmosphere. The water is distributed in the cooling tower by a distribution system which can be a combination of spray nozzles, or splash bars and fill packing. Fill packing is a structure designed to provide a large surface area for water to evaporate. PVC is increasingly used as the fill material. Some of the water evaporates as it comes into contact with air flowing through the cooling tower. The latent heat of evaporation is removed from the remainder of the water and transferred to the air stream. As a result, the wet-bulb temperature of the air increases and the water temperature reduces as the two fluid streams pass through the cooling tower.

The temperature distribution within the cooling tower is shown in Figure 7.6. The temperature difference between the water entering and leaving the tower is called the range. The difference between the leaving water temperature and the entering air wet-bulb temperature is called the approach. The approach is a function of the performance capability of the cooling tower, and the larger the tower the closer the approach. The performance of cooling towers is usually specified in terms of flow rate for a specified set of conditions such as entering and leaving water temperatures and entering air wet-bulb temperature. The rating or thermal capability of cooling towers is stated in terms of refrigeration capacity which is calculated on the basis of heat rejection of 1.2kW per kW of cooling capacity of the refrigeration plant, a range of 5K, and a water flow rate of 0.057 litres per second per kW of refrigeration capacity. This assumes that 1kW of refrigeration capacity will produce approximately 1.2kW of heat to be rejected at the condenser.

The air flow in cooling towers may be caused by mechanical means, convection currents, or natural wind currents. The air may flow in a cross or counterflow direction with respect to the direction of the water flow. In air-conditioning applications,

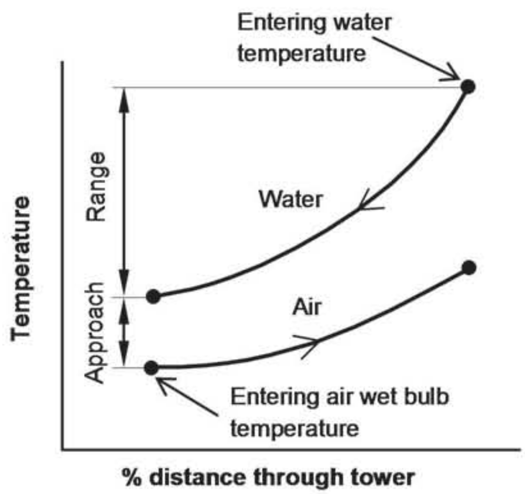


Figure 7.6 Temperature distribution within a cooling tower

the mechanical draft cooling tower is most commonly used. For this reason we will concentrate the discussion on this type of tower.

Mechanical draft cooling towers may be classified as direct contact and indirect contact towers. In direct contact towers (open towers) the fluid to be cooled is directly exposed to the atmosphere, whereas in indirect contact towers (closed towers) the fluid to be cooled does not come into direct contact with the atmosphere.

Direct contact (open towers). In direct contact mechanical draft towers, the fan may be placed at the air inlet side (forced-draft) or at the air outlet side (induced draft). The fan selection (centrifugal or axial) depends to a large extent on pressure, noise and energy consumption requirements. Cooling towers may also be classified as factory assembled or field assembled towers. Factory assembled counterflow towers often use centrifugal fans in forced-draft configuration as shown in Figure 7.7(a). Field assembled units often use axial flow fans in induced draft configuration, Figure 7.7(b). Crossflow towers have low air side pressure drop per unit heat transfer area and produce more uniform flow on both the water and air sides compared with counterflow towers. A crossflow tower is shown in Figure 7.8.

Indirect contact cooling towers. In indirect contact cooling towers the primary fluid to be cooled circulates in the tubes of a coil in the tower. The secondary fluid (water) is sprayed on to the external heat transfer surface of the coil and removes heat from the primary fluid through evaporative cooling as shown in Figure 7.9. Since the primary fluid does not come into direct contact with the air, this type of cooling tower can be used to cool fluids other than water. Indirect contact towers can also be used in atmospheres where there is a danger of contamination of the primary water with dirt or airborne contaminants.

Legionella in cooling towers

Legionellosis, or legionnaires' disease as it is most commonly known, is caused by members of the genus *Legionella*, which are fresh water bacteria that can be spread through the air. Water associated with cooling towers and other heat rejection equipment has been shown to be a habitat of this organism. This disease has taken its name from an outbreak in 1976 which caused the death from pneumonic disease of 29 members of the Pennsylvania American Legion attending a convention in Philadelphia. A number of other outbreaks have taken place around the world since then.

The *Legionella* species are widespread in aquatic habitats but in most cases no disease is associated with their presence. Only a small number of species have been implicated as causing legionnaires' disease, the most common being *Legionella pneumophilia*. It has been found that at low temperatures, below 20°C, the bacterium remains dormant. The bacterium multiplies rapidly in temperatures between 25 and 40°C and is killed at temperatures above 55°C.

Once the *Legionella* cells have multiplied within the aquatic environment, transmission takes place through aerosols of water droplets escaping from cooling towers and other misting devices. The survival of *Legionellae* in the air depends on the relative humidity and the size of the cells. Studies have shown that relative humidities above 60% are conducive to the transmission of *Legionellae* through the air. Other

Figure 7.7
Mechanical draft counter-flow cooling towers

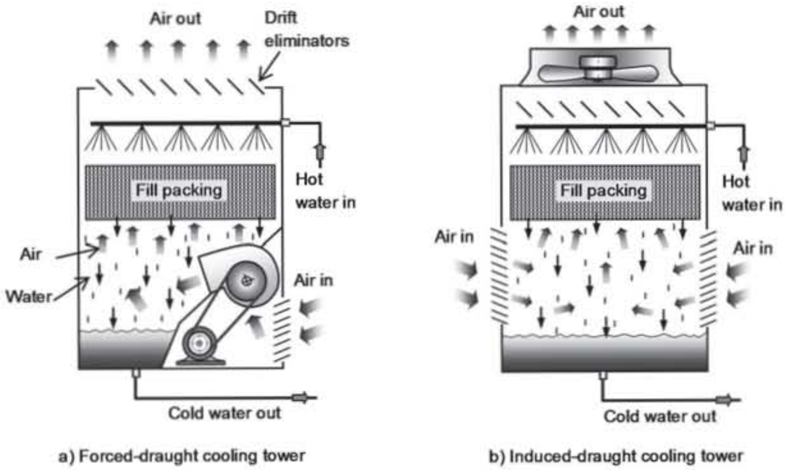


Figure 7.8
Mechanical draft crossflow cooling tower

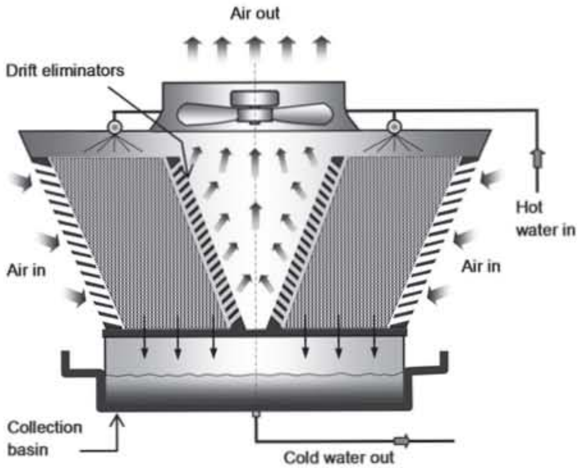
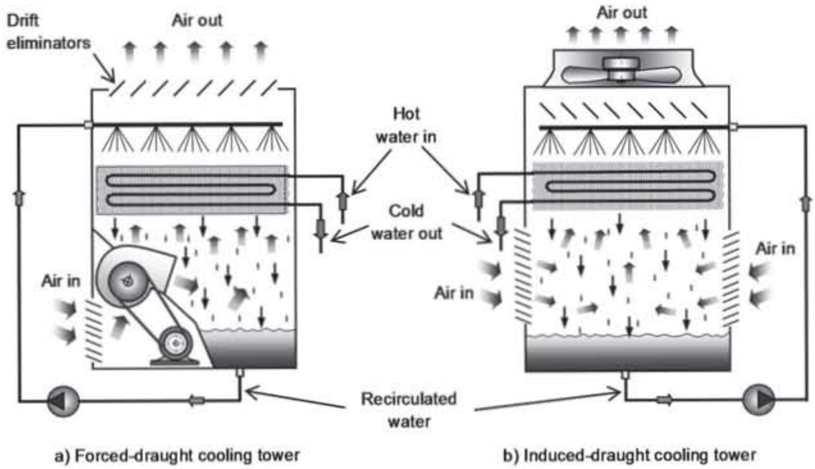


Figure 7.9
Indirect contact cooling tower



factors that influence the transmission of airborne *Legionellae* are wind velocity and direction, and vapour pressure.

Legionella cells of 0.5µm in size or less can reach the inner spaces of the lungs and are associated with causing pneumonia. Factors influencing contraction of the disease are smoking, age, steroid therapy and other underlying diseases.

The risks associated with cooling towers and legionnaires' disease have led, over the last few years, to increased use of air-cooled condensers as heat rejection equipment for central air-conditioning plant. Air-cooled condensers, however, result in increased energy consumption compared to cooling towers due to higher condensing temperatures. The condensing temperature is a function of the temperature of the cooling medium. In the case of air-cooled condensers, the condensing temperature is a function of the dry-bulb temperature of the ambient air whereas in wet cooling towers, the temperature of the condenser water is a function of the wet-bulb temperature of the ambient air which is lower than the dry-bulb temperature. The use of an air-cooled condenser in place of a cooling tower may lead to a 30% increase in the power consumption of the refrigeration system.

Prevention or control of the risk of legionnaires' disease from cooling systems can be achieved by:

- careful design and construction of cooling towers to minimise the release of aerosol;
- tower construction from durable materials with surfaces that can be easily cleaned and do not provide nutrients for bacteria to multiply;
- positioning the towers away from the air intakes of air conditioning and ventilation systems;
- providing easy access to the tower and components such as the eliminators and fill so that the tower can be periodically cleaned;
- careful cleaning and disinfection;
- water treatment.

Cooling systems should be maintained carefully. They should be cleaned and disinfected at regular intervals to prevent conditions conducive to the growth and multiplication of *Legionella* and to allow water treatment chemicals to work more effectively. Water treatment is necessary to prevent corrosion and organic growth in the system. Because *Legionellae* benefit from the presence of some host organisms, minimising organic growth indirectly affects these bacteria. A water treatment programme that controls biologic activity is therefore essential in controlling *Legionellae* in the same environment.

7.4 Heating equipment

7.4.1 Boilers

Thermal energy for space heating and domestic hot water for commercial buildings is normally provided by boilers. Boiler systems can be classified in a variety of ways based on: type of application; operating pressure; materials of construction; heat source; method of heat transfer from the combustion gases to water. Boilers can also be distinguished by their method of fabrication, for example, packaged or field erected.

Based on the heat source, boilers are often referred to as oil-fired, gas-fired, coal or solid fuel fired, or biomass. Gas-fired boilers are by far the most widely used for domestic and commercial space heating in Europe and the US. In terms of method of heat transfer between the combustion gases and water, most boilers fall into two major categories: water-tube and fire-tube.

In a water-tube boiler, water flows through tubes inside the furnace and absorbs heat directly from the combustion gases. The heat transfer is fast and the system can tolerate variable load requirements. Fire-tube boilers consist of a series of straight tubes that are housed inside a water-filled outer shell. The tubes are arranged so that hot combustion gases flow through the tubes. As the hot gases flow through the tubes, they heat the water surrounding the tubes and are confined by the outer shell of the boiler. Most modern fire-tube boilers have cylindrical outer shells with a small round combustion chamber located inside the bottom of the shell. Depending on the construction details, these boilers have tubes configured in one, two, three, or four pass arrangements.

Boilers are also distinguished by their method of fabrication. Smaller commercial boilers are manufactured and assembled in a factory and transported to the site as a finished product. These units are referred to as packaged boilers. Packaged boilers are generally of the shell fire-tube design (Figure 7.10). Large boilers that are not easily transportable as a single assembly due to size and weight limitations, are assembled on-site from individual components or sub-assemblies. These boilers are referred to as field erected boilers.

Boilers can be manufactured with a variety of materials. Most conventional (non-condensing) boilers are made with cast-iron sections or steel. Cast-iron boilers are

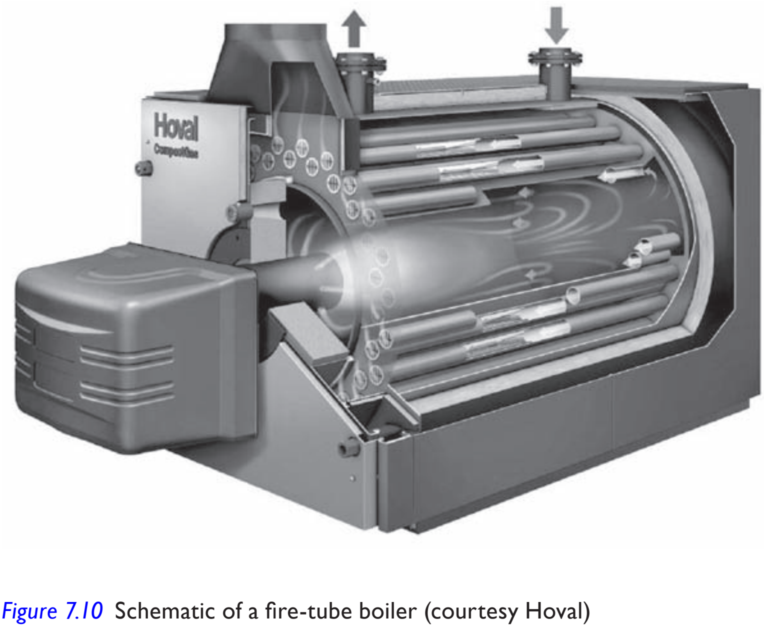


Figure 7.10 Schematic of a fire-tube boiler (courtesy Hoval)

composed of precast sections and thus can be more readily field assembled than steel boilers. They have a long life and are normally used in relatively small capacity installations and where long service life is important. However, they tend to be heavier and more expensive than steel boilers. Small boilers can also be made of copper tubes whereas condensing boilers can be made of stainless steel or aluminium.

Even though gas boilers are the most common type of boiler for space heating applications, biomass boilers are increasing in popularity due to their environmental credentials. They can burn a variety of biomass types such as wood chips, wood pellets, wood shavings, *Miscanthus* and many other materials. These fuels have different properties which determine the type of boilers and fuel handling system required.

Conventional boilers are designed such that the flue gas does not condense in the boiler. This precaution, which requires the boiler to operate with minimum water temperature of 60°C, is necessary to prevent corrosion of the construction materials of the boiler such as steel, cast iron and copper. New boilers, known as high efficiency or condensing boilers, are specifically designed to condense the water vapour present in the flue gases using lower water return temperatures. This improves boiler efficiency to over 90% but requires the use of non-corrosive materials such as aluminium and stainless steel for the combustion chamber and heat exchanger. For this reason, condensing boilers are more expensive than conventional boilers but the additional cost can be recovered very quickly from the savings in fuel costs.

Boiler efficiency. The efficiency of a boiler is normally defined as the net energy output measured on the water side divided by the energy input from the combustion of the fuel. The variation of typical efficiencies with load for conventional and condensing boilers is shown in Figure 7.11. It can be seen that the efficiency of conventional boilers increases as the load increases, whereas the efficiency of condensing boilers remains fairly high, in the range between 88 and 95% irrespective of the load. The small increase in steady state efficiency shown for condensing boilers at reduced loads is due to the higher potential to recover more energy from the exhaust gases at part load.

The seasonal efficiency of boilers will be lower than the overall efficiency which is determined at steady state conditions because of the heat losses from the boiler casing when the boiler is off. These losses can be reduced by continuous modulation of the firing rate of the burner as opposed to on–off firing control.

The update to the 2010 Part L Building Regulations specifies the following minimum efficiency standards for commercial boilers in new buildings as shown in Table 7.1 opposite.

7.5 Air distribution systems

The air for heating, ventilation and air conditioning of buildings is distributed from the air-handling units (AHUs) to the conditioned spaces by ductwork (Figure 7.12).

The design of the ductwork and other air distribution components has a large influence on both the capital and operating cost of the system and will also be the determining factor in deciding the horizontal service zone depth.

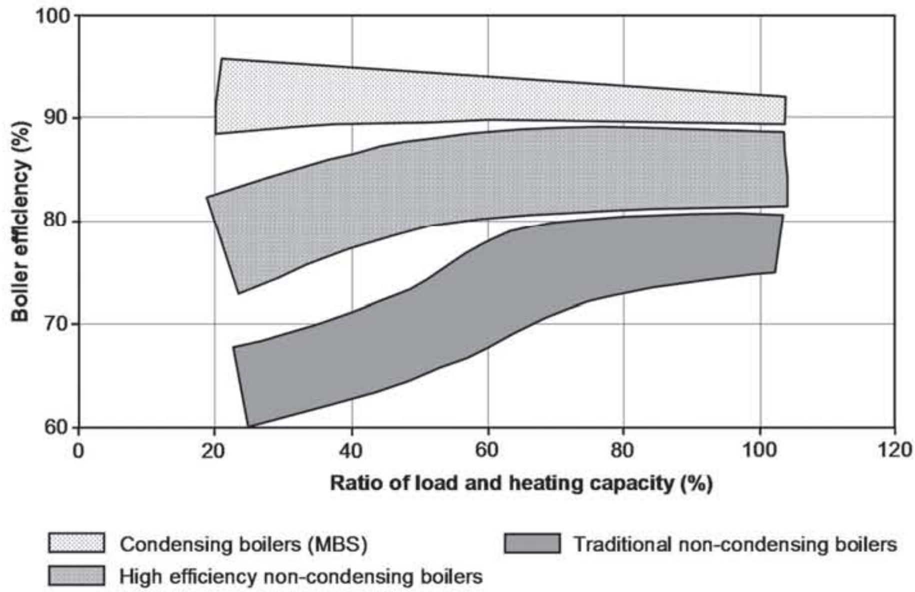


Figure 7.11 Typical boiler efficiency curves

Table 7.1 Boiler efficiency standards for commercial buildings

Gas, oil and biomass boilers in new buildings		*Boiler seasonal efficiency*
Natural gas	Single boiler system	86%
	Multiple boiler system	82% for any individual boiler 86% for the overall multi-boiler system
LPG	Single boiler system	87%
	Multiple boiler system	82% for any individual boiler 87% for the overall multi-boiler system
Oil	Single boiler system	84%
	Multiple boiler system	82% for any individual boiler 84% for the overall multi-boiler system
Biomass-independent automatic pellet/woodchip		75%

7.5.1 Ductwork sizing methods

There are three basic methods for manual duct sizing which are:

- velocity reduction method
- equal friction method
- static regain method.

Each of the three methods is briefly outlined in the following notes.

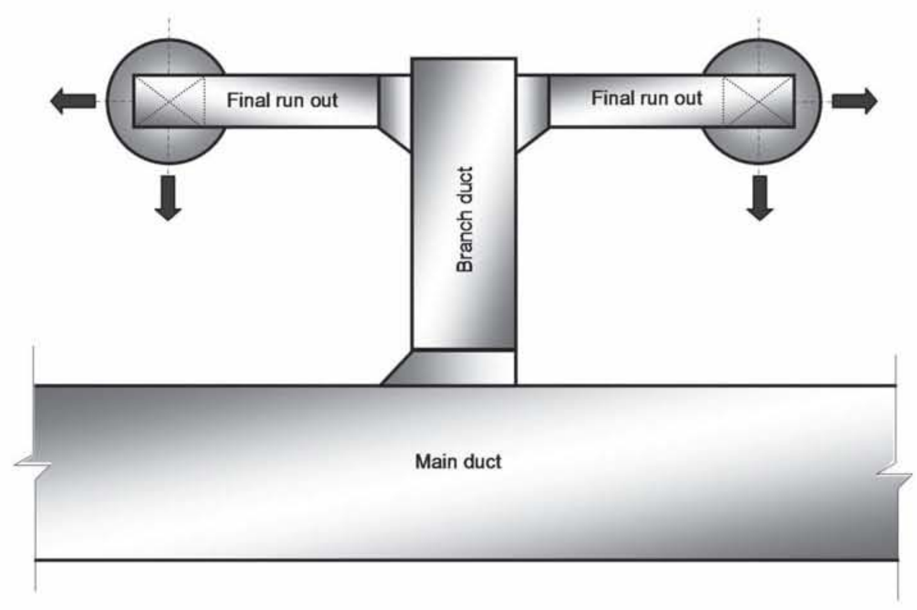


Figure 7.12 Schematic diagram of main duct, branch duct, and final run outs

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Velocity reduction method

With this method the ducts are sized so that the duct velocities are progressively reduced from the fan throughout the system to the final terminals. The design velocities are selected based on the limitation of noise criteria. The noise generated by the turbulent air within the ductwork increases as the duct air velocities are increased. Therefore, for a given noise criteria there are recommended maximum duct velocities. Refer to Table 7.2 for recommended duct velocities for low pressure systems.

Equal friction method

Using this method a design pressure drop per metre of ductwork is selected and then ducts are sized using the duct sizing chart like that shown in Figure 7.13 for circular duct. Figure 7.13 can still be used to size ducts with rectangular or flat oval sections after obtaining the duct equivalent diameter. Equivalent diameters for rectangular duct sections can be determined from Equation 7.9, where a and b are the width and depth of the duct respectively:

$$d = 1.265 \left[\frac{(ab)^3}{a+b}\right]^{0.2} \tag{7.9}$$

Table 7.2 Recommended duct velocities for low pressure systems

Application	*Controlling factor (m/s)*				
	Noise generation	*Duct friction*			
	Main ducts	*Main ducts*		*Supply ducts*	
		Supply	*Return*	*Supply*	*Return*
Domestic building	3	5	4	3	3
Bedrooms in non-domestic building	5	7.5	6.5	6	5
Private offices, libraries	6	10	7.5	8	6
Theatres, auditoria	4	6.5	5.5	5	4
General offices, restaurants, department stores, banks	7.5	10	7.5	8	6
Shops, cafeterias	8	10	7.5	8	6

Source: CIBSE TM8 1983

The normal design pressure drop values selected for this method are in the range 0.8–1.2 Pa/m. This method is commonly used for sizing low pressure extract and supply systems.

Static regain method

This method uses the principle that if the velocity within a duct is reduced, for example at an expansion or a branch, then the reduction in velocity pressure is converted to an increase in static pressure less any friction losses that occur. The sizing of ductwork based on this principle therefore seeks to equalise the static pressure at all the branch take-offs in a system and thus provide an inherently self-balanced system. There is a reduction in velocity pressure throughout the ductwork system where the air quantities are reduced at branches within the system. The decrease in velocity pressure results in an increase in the static pressure, and the aim of sizing the ductwork is to achieve a counterbalance of the increase in static pressure to the static pressure loss due to friction.

7.5.2 Recommendations for practical duct sizing

In practice, the most commonly used method of duct sizing is a combination of the velocity reduction method and the equal friction method. The selection of the design velocities and pressure drop criteria are generally based on experience and require an engineering judgement. This seeks to balance the requirement for smaller ducts to minimise the space required and at the same time avoid large pressure drops and too high velocities, which will increase fan pressures and energy consumption. There are several criteria that must be taken into account when duct sizing.

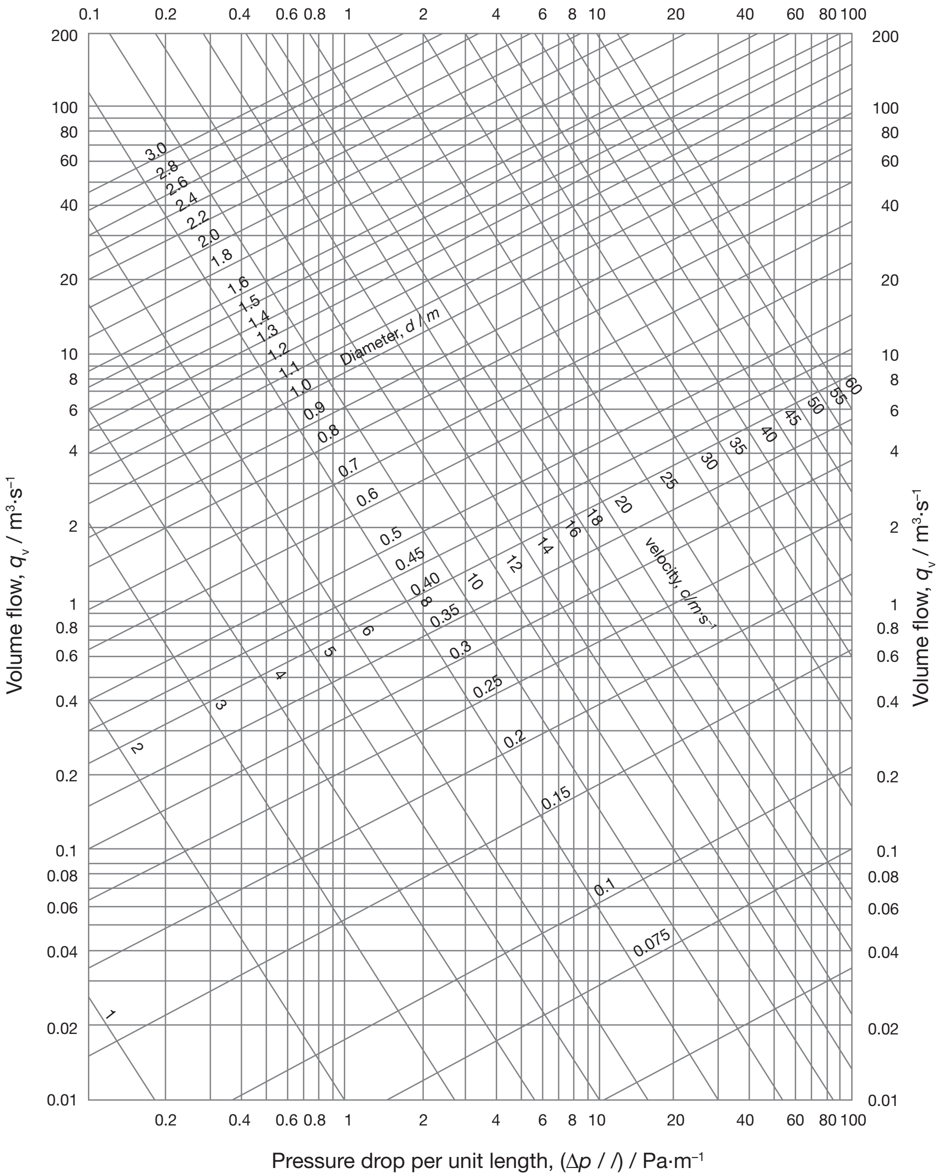

Figure 7.13 Air flow in circular ducts – air temperature 293 K and ρ = 1.2 kg/m^3

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These are:

- The air velocities must be limited to those required to achieve the design noise criteria within the space.
- The pressure drop between air diffusers/grilles or terminal units must not be excessive otherwise it will not be possible to balance the system without creating noise problems from nearly closed volume control dampers. In ductwork systems with varying lengths between the outlets, it will be necessary to provide dampers within the system. These dampers will provide additional resistance to the outlets nearest to the fan. This will add additional pressure drop to those branches to balance the pressure loss due to friction for the longer branches which are furthest from the fan. It is recommended that this pressure imbalance should be limited to about 50 Pa when sizing the ductwork for conventional low velocity systems with volume control dampers within the branch ducts serving the grilles of spaces with noise criteria of NR 35. For VAV terminals which have secondary attenuation this should be limited to about 150 Pa.
- The space required for distribution ducts within the building, particularly the horizontal distribution within the ceiling voids, must be carefully considered and a balance must be found between reducing the building costs and increasing the ductwork costs. Obviously if the horizontal distribution space within the ceiling voids can be minimised there will be capital cost savings on the building due to a reduced area of external cladding, structural column lengths, etc.
- The fan energy must be considered and the duct sizing has a direct bearing on this. Unfortunately it is difficult to determine the cost benefit in terms of reduced fan energy when sizing a ductwork system without undertaking a detailed life cycle costing exercise which would include the building costs. Therefore it is only possible to recommend that low fan pressures should be aimed for by careful design of the ductwork systems. This is particularly important as the fan energy can account for typically 15% of the total energy consumption of an air-conditioned office building. (For VAV systems about 550 Pa supply and 100 Pa extract should be aimed for.)

Practical considerations also apply relating to standard dimensions for rectangular, circular and flat oval ductwork. The HVCA have established a range of standard sizes in order to introduce some uniformity; if non-standard sizes are specified the cost of the installation will be increased.

How each of the above factors is taken into account will vary from project to project depending on the particular emphasis given by the design team and client. However, noise will always be an overriding criterion and, therefore, the maximum duct velocities will always be one of the limiting factors.

The pressure imbalance within the system needs to be limited as described and, therefore, it is generally these two criteria that are used to determine the circular duct sizes initially. Then the space requirement criteria come into the design process and the circular duct sizes selected using the duct sizing chart are converted into the equivalent rectangular or flat oval duct sizes using tables given by the CIBSE.

The table used should be that for equal volume flow rate, pressure loss and surface roughness. In this case the actual mean velocity within the equivalent duct will not be the same as in the circular duct, but in practice the differences are relatively small and usually within 10%.

Recommended maximum duct velocities in m/s for low pressure systems are given in Table 7.3, which shows that the design air velocities are reduced as the air passes through the system to the final air diffuser within the room.

For a VAV system the maximum duct velocities for an NR design level of 35 are in the range of 10 m/s for the main ducts and the branch ducts at 8 m/s. The maximum recommended design velocities for supply ductwork for a VAV system are much higher than conventional systems. This is because the VAV system has terminal attenuators built into each VAV terminal box downstream of the control damper. This attenuator deals with both the noise generated by the control damper and also the velocity generated noise of the air within the upstream ductwork system. All ductwork downstream of the VAV terminal box should be sized on the conventional low velocities given in the preceding table for the final run outs.

For flexible ducts that are used in many cases for final connections to air diffusers, the maximum velocity should be limited to 0.5–1.0 m/s below the tabulated values for the final run outs.

When selecting the equivalent rectangular duct for a circular duct it is recommended that an aspect ratio of not greater than 5:1 is used. The aspect ratio of a duct is the ratio of the longest side to the shortest side, which is normally the width to the height. This is because ducts sized with higher aspect ratios are difficult to adequately stiffen and there is the possibility of increased noise breakout and drumming caused by movement of the long sides of the duct.

The performance and characteristics of a circular and an equivalent rectangular duct are compared in Table 7.4. Both ducts are sized to handle the same quantity of air.

From the engineering and cost viewpoint, circular ducts have a distinct advantage over rectangular ducts but unfortunately it is not normally possible to design ductwork systems with only circular ducts because of the need to optimise the overall design of the building and space for services.

Extract duct systems are not normally sized on medium or high velocities because the ductwork, particularly if rectangular, will become unstable under large suction pressures. Therefore, extract ductwork systems are normally sized on low velocity criteria even when the supply ductwork is sized on medium velocity criteria.

Extract ductwork can be minimised if the ceiling void is used as an air plenum returning air into the void either through specially designed openings within the body

Table 7.3 Recommended maximum velocities in m/s for low pressure systems

NR design level	*Main ducts*	*Branch ducts*	*Final run outs*
20	4.5	3.5	2.0
25	5.0	4.5	2.5
30	6.5	5.5	3.3
35	7.5	6.0	4.0
40	8.0	7.0	5.0

Table 7.4 Comparison between circular and rectangular ducts for the same air flow

	Circular	*Rectangular*
Size	600mm Ø	1200mm × 300mm
Surface area per metre length	1.88m²	3.00m²
Minimum sheet thickness	0.8mm	1.0mm
Air leakage per metre length	2.87 l/s	4.58 l/s
Horizontal service zone required for insulated duct	760mm	430mm
Installed cost per metre length including 40mm insulation	50% of rectangular duct	Reference duct
Noise breakout loss at 125Hz	50dB	22dB

of recessed light fittings or through grilles. It is possible to draw the air about 20–25 metres within a ceiling void provided the air velocity within the void does not exceed 1.5m/s.

Flexible ducts are often used to make the final connections to ceiling mounted grilles and diffusers to ease installation and future changes. Care should be taken in limiting the lengths of flexible ducts used as they cannot be easily supported and can become sharply bent. Flexible ducts should never be used for the connection from the main duct to VAV terminal units as the high velocity air generates noise and the noise breakout through the flexible duct can be a problem.

Rectangular ducts are most commonly used for low pressure and low velocity (0–10m/s) conventional ventilation and air-conditioning systems. At higher velocities rectangular ducts of larger sizes can tend to drum and the sides can be difficult to adequately stiffen.

Circular ducts are particularly suitable for medium velocity (10–20m/s) systems. The normal method of manufacture which involves forming the circular duct from a continuous strip with an interlocking joining seam provides good rigidity and airtightness. This type of duct is referred to as spirally wound circular. Because of their inherent high rigidity, the noise transfer from within the duct to the surrounding area is low when compared to the rectangular duct. Standard ranges of circular duct fittings and bends are manufactured, making the ductwork system costs economical.

Flat oval ducts are formed from spirally wound circular ducts that are mechanically transformed to the flat oval shape. This duct section has a higher rigidity than the rectangular duct and is more suitable for medium velocity systems. The flat oval duct is a compromise between the characteristics desirable from a circular duct and the space saving advantage of a rectangular duct. The widespread use of flat oval ductwork has reduced because the bends and fittings required can become relatively complex and the ductwork system costs are higher.

7.5.3 Ductwork materials

For normal air-conditioning and ventilation systems, ductwork is manufactured in galvanised sheet steel. The sheet thickness depends on the size of the duct's longer side and the classification of the ductwork, i.e. low, medium or high pressure. Typically sheet thicknesses are 0.8mm and 1.0mm for ducts of between 600mm and 1600mm longest side.

Other duct materials used for special applications include PVC, generally used for laboratory fume extract systems, where a high resistance to corrosion is required.

7.5.4 Standard ductwork sizes

Standard duct dimensions are used in the UK to provide uniformity in the range of sizes of ductwork and fittings (i.e. bends, tees, branches, etc.) used for systems. The standard sizes are defined by the Heating and Ventilating Contractors Association specification DW/142 (HVCA 1988). The standard sizes do not include very large ducts, which are manufactured to the particular sizes required. The advantages of using standard sizes are that the cost of the design, manufacture and installation of the ductwork, which can typically account for 25% of the total air-conditioning system cost, can be minimised.

The standard sizes for circular and rectangular ducts are given in Tables 7.5 and 7.6 respectively.

Table 7.5 Standard circular duct size

Duct diameter (mm)													
63	80	100	125	160	200	250	315	400	500	630	800	1000	1250

Table 7.6 Standard rectangular duct sizes

Long side (mm)	*Short side (mm)*										
	100	*150*	*200*	*250*	*300*	*400*	*500*	*600*	*800*	*1000*	*1200*
150											
200											
250											
300											
400											
500											
600											
800											
1000											
1200											
1400											
1600											
1800											
2000											

7.6 Hot and chilled water systems

The design of the hydraulic system is fundamental to the correct operation and control of heating and cooling systems. This section covers the design of recirculating closed loop heating and cooling water systems for heating, cooling and air conditioning. It includes the design aspects of system pipework circuits and primary/secondary system pumping.

7.6.1 Hot water system design

Constant and variable temperature circuits

Air-conditioned buildings are normally required to have two separately controlled heated water pipework systems supplied from a common boiler plant. These systems are: a) constant temperature circuit; and b) variable temperature circuit.

Constant temperature heated water is required to serve the heating coils within AHUs. This circuit of heated water is supplied from the heating plant at a constant temperature throughout the year. The circuit can also be used to supply the primary coil of hot water storage calorifiers.

Variable temperature heated water is required for heating circuits that include radiators, convector heaters, under floor heating pipes and other such heat emitters that require the temperature of the heated water to be varied depending on the required heating demand. The variable temperature circuit incorporates a three-port mixing valve to allow the flow temperature to be varied by mixing a portion of the lower temperature return water back into the flow without passing it through the boiler plant. The flow temperature is normally varied based on the outside air temperature, but can also be varied additionally by solar or wind sensors. This type of system is referred to as a compensated heating system. The variable temperature circuit has the benefit of reduced heat losses from the distribution pipework at times when the flow temperature is reduced, thereby improving the energy efficiency of the system.

Heating system pipework circuits

The following section outlines the basic forms of pipework circuits for a radiator heating system. The principles also apply to other heat emitters such as convectors, coils, heat exchangers and radiant panel heaters. There are three basic heating pipework circuit configurations, namely: a) single pipe circuit, b) two-pipe system, c) reversed return system.

SINGLE PIPE CIRCUIT

In this system, as illustrated in Figure 7.14 overleaf, the flow pipe from the heat source is routed in one continuous pipe loop around the system, and radiator flow and return pipes are connected to the single pipe. The water circulation through each radiator is mostly by gravity and therefore the pressure available for flow through the radiators is very low. If thermostatic radiator valves are used to locally control the output of each radiator, they have to be of a very low resistance type to allow flow through the radiator by gravity circulation. Because the circulation through the heat emitter

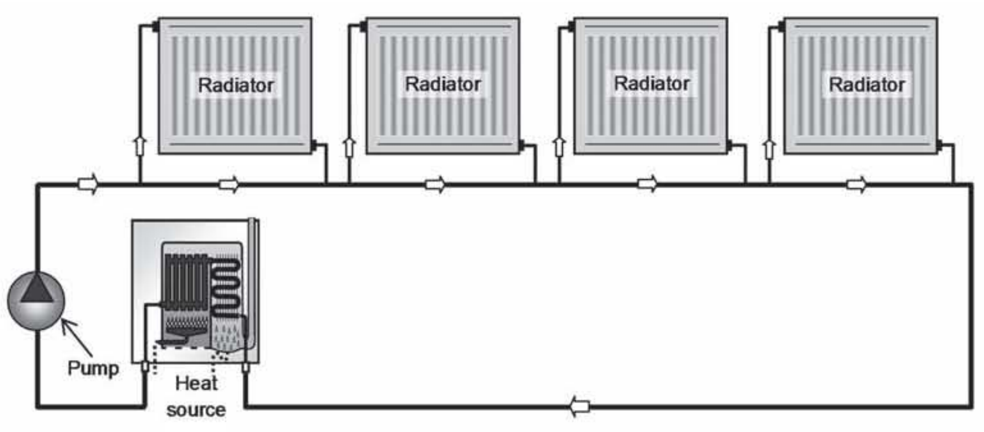


Figure 7.14 Schematic diagram of a single system

is mostly due to gravity circulation, as the pressure drop through the main pipe is relatively low, this system is only really suitable for low pressure drop heat emitters such as radiators.

Each radiator in the circuit progressively receives a lower flow temperature from the mixing of return water into the main from the preceding radiators. The radiators at the end of the circuit receive water close to the boiler design return water temperature. This leads to the radiators needing a larger surface area compared with those at the start of the circuit. This requirement for increased radiator sizes does not always prove aesthetically acceptable.

The main advantage of the single pipe system design is its simplicity and low cost. The single pipe is of one constant size throughout the system. The disadvantage is that the last radiators on the circuit are large in comparison with those at the start of the circuit. In practice, if this pipework arrangement is used within, for example an open-plan office, the radiators are all sized for the same area resulting in the radiators at the start of the circuit being oversized for aesthetic reasons.

TWO-PIPE SYSTEM

The two-pipe system is the most commonly used pipework arrangement for heating systems. With this system all radiators receive the same flow temperature and radiators of the same output are of equal size. The flow through each radiator is determined by the system pump pressure and can therefore be of relatively high pressure drop.

The pipework system is more complicated than a single pipe system and the flow and return pipes reduce in size throughout the circuit. The inherent problem in this distribution is the pressure imbalance throughout the system. This means that the installation of balancing valves is important to adjust the resistance through each parallel path to match the required flow to the available head in the mains at each junction. A schematic of this system is shown in Figure 7.15.

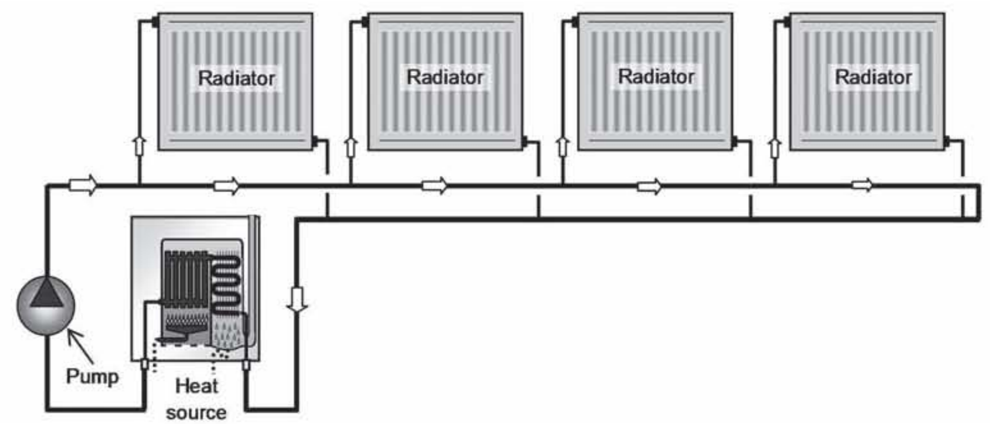


Figure 7.15 Schematic diagram of a two-pipe system

REVERSED RETURN SYSTEM

The reversed return system is a variation of the two-pipe system and generally has similar characteristics. The reverse return pipework distribution system, however, overcomes the problem of unequal pressures throughout the circuit and provides approximately an equal pressure at each radiator. It is not generally possible to design a system so that the entire pipework network is a reverse return circuit other than in relatively small and simple systems.

The system has the advantage of making the balancing of the system easier. The disadvantage is that an additional pipe to the flow and return pipe is needed, making the pipework cost greater and requiring more space for the additional return pipe.

Selection of heating system design temperatures

Conventional heated water systems for buildings are operated at what is classified as low temperature hot water (LTHW). This is classified as a system with a flow temperature of up to 100°C. Conventional LTHW heating systems are designed for a flow temperature of 82°C and a return water temperature of 71°C (ΔT = 11 K).

In larger systems it may be advantageous to design the heating system for a greater temperature difference between the flow and return temperatures with say 80°C flow and 60°C return (ΔT = 20 K). For a given heating load this allows the flow rates to be about one half of those of a conventionally designed system. The higher temperature difference reduces the pipe sizes and the pump energy requirement. The disadvantage is that the mean surface temperature of the heat emitters is lower, resulting in the need for larger surface areas.

The wider temperature difference systems require more careful design since they are much less forgiving with respect to design errors. Heat transfer surfaces must be selected with care and piping must be sized correctly with low resistance.

Primary and secondary pumping

In large systems, a suitable way to avoid problems of system and control valve interaction and flow variation through boilers and chillers is to use primary and secondary pumping as illustrated in Figure 7.16. This ensures that the flow rate on the boiler or chiller side remains constant, and that there is no interaction between the control valves.

The primary pump is sized to pump through the primary side only of the system and each secondary pump sized for its own secondary circuit. The balance pipe is required to avoid the primary pump pressure causing water to flow the wrong way through the three-port mixing valve. It is necessary to install a regulating valve to avoid short-circuiting the secondary system.

A practical adaptation of the above system is to pump into a main primary header that eliminates the requirement for balance pipes and regulating valves. The header is sized for low pressure drop so that any change in flow in the header does not result in a system pressure change. This is shown in Figure 7.17.

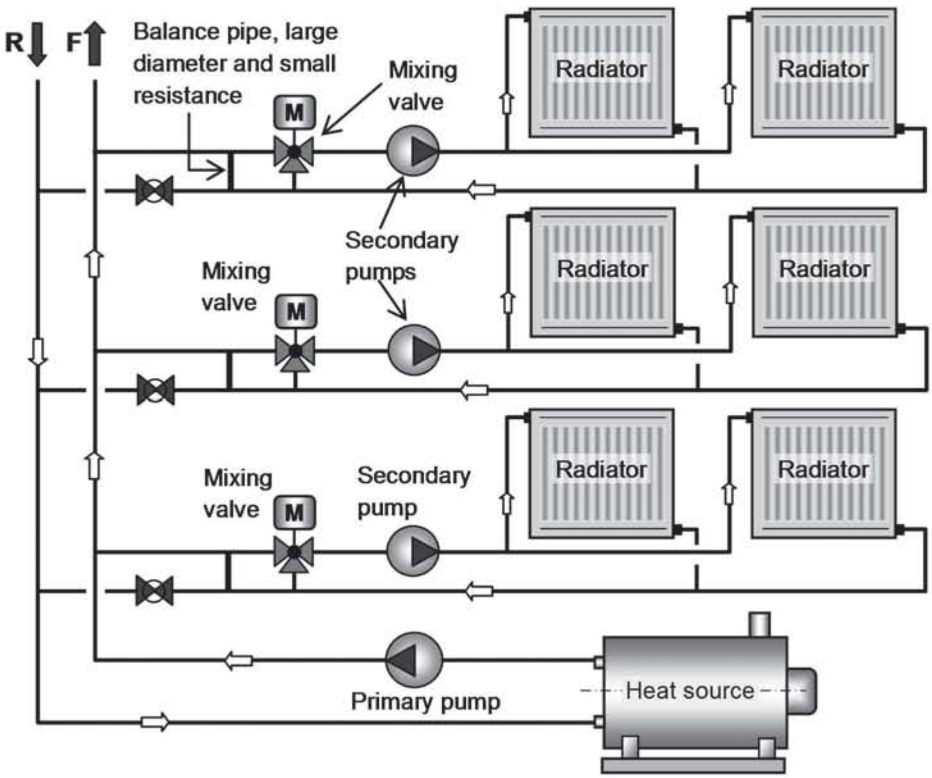


Figure 7.16 Primary and secondary pumping arrangement

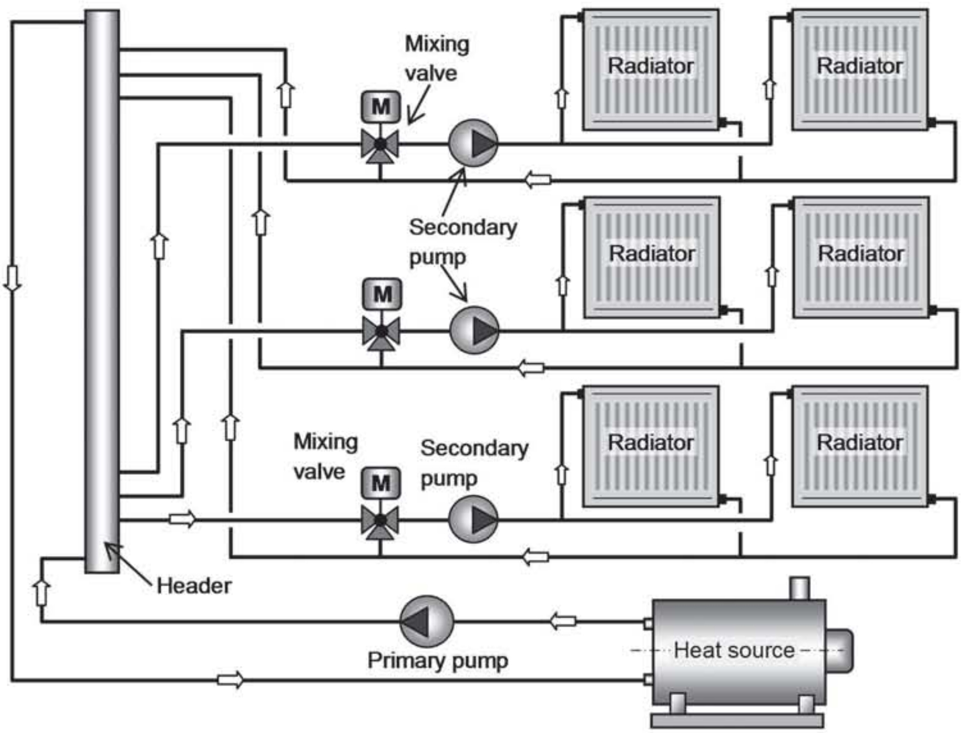


Figure 7.17 Pumping arrangement employing a header

7.6.2 Chilled water system design

Chilled water systems are generally designed as constant temperature systems for 'all-air' air-conditioning systems. The chilled water is supplied to the cooling coils within the AHUs at a constant supply temperature to ensure that the coil apparatus dew point provides the required dehumidification of the supply air.

In 'air-water' air-conditioning systems there is a requirement to provide two separate temperature controlled chilled water circuits. One of the circuits supplies chilled water at a constant temperature to the air-handling unit coils to cool and dehumidify the primary air. A second chilled water circuit is required to serve the terminal units. In the case of a fan coil unit, the chilled water may be supplied to the units at a temperature above the dew point temperature of the air so that the fan coils operate dry. In the case of a chilled beam/ceiling system, it is essential that the chilled water temperature is always above the room dew point temperature otherwise condensate will form on the ceiling. This type of chilled water circuit arrangement can be accomplished using an injection circuit.

An injection circuit is similar to the standard mixing circuit but is used where the secondary flow temperature is designed not to be the same as the primary flow temperature and where the secondary temperature must be limited to a predetermined level.

The circuit is shown in Figure 7.18, which illustrates both the primary/secondary pumping and constant temperature circuits for a chilled water system.

It can be seen that the injection circuit includes a bypass line between the secondary pump and the mixing valve. The regulating valve within this pipe is set to provide a constant bypass of water which ensures that when the three-port valve opens fully to the primary circuit, the secondary flow temperature will be limited to above the room dew point by the mixing of the return water within the bypass line. This circuit also allows a smaller valve for the secondary circuit, and one that operates across its full range.

Chilled water systems employ primary/secondary pumping as described in the preceding section for heating systems, as it is normally essential to maintain constant water flow through an operating chiller. A reduced flow can lead to a freeze-up of the evaporator.

Chilled water pipework circuits are normally of the two-pipe design. They can also benefit from reversed return pipework design to ease the balancing of the hydraulic system.

The standard temperatures used for chilled water supply to the cooling coils within AHUs are 6°C flow and 12°C return. On large systems where the pipework is extensive, the pipework sizes and pump energy can be reduced if the cooling system is designed with a higher temperature difference between the flow and return.

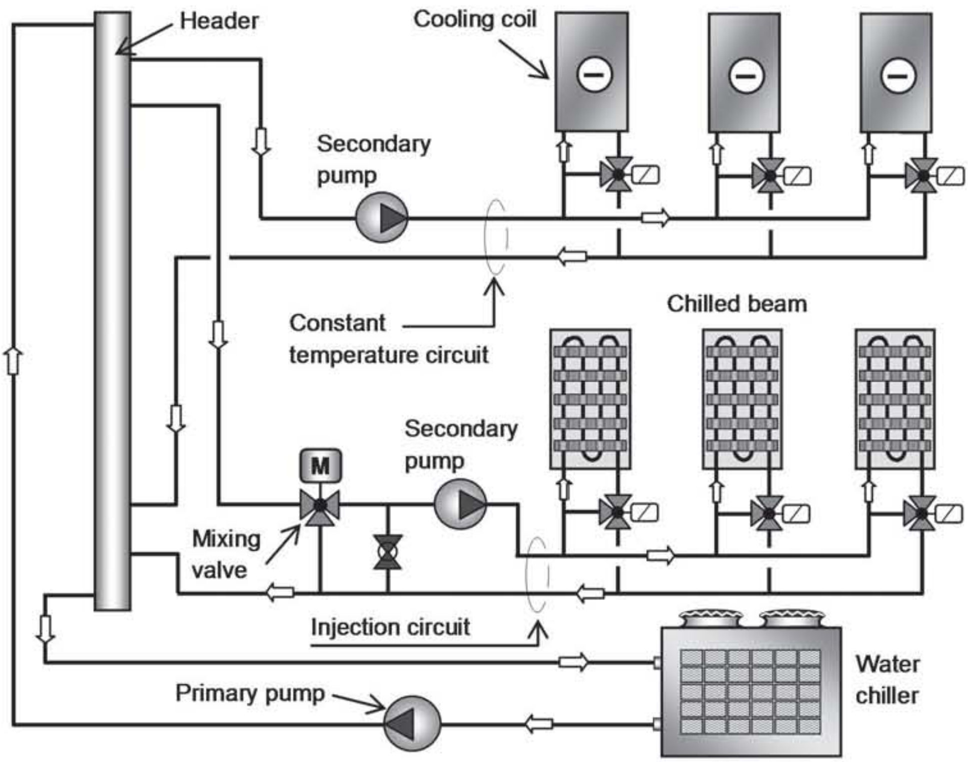


Figure 7.18 Primary/secondary pumping and injection circuit

7.7 Summary

In this chapter, we have considered the major technologies and equipment employed to generate the cooling and heating energy for the control of the thermal environment in buildings. We have also considered aspects of design of ductwork and pipework systems for the distribution of thermal energy to the terminal devices in the conditioned spaces. The selection of heating and cooling technologies for a given application will have an influence on the energy consumption and environmental impacts of the building and should be given careful consideration at the design stage.

Vapour compression refrigeration systems have higher COPs than absorption systems but the latter can offer a viable alternative where waste heat is available to drive the generator. Solar thermal energy can also be used for this purpose, particularly in locations with high solar insolation.

The selection of heat rejection equipment will have an influence on the power consumption of the refrigeration plant. Air-cooled condensers and 'dry coolers' (water-to-air heat exchangers) are the most commonly employed heat rejection equipment in temperate and cold climates for small to medium heat rejection duties. For higher duties than about 400kW and in warm climates heat rejection through cooling towers becomes economically viable.

In this chapter we have also considered the various ductwork sizing methods and the practical aspects of ductwork system design. The advantages of using standard sizes have been considered and listings of standard sizes for circular, rectangular and oval ducts have been provided for reference. Common piping arrangements for cold and hot water distribution to terminal devices have also been discussed.

Chapter 8

Low energy approaches for the thermal control of buildings

8.1 Introduction

Concerns over global warming and the escalating costs of fossil fuels over the last few years have put pressure on governments, professional bodies and engineers to re-examine the whole approach to building design and control. There are considerable pressures on architects to design less energy dependent buildings while maintaining or even improving thermal comfort. Low energy thermal control technologies that have been used for centuries in various parts of the world are now being re-examined and re-engineered to fit within modern building forms.

Low energy technologies can be considered as alternatives to the traditional approaches for the environmental control of buildings described in Chapters 6 and 7. They may employ natural sources such as outdoor air, water or ground to provide cooling and heating to buildings or other facilities without lowering the desired level of indoor air quality and thermal comfort. Low energy technologies have the potential to offer reductions in energy consumption, peak electrical demand and energy costs, provided they are properly designed and implemented.

There are various low energy design concepts that can be applied to non-residential buildings, as well as to new and retrofit structures in a wide range of weather conditions. These technologies are also often used in combination with traditional cooling and heating systems. In this chapter we consider the characteristics and applications of the most promising low energy approaches for the control of the indoor thermal environment of buildings.

8.2 Thermal energy recovery

In modern commercial buildings it is estimated that 20–30% of energy is lost due to the requirement to provide and condition fresh air for the building's occupants. Fresh air is necessary for the health and productivity of the occupants and the control of relative humidity. A way of reducing the energy consumption arising from mechanical ventilation, apart from demand control ventilation (control of ventilation rate based on actual occupancy and CO_2 generated by the occupants in the building) is through thermal energy recovery.

The main methods of air-to-air thermal energy recovery are: a) fixed plate heat exchangers; b) rotary air-to-air exchangers (rotating wheels); c) run-around coil systems; d) heat pipes. For all types of thermal energy recovery equipment, the efficiency of the process is defined by the total effectiveness of the process given by:

$$\varepsilon_t = \frac{\textit{actual transfer of thermal energy across the device}}{\textit{maximum possible transfer of thermal energy across the device}} \tag{8.1}$$

8.2.1 Fixed plate thermal energy exchangers

Plate heat exchanger heat recovery systems (Figure 8.1) are available in many different configurations, materials, sizes and flow patterns. In their simplest form they are composed of a cubical sandwich of thin metal or plastic plates. These plates allow the exhaust and supply air streams to exchange thermal energy through heat transfer across the separating plate walls. The space between the plates can vary between 2.5 and 12.5mm, depending on the design and application. The plates are arranged into modules which can range in capacity from 0.01 to 5m^3/s. Multiple modules can be used in different sizes and configurations to satisfy individual application requirements (ASHRAE 2012a). Plate heat exchangers have a number of advantageous features, including:

- no moving parts reducing maintenance requirements;
- no cross contamination as the two air streams are kept apart and do not mix;
- very low energy requirements. Only small additional fan power energy is required to overcome the pressure drop in the plates.

8.3 Rotary air-to-air thermal energy exchangers

Rotary energy exchangers or thermal wheels are composed of a revolving circular matrix of air-permeable material which provides a large internal surface area for heat transfer (Figure 8.2). For commercial building applications, the matrix material can be aluminium foil, paper, plastic or other synthetic material in a variety of configurations that provide small air passages (1.5–2mm) in the direction of air flow. The wheel is positioned across parallel ducts which carry the supply and exhaust air streams in

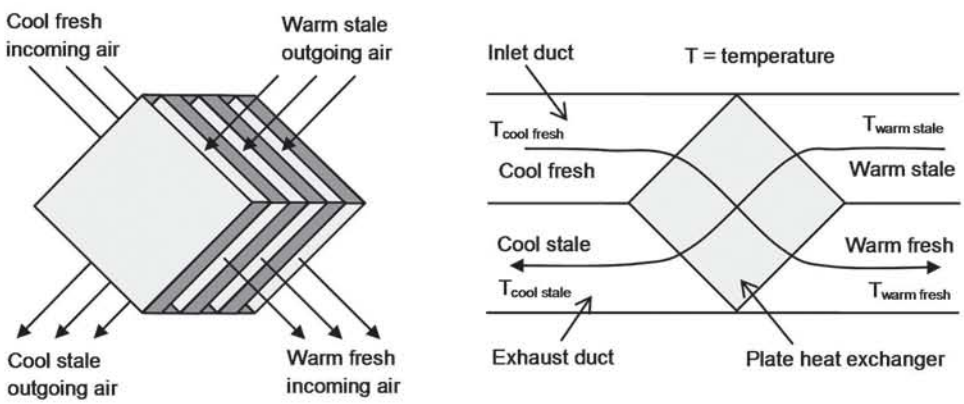


Figure 8.1 Fixed plate thermal energy exchanger

a counterflow arrangement. The exhaust air stream flows through half of the wheel where energy is transferred from the air stream to the cooler wheel matrix material. As the wheel rotates slowly, the warm part of the wheel enters the air supply duct and transfers the stored heat to the cooler supply air to the building.

Thermal wheels can be used for both sensible and latent heat transfer. Latent heat transfer can be achieved if the matrix of the wheel is coated with desiccant material. The desiccant will absorb moisture from the higher humidity (higher vapour pressure) air stream and desorb it (release it) to the lower humidity (lower vapour pressure) air stream. The absorption and desorption processes are driven by vapour pressure differences between the surface of the desiccant and the respective air streams.

The thermal wheel is normally driven by an electric motor which introduces a small energy penalty, and this should be considered in the assessment of the overall thermal energy recovery efficiency. Rotary thermal wheels require little maintenance and tend to be self-cleaning because the direction of air flow through the matrix is reversed as each section of the wheel rotates from the supply to the exhaust air stream.

8.3.3 Run-around coil systems

Run-around coils or loops are heat recovery devices which employ finned tube water heat exchangers (coils) in the supply and exhaust air streams of buildings or processes as shown in Figure 8.3. The coils in the two air streams are connected in a way that forms a closed loop through which water or antifreeze solution is pumped in a counterflow arrangement with the air flow. Precautions must be taken at the design stage to ensure that water vapour does not condense and freeze on the coil in the supply air duct.

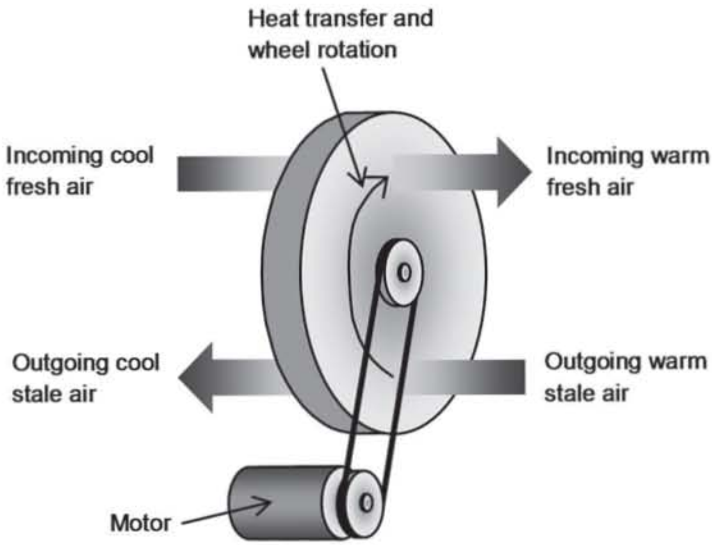


Figure 8.2 Rotary air-to-air thermal energy exchanger

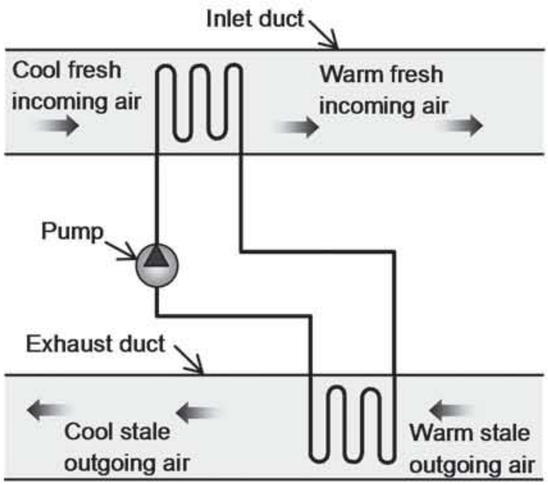


Figure 8.3
Run-around coil thermal energy exchanger

Run-around coils are very flexible devices and can be used where supply and exhaust air ducts are not located close to each other. They can also enable heat to be transferred from a variety of sources and uses. To accommodate changes in the fluid volume during operation at different temperatures, an expansion vessel should be provided in the closed loop. Typical effectiveness values for run-around coil heat recovery systems range between 45 and 65% (ASHRAE 2012a).

8.3.4 Heat pipe heat exchangers

Heat pipe heat exchangers are two-phase closed loop thermal energy transfer devices that contain no moving parts. A volatile fluid in the pipe (Figure 8.4, overleaf) vaporises at one end by absorbing heat from the air flowing over the evaporator section. The pressure that is created from the evaporation process transfers the vapour to the condenser end of the tube where it is cooled by the cooling air flowing over the tube and condenses to liquid. The liquid then flows back to the evaporator by gravity, the pressure difference between the two sections and, in some cases, capillary action created by a wick-type material for the repetition of the cycle.

Because of the two-phase heat transfer, heat exchange with heat pipes can be many times higher than other heat recovery devices, reducing the size of the equipment required. The performance of heat pipes depends on many parameters including the working fluid, orientation to facilitate vapour and liquid flow; and other design parameters such as pipe material, diameter, extended heat transfer surfaces employed (fins), wick structure, material and arrangement of heat pipes in a heat exchanger block, etc.

8.4 Heat pump systems

As described in Section 7.2.1, heat pumps are devices that extract heat from a low temperature source and reject this heat at a higher temperature level. Heat pump systems can normally be classified on the heat source medium such as air, water or

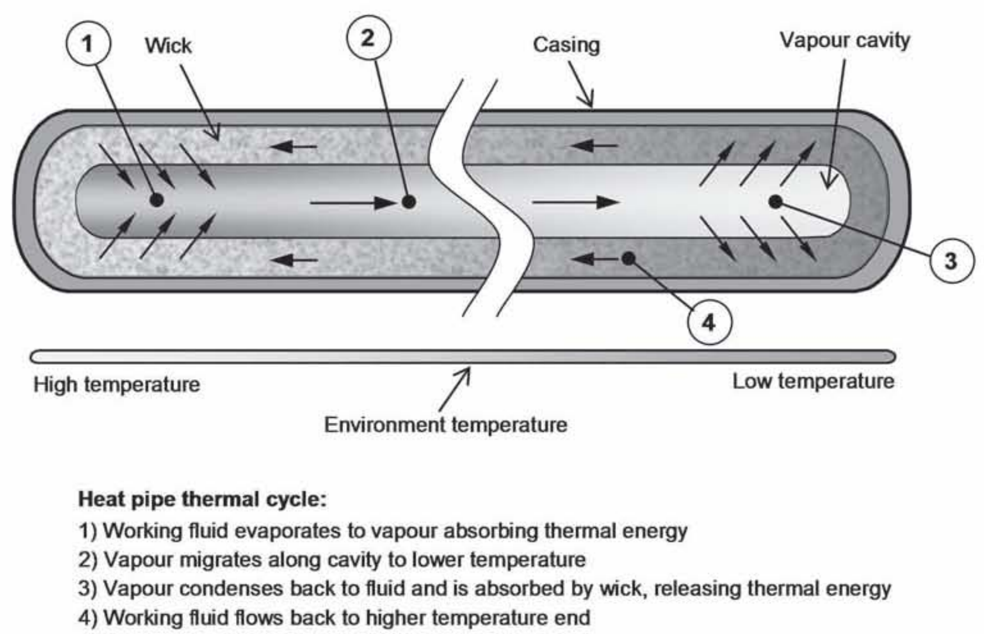


Figure 8.4 Principle of operation of heat pipe

ground and the heat rejection medium, normally air or water. The vast majority of heat pump systems on the market today operate on the vapour compression cycle but sorption systems are also commercially available. Extensive research and development such as more efficient heat exchangers and controls, including inverter control of the compressor to better match the heating capacity of the system to the load, have resulted in substantial improvements in the coefficient of performance (COP) of these systems. The COP is a function of the difference between the heat source and sink temperatures, and for moderate temperature differences high values of COP can be obtained making heat pumps attractive in terms of primary energy savings compared to other heating equipment.

Because of the flexibility to reverse the refrigeration cycle, many heat pump systems can provide cooling in the summer and heating in winter. When air is used as a heat source, the COP of the system will be a function of the ambient temperature. At low ambient temperatures the evaporator surface temperature will be below 0°C and this will cause moisture condensation and freezing on the evaporator surface. Frost accumulation on the coil will reduce heat transfer performance, and to maintain satisfactory performance at low ambient temperatures the coil needs to be defrosted periodically.

The use of the ground as a heat source can overcome some of the disadvantages of air as the ground temperature beyond a certain depth remains fairly constant throughout the year. At 10m below ground depth in the UK, the ground temperature remains approximately constant at around 10°C. The ground can also be used as a heat sink when the heat pump operates in the cooling mode in the summer. Typical arrangements of a ground heat exchanger for ground source heat pumps are shown in Figure 8.5.

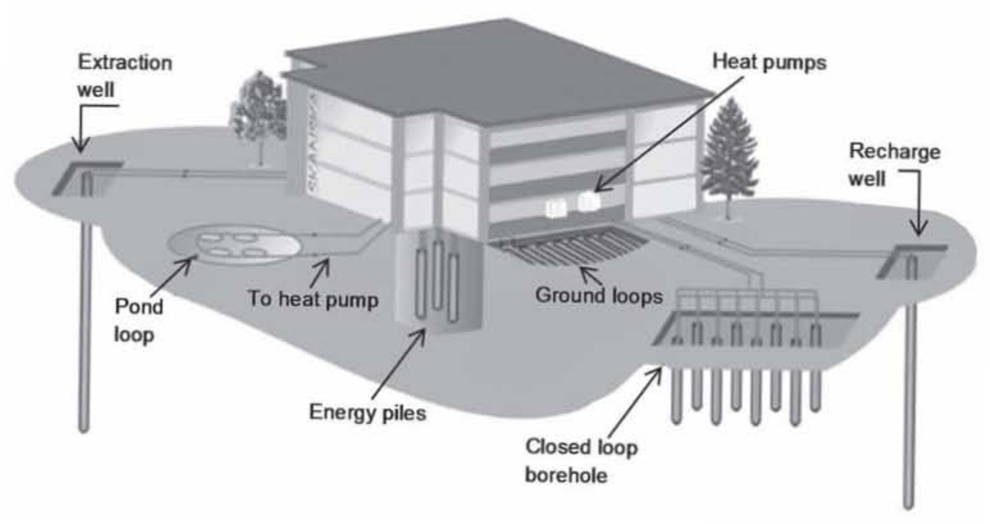


Figure 8.5 Possible arrangements of ground heat exchangers for ground source heat pumps

Source: Geothermalint.co.uk

Ground heat *exchange systems consist of two main subsystems: the ground loop* and the *thermal energy distribution system*. There are two basic types of loops: closed and open. In open-loop systems groundwater is abstracted from an aquifer through one borehole, passed through the heat exchanger and then discharged to the same aquifer through a second borehole some distance away. In the UK, abstraction and discharge of groundwater requires a licence from the Environment Agency. In closed loop vertical systems, water or antifreeze (brine) is circulated through a U-tube in a borehole or a series of boreholes spaced uniformly in a grid. In closed loop horizontal systems the fluid is circulated in a pipework laid horizontally in a trench and exchanges heat indirectly with the ground.

Ground heat exchange systems have been extensively and successfully used worldwide for many years. Most applications have been in North America, Northern Europe and Japan for space heating in the domestic sector in conjunction with heat pumps. There have also been successful applications in the commercial sector in schools, hotels and office buildings. Ground heat exchange systems have been less successful where cooling was the predominant load.

8.5 Solar thermal technologies

Solar thermal technologies transform solar radiation into useful thermal energy. The solar yield replaces conventional sources of heat, mainly fossil fuels or electricity. The simplest way of utilising solar energy for the heating of buildings is through passive means. The primary elements in passive solar heating systems are windows. Glass has the beneficial property of transmitting solar radiation allowing energy from the sun to enter the building and warm the interior spaces. Clearly, the larger the windows the more sunlight will enter the building. Unfortunately, though, windows are not as thermally insulating as the building walls, and a passive solar design will optimise window surface area, orientation and thermal properties to increase the energy input from the sun and minimise heat losses to the outside, while ensuring occupant comfort.

Passive solar heating is best applied to buildings where the heating demand is high relative to the cooling demand. Low-rise residential buildings in moderate to cold climates offer the greatest potential. Passive solar heating is more difficult to apply to office and other commercial or industrial buildings where there are high internal heat gains especially during the day.

An indirect way of collecting and utilising solar energy is through solar collectors which collect solar energy on absorber plates, as shown in Figure 8.6. Selective coatings are often applied to the absorber plates to improve the overall collection efficiency. A thermal fluid absorbs and transfers the energy from the collector plates to a storage tank from where it can be used for domestic hot water heating, space or process heating.

There are several types of solar collectors used to heat liquids. The selection will depend on the temperature of the application being considered and the climate in which the system will operate. Non-concentrating solar collectors are the most common type of collectors and are normally used for domestic hot water applications or space and process heating. Concentrating solar collectors use reflectors to concentrate sunlight onto the absorber area. These collectors are used for high temperature applications and in particular power generation.

Flat-plate collectors can have many different designs but generally all consist of a) a flat-plate absorber which intercepts and absorbs the solar energy, b) a transparent cover that allows solar energy to pass through but reduces heat loss from the absorber, c) a heat-transport fluid flowing through tubes to remove heat from the absorber, and d) a heat insulating backing. An evacuated tube collector differs as it uses a vacuum between the absorber and the glass surface to minimise heat loss.

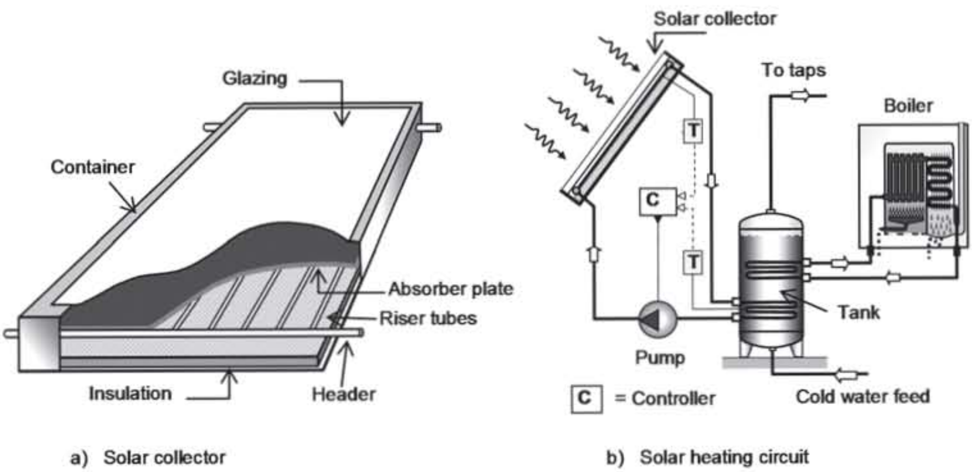


Figure 8.6 Solar thermal heating system

8.5.1 Costs

Investment costs of solar thermal systems consist of the cost of hardware (collector, tank, piping and where appropriate the control unit and pump) and the cost of installation. Solar thermal systems are sold in a wide range of sizes and applications, and the cost of the hardware therefore varies substantially. This also depends on quality criteria. The cost of installation also varies depending very much on the timing; it is much cheaper to install a solar thermal system during the construction or refurbishment of a building than at a later time. For small systems, installation typically accounts for 20–30% of the total investment costs.

The system price for large collector fields (thousands of square metres), as used for industrial process heat or district heating, is approximately £175/m^2.The initial investment constitutes by far the largest part of heat production costs. Modern, good quality solar thermal systems have a lifetime of 20–25 years with very low maintenance requirements. As with investment costs, the final heat production costs vary greatly depending on the type and size of the system, the location, the timing of the installation and several other factors.

Annual operation and maintenance costs are usually below 1% of the investment. The simplest systems hardly require any maintenance; more complex systems need regular monitoring and some maintenance to keep up high productivity throughout their lifetime.

8.6 Evaporative cooling

Evaporative cooling utilises the evaporative capacity of water to cool air supplied to the conditioned spaces. Evaporating cooling can be achieved through direct air cooling, indirect air cooling, a multistage combination of both, or through a combination with existing mechanical refrigeration systems and desiccant technologies.

In direct evaporative cooling systems, water evaporates directly into a supply air stream, producing both cooling and humidification. The principle of operation is shown in Figure 8.7.

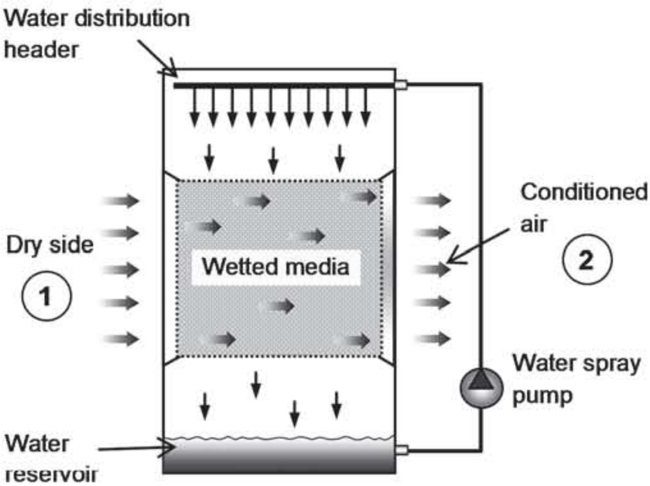


Figure 8.7
Schematic diagram of direct evaporative cooling

Indirect evaporative air cooling evaporates water into a secondary air stream flowing in one direction through channels of a heat exchanger. This sensibly cools a primary (supply) air stream flowing through other channels in the heat exchanger in a crossflow direction to the secondary air, as shown in Figure 8.8. This results in sensible cooling only. The secondary air can be all outside air or all exhaust air, or a mixture of the two. In the case of exhaust air, the same heat exchanger can become a preheater for the outside air in the heating season. Except in extreme dry climates, most indirect systems require several stages to further cool the primary air entering the conditioned spaces.

The psychrometric processes for direct and indirect evaporative cooling are shown in Figures 8.9 and 8.10.

Most common system layouts combine indirect with direct evaporative cooling. When lower design temperatures are required than those available from indirect/direct cooling, a third cooling stage may be used, provided by a small-sized refrigerative direct expansion or chilled water coil as shown in Figure 8.11.

In direct, indirect or indirect/direct stage systems, the capability of cooling relies on the outside air climate. In general, some benefits of evaporative cooling technology are:

- providing comfort cooling in arid and semi-arid regions or relatively dry environments;
- improved indoor air quality by introducing high ventilation rates, diluting certain indoor airborne contaminants;
- easily combined with existing air-conditioning systems, integrated with other cooling technologies or operated with heat recovery.

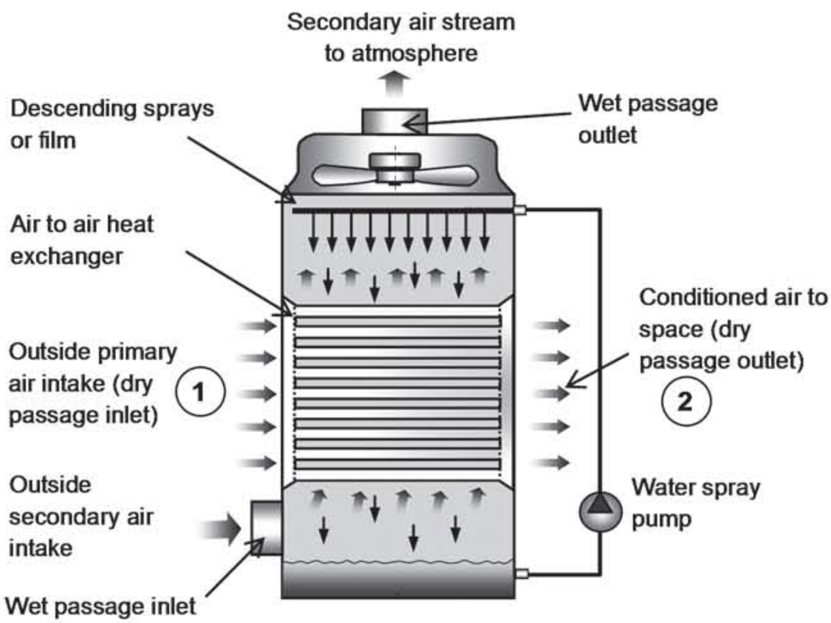
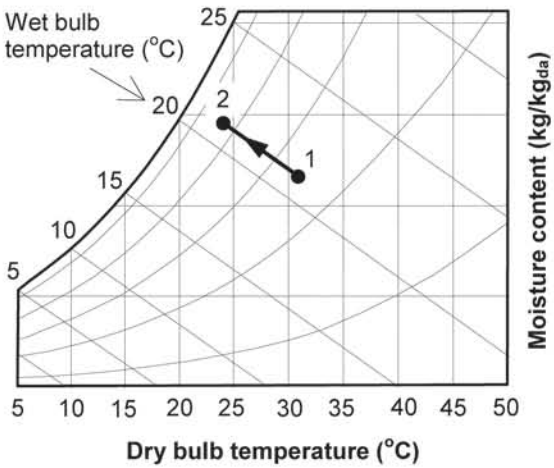


Figure 8.8 Indirect evaporative cooling system

Figure 8.9
Psychrometric process of direct evaporative cooling



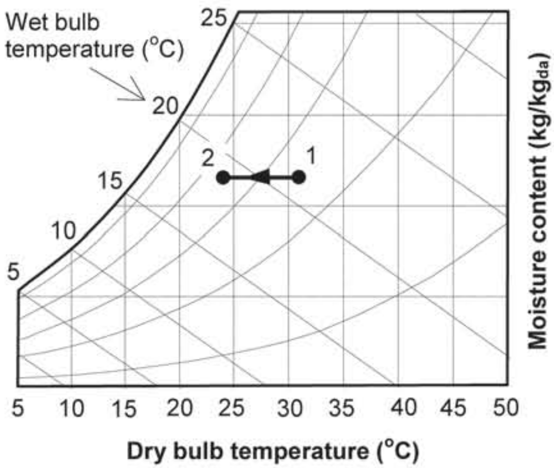


Figure 8.10
Psychrometric process of indirect evaporative cooling

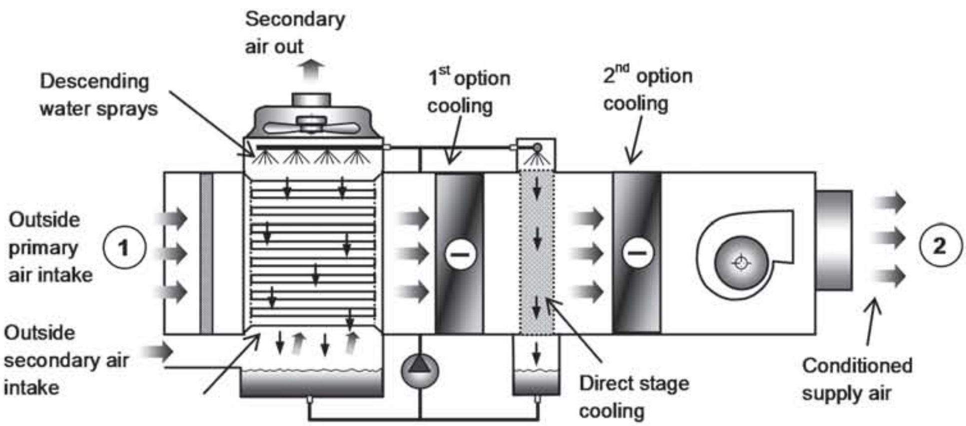


Figure 8.11 Indirect/direct evaporative cooling diagram

Applications and performance

Evaporative cooling is effectively employed in arid climates. It can provide relief as well as comfort cooling, depending on regional weather conditions and types of building. In very humid areas or when a lower supply air temperature is specified, there are several approaches, such as integration into other cooling systems or multi-stage evaporative cooling. Applications can be found in industrial, commercial and residential buildings. Some examples are factories, power plants and warehouses.

Direct evaporative cooling systems are used in residential cooling applications. The once-through airflow principle is normally employed without air recirculation.

Indirect or indirect/direct evaporative cooling systems can be coupled to central fan systems for humidity control in commercial buildings. Also, because of the constant moisture content of indirect evaporative cooling, the principle can be used to pre-cool without the addition of water moisture. The effectiveness of indirect systems can be in the range between 50 and 70%.

Table 8.1 shows the performance of evaporative cooling systems for selected locations around the world. The assumptions are: 65% of cooling effectiveness for the indirect systems and 85% for the direct systems (Foster 1996).

Since evaporative cooling systems use evaporation of water to cool large quantities of ambient air, they work best in arid regions where water can be very expensive. Water usage is highly dependent on the airflow, the effectiveness of the wetted media, and the wet-bulb depression (ambient dry-bulb temperature less wet-bulb temperature) of the intake air.

Table 8.1 Evaporative cooling performance for selected regions

Locations	*1% design DB/WB temperature (°C)*	*Direct supply air DB temperature (°C)*	*Indirect/direct supply air DB temperature (°C)*
Asia/Pacific			
Alice Springs, Australia	39.4/20.0	22.9	17.6
Christchurch, New Zealand	27.8/17.8	19.3	16.4
Middle East			
Riyadh, Saudi Arabia	43.9/20.0	23.6	17.1
Jerusalem, Israel	33.3/17.2	19.6	15.0
Africa			
Cairo, Egypt	38.9/23.3	25.6	22.1
Casablanca, Morocco	34.4/21.1	23.1	19.0
Europe			
Madrid, Spain	35.6/20.0	22.3	18.2
South/Central America			
Santiago, Chile	32.2/19.4	21.4	17.9
Caracas, Venezuela	28.9/20.6	21.8	19.7
North America			
Las Vegas, Nevada, USA	42.2/18.9	22.4	16.1
Mexico City, Mexico	28.9/15.6	17.6	13.9

Source: Foster 1996

The energy savings of evaporative cooling over conventional cooling systems will depend on the climatic conditions and the type of evaporative cooling system employed. Experimental observations for Dallas, Texas, showed that the seasonal energy efficiency ratio (SEER) of an indirect evaporative cooler could be 70% higher than that of a conventional air-conditioning system and that it could displace nearly 12% of the conventional air-conditioning capacity (Hunn and Peterson 1991). The two-stage systems can provide energy savings in the order of 80% in very dry regions, to 20% in humid regions. Where the mean coincident wet-bulb design temperature is 19°C or lower, the average annual cooling power consumption of indirect/direct systems may be as low as 0.06kW/kW; if the wet-bulb temperature is as high as 23°C, an indirect/direct system can offer an average annual cooling power usage in the order of 0.23kW/kW. By comparison, the power consumption of a conventional air-conditioning system utilising air-cooled condensers can be greater than 0.28kW/kW (ASHRAE 2011). Further energy cost advantages can be obtained when the indirect/direct system is employed in the heat recovery mode.

8.7 Desiccant cooling

Desiccants can be solid or liquid materials that can dry either liquids or gases, including ambient air, and can be employed in many air-conditioning systems. To demonstrate the principle of operation, a typical solid desiccant cooling system is illustrated in Figure 8.12 and the psychrometric cycle in Figure 8.13.

The ambient air (point 1) is first dried as it passes through the dehumidifier where it comes into contact with the matrix surface which is coated with a solid adsorbent. The air is heated up during the adsorption process. Then the air passes through a heat exchanger where it transfers heat to the regeneration air and its temperature is reduced. The precooled dry air then passes through an evaporative cooler where it is cooled and humidified before it is supplied to the conditioned spaces (point 4). Because of the direct removal of moisture from the air without cooling it, this technology can perform independent control of humidity (latent cooling) and temperature (sensible cooling) if desired, and reduce a large portion of the cooling load and the size of the air-conditioning system.

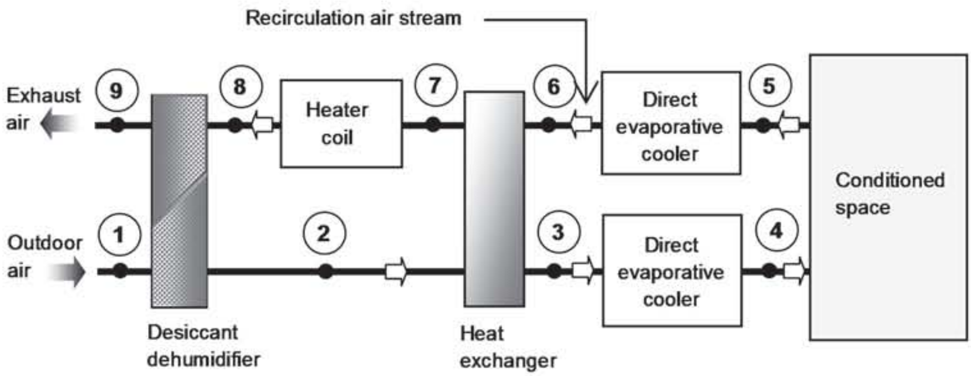


Figure 8.12 Schematic of a solid desiccant cooling system

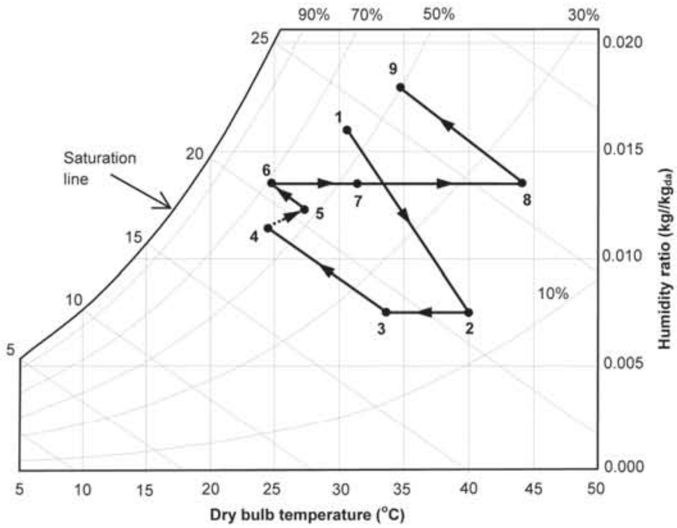


Figure 8.13 Psychrometric diagram for the solid desiccant cooling system

Solid desiccants include silica gel, zeolites, molecular sieves, calcium bromide, lithium chloride, lithium bromide, carbons, activated aluminas, titanium silicate and polymers. Polymer materials have some commercial potential and are regarded as advanced desiccants for the future. Solid desiccants can be non-regenerated, disposable packages; periodically regenerated cartridges; and continuously regenerated. The selection is dependent on the size of the moisture load and the application. Rotary solid desiccant systems constitute the most common arrangement in the continuous removal of moisture from the air. The desiccant wheel rotates through two separate air streams: the process air is dehumidified by adsorption, which does not change the physical characteristics of the desiccant, while the reactivation or regeneration air, which is first heated, dries the desiccant.

For liquid desiccant systems, the moisture is removed by absorption, through spraying a concentrated solution of desiccant into the incoming air. The diluted solution is then passed over the recovery units where it is heated by a return air stream, reconcentrating the liquid desiccant to absorb moisture again. Liquid desiccants in common use are triethylene glycol and solutions of lithium chloride and lithium bromide (Pearson 1997).

In practice, the adsorption performance of solid based desiccants can be controlled by their total contact area, the total volume of their capillaries, and the range of their capillary diameters. The absorption of liquid desiccants can be regulated by their concentration, their temperatures, or both.

The benefits of desiccant cooling technology are:

- ability to maintain lower humidities or satisfy high latent loads;
- indoor air quality can be improved by handling large quantities of fresh air, drying the process air, removing certain airborne contaminants and minimising health risks;

- ability of using various energy sources such as waste heat, solar power and natural gas;
- reduction or elimination of the use of hydrofluorocarbon (HFC) refrigerants;
- independent temperature and humidity control.

Applications and performance

Desiccant based systems have been employed in industry for over 50 years but have only recently been developed for HVAC systems for commercial and residential, as well as for new and retrofit, applications. Other uses showing promise include supermarkets, retail stores, restaurants, hotels, hospitals, etc. Thermal sources most widely used for desiccant reactivation in the market are gas, condenser heat and solar energy.

Starting from the Pennington cycle in 1955 (Figure 8.12), several configurations have been developed together with various definitions of the thermal COP, which is used to evaluate the performance of alternative designs. In general though, the COP of this technology is around 1.0. Heat sources for regeneration can be solar energy, heat pumps and gas-fired systems. Electricity is still necessary to rotate the desiccant wheel, fans and pumps. The energy performance is highly dependent on the system configuration, geometries of dehumidifiers, types and properties of the desiccant material, degree of desiccant degradation, etc.

The economics of desiccant applications depend largely on the energy cost savings in dehumidification and the relative utility charges for gas and electricity. Depending on the installation location, the application and relative energy costs, paybacks of three to five years have been reported for dehumidification applications.

The life of a desiccant cooling system primarily relies on the life of the desiccant itself and is a function of the material, the manufacturing process and the application. The life of commercial desiccant materials can be between 10,000 and 100,000 hours. Manufacturers normally anticipate 10–20 years' plant life (ASHRAE 2009).

8.8 Slab cooling

Slab cooling can be classified as a thermal storage system. The technology provides short-term storage and sensible cooling only, but it has greater potential for either the cooling or heating of buildings in moderate climates. Using the building's thermal mass as the storage medium, cooling or heating is implemented by bringing air (the approach in Figure 8.14) or water (the approach in Figure 8.15) into contact with the slabs in the building envelope. The slabs can be the floors, walls or ceilings. At present, most systems utilise floor and ceiling slabs.

8.8.1 Air slab cooling

During the summer, cool night outdoor air is brought into contact with the slabs (Figure 8.14) at low velocity before entering the occupied space, cooling down the slabs. During the day the cooling energy stored in the slabs is used to cool the air supplied for day ventilation.

During winter, the outdoor air can be heated up and then brought into contact with the slabs at night. The heat energy stored in the slabs is then used to warm the supply air to the indoor spaces in the daytime.

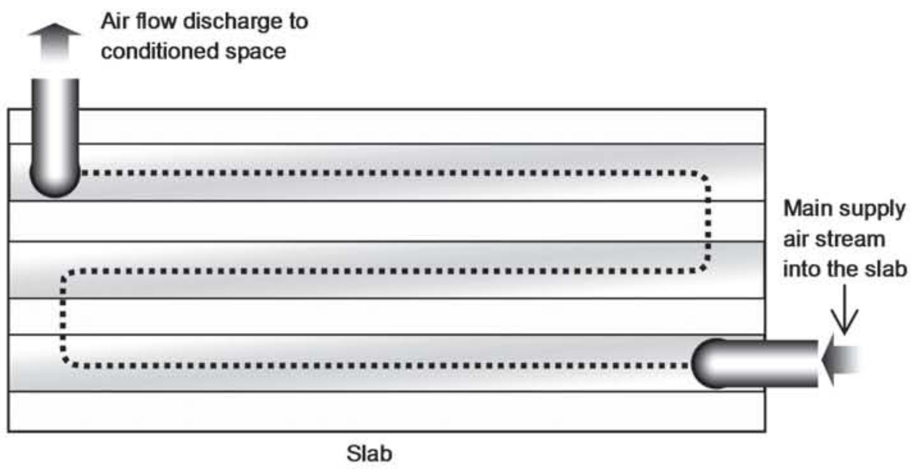


Figure 8.14 Schematic diagram of air slab cooling

The fabric energy storage (FES) slab (trade name: TermoDeck) is the most widely used system. It is a prefabricated rectangular concrete block 1200mm wide with a variable length/depth determined at the design stage. Each block contains a minimum of three and a maximum of five cores of sufficient size and shape to allow the required air volume through one inlet hole. The air path is established by interconnecting the hollow-core slabs and the cooled or heated air is discharged via ceiling diffusers to the indoor spaces.

In general, the merits of the air slab cooling technology are:

- reducing or eliminating mechanical cooling
- use of off-peak electricity
- avoidance of suspended ceilings
- low capital and operating cost
- high levels of human comfort.

The drawbacks are:

- slow thermal response to indoor variations in load
- possibility of air leakage at connections between cores
- extra access holes may be required for maintenance of dead regions at the core junctions.

Applications and performance

The technology is not suitable for regions where high levels of humidity control are required, as it provides sensible cooling only.

As with the night cooling technology, the potential of slab cooling is highly dependent on the level of overnight ambient air temperatures. For applications in the UK climate, this should not be a severe problem. Recent research in the field has found that the bulk temperature of the concrete slabs appears to remain within the accepted range under a daily maximum air temperature of 28°C. Overcooling can be avoided by introducing appropriate night control strategies.

Since the channels of the FES slabs are used as air distribution ducts, the system pressure drop should be minimised. The system would still require space for air terminal devices in conditioned rooms and air-handling units in the plant room.

Apart from the integration with mechanical supply and exhaust ventilation night cooling, air slab cooling can work with evaporative cooling and displacement ventilation.

From past experience with TermoDeck, the cooling load applicable to air slab cooling technology is around 40 W/m^2 without exposing the lower slab surface to the indoor air, and 60 W/m^2 with the lower surface exposed. The COP (night cooling/fan energy) of slab technology is strongly dependent on system pressure loss. Typical COP values of 2.5 and 3 have been estimated for pressure losses of 1,000 Pa and 100 Pa respectively. High pressure drops can also induce fan heat pick-up that will subsequently lower the cooling capability.

The air slab technology also provides flexibility to work with other technologies, like natural, mechanical or mixed mode ventilation cooling and evaporative cooling.

Costs

This technology is an integral part of the building structure in which the slab channels serve as air distribution ducts. In addition to short-term cooling storage, the advanced FES slab cores have been used for heating energy storage and accommodating the utility services such as water pipework and electric cables. As the advanced FES slabs are mainly prefabricated concrete blocks, a large portion of the installation costs related to the ductwork system is transferred to the builder's work accounts which may need skilled labour, special handling equipment and may have to deal with safety issues during system construction. Although the capital cost of the FES slab technology is difficult to establish in the traditional sense, when directly compared to the capital cost of conventional air-conditioning systems it should be less.

Because the characteristics of FES slabs can allow the use of off-peak electricity at night, energy savings are greatly dependent on the quality of slabs, overnight climate, air flow rates and control strategies. The life span of FES slab cooling systems is normally expected to be equivalent to that of the building.

8.8.2 Water slab cooling

Similar to the principle of the air slab cooling technology, where the thermal storage features of the building mass are utilised to provide cooling in the summer and heating in the winter, a water slab heat transfer system relies on the mechanism of temperature difference between circulating water and the slab. The technology employs embedded water tubing or attached piping in the slab where surface temperatures are maintained by circulating water. The water pipework can be in a layer of screed of about 75mm thick or a layer of solid concrete slab exposed to the conditioned space as shown in Figure 8.15 (ASHRAE 2012b). The cooling source for the embedded water circuit can be:

- a heat pump with a reversing cycle
- a heat exchanger
- a chiller.

The merits of water slab cooling can be:

- reduction or elimination of mechanical cooling
- the use of off-peak electricity
- low capital and operating cost, if radiant heating is employed.

The drawbacks are:

- possibility of water leakage at embedded piping connections under cyclic cooling and heating during interseasonal changes
- difficulty in replacing damaged embedded pipework due to corrosion and erosion problems.

The cooling capability of this technology is approximately between 30 W/m^2 and 50 W/m^2 with cooling water temperatures of about 19°C and occupied space temperatures of less than 28°C.

8.9 Thermal energy storage with phase change materials

Slab cooling systems utilise the sensible heat principle to store thermal energy in the building fabric. With sensible thermal energy storage, however, the quantity of energy that can be stored is limited by the specific heat capacity of the material used. An order of magnitude increase in thermal energy storage capacity can be achieved if the energy is stored and released by materials during phase change, i.e. freezing or melting. Apart from their high thermal energy storage capacity, phase change materials (PCMs) also offer the advantage of near isothermal energy discharge.

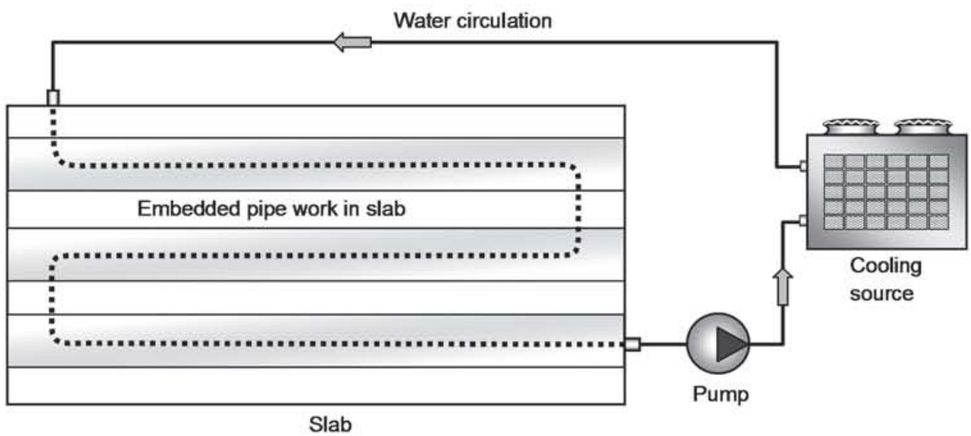


Figure 8.15 Schematic diagram of water slab cooling

Ice has been employed as a phase change material for air-conditioning applications for many years. A variety of storage methods are available, including encapsulated ice storage systems where water is stored in small polymeric vessels which are placed in tanks through which a secondary fluid circulates alternately freezing and melting the water in the vessels; ice on coil systems where coils are immersed in tanks of water and a secondary fluid flows through the pipe forming ice on the coil; ice harvesting systems where the ice forms on plate or circular tube evaporator coils to a thickness of 6–10mm, melted through a coil defrost system and then gathered in a storage tank below the coil; and ice slurry systems (ASHRAE 2012c).

An ice slurry is a mixture of ice 'micro-crystals' (typically 0.1–1mm in diameter) formed and suspended within a solution of water and a freezing point depressant. The ice slurry can be formed by a variety of methods, including scraped surface generators, direct contact generators and supercooling generators. The slurry can be stored in tanks and used as a static storage medium. It can also be pumped and used as a secondary two-phase heat transfer fluid in heat exchangers (IIR 2005). The high energy content of the slurry allows significant reductions to be made in the size of pipes and storage tanks compared to single-phase energy storage and heat transfer with water. A number of energy storage applications of ice slurries are described by Bellas and Tassou (2005).

One disadvantage of ice thermal energy storage is the narrow temperature range of operation, around 0°C, and the significant change in volume with the change of phase from liquid to solid. A number of other PCM materials have been investigated in recent years for thermal energy storage at temperatures both below and above 0°C. The most common of these materials can be classified into two groups: organic and inorganic compounds. Inorganic materials such as hydrates and eutectics have low cost but exhibit problems of phase separation, incongruent melting, and subcooling or superheating. To overcome these problems these materials are normally packaged in small capsules (0.02–0.1m diameter) and are referred to as encapsulated PCMs. Organic materials such as alkanes, waxes and paraffin do not have the disadvantages of organic materials but have lower thermal conductivity, higher cost and can be flammable.

Significant research has been conducted on PCMs for the space heating and cooling of buildings in recent years but at present there are only a small number of demonstration systems in use and limited experimental data from real installations. By embedding PCMs in gypsum board, plaster or structural elements such as the floor or roof, the building can store large amounts of energy while maintaining the indoor temperature within a relatively narrow range (Sharma *et al.* 2009).

8.10 Summary

In this chapter we have considered a number of approaches that can be employed in isolation or in combination with traditional technologies to satisfy the heating and cooling requirements of commercial buildings. One such low energy technology that can be employed to provide both heating and cooling is the heat pump. Heat pumps remove thermal energy from a low temperature source and supply it to a higher temperature sink. In recent years the ground has become a popular energy source for space heating as well as a sink for heat rejection due to its relative constant temperature throughout the year. Heat pumps can also be used to recover and upgrade heat from the exhaust air from buildings. Other thermal energy recovery systems include fixed plate and rotary heat exchangers, run-around coils and heat pipes.

A number of low energy cooling technologies can also be considered alongside or in place of conventional refrigeration technologies in appropriate climatic conditions. These include evaporative cooling as well as desiccant cooling. Thermal energy storage can also provide a means of reducing peak heating and cooling loads and shifting these loads to off-peak periods where the cost of electricity and environmental impacts may be much lower than in peak demand periods. Energy can be stored in the building fabric or in specially designed thermal stores that employ single-phase or two-phase fluids as storage media. Examples of these are water, ice and ice slurries. In recent years, a number of organic and inorganic compounds have also been developed and applied for thermal energy storage in the building fabric.

Chapter 9

Energy efficient electrical systems, controls and metering

9.1 Introduction

This chapter describes some of the key design features that can reduce carbon emissions arising from the main energy consuming electrical systems, together with the controls and metering systems that can enable energy management across all active building services systems. As with thermal systems, the desired carbon reduction features are a mix of those that control demand to achieve comfort or function; those directly related to minimising losses in distribution between plant and terminal devices; and accepting that there is some overlap between these. The key design decisions are always related to selection of appropriate systems, equipment and distribution arrangements; and inclusion of features to limit demand to that necessary to achieve the required criteria at any point in time.

It must be emphasised that the primary consideration when designing power systems is always to address the safety aspects, and design in accordance with the relevant codes and regulations, such as BS7671 (2008). This will include design considerations such as current-carrying capacity; voltage drop; overload, overcurrent and earth-fault protection; discrimination, or selectivity, of circuit protective devices; disconnection time; and earthing and bonding. The energy efficiency aspects covered here should be considered alongside design to achieve code compliance.

9.2 Energy efficient power distribution arrangements

9.2.1 Optimising substation locations

A brief outline of the typical arrangement and principal components in a building's power distribution system is provided in Chapter 11.

As outlined in Chapter 3, key design measures for reducing carbon emissions in any system are the location of main plant items close to the principal load centres and energy efficient distribution. The primary energy carbon factors for fuels in the UK were outlined in Chapter 1. It is clear that, based on the present UK generation mix of fuel sources and technologies – and that anticipated in the near term – carbon emissions per unit of delivered energy using electricity are considerably higher than those for other fuels. The same is true for many other countries with a similar generation mix. As such, any power distribution arrangement that can minimise energy losses will have a major beneficial impact on the overall carbon performance. For large sites and systems, with widely dispersed loads, the most important design consideration is to plan the location of the substations on the site so that they are close to the main load centres. This will mean that the lengths of low voltage (LV) distribution cables are kept short, thereby reducing I^2R power losses on cables. Where a single substation is to be provided for a group of buildings on a site, the location should be the optimum for minimising losses taking into account the load profile for each building.

The selection of a location for a substation must take account of many factors, including the generic issues for space planning outlined in Chapter 12. The sizing of the distribution cabling will take into account the relevant electrical design factors, including protective device rating, design current, prospective fault level and voltage drop; together with any group rating applicable to the relevant installation arrangement. However, for optimum energy performance, the location should be selected so that energy losses on the LV distribution systems are minimised. This is a different (although similar) approach to optimising substation location by reducing losses solely in relation to the maximum demand at each load centre. Because loads are dynamic, it is the summated load profiles over a whole year – taking account of the diurnal and seasonal load patterns – that are important. The situation is, of course, more complicated because the losses are proportional to the square of the load. The only way to obtain a complete figure would be from computer modelling with a full annual load pattern.

To minimise carbon impact, transformers should, ideally, be selected to achieve optimum energy efficiency for the anticipated duty cycle and foreseeable load growth; however, transformer selection is a complicated issue. The step-down HV/LV transformers will have losses, which can be separated into iron (no-load) losses and copper (running) losses. For most modern transformers the full load losses will be about 1–2%. However, the value of total losses, and the proportional split between iron and copper losses, will vary between transformer types. The operating efficiency will be a function of the losses and the load profile and could be determined by calculation from published losses for different levels of load. In its simplest sense, where the transformer will be running on low load for much of the time, the iron loss value becomes more important; and where the transformer will be running on a low load for a minimal amount of time, the copper loss value becomes more important. It is not the case that transformers are most efficient at full load, as the optimum efficiency point can sometimes be at about two-thirds of the rated load; so transformers might have to be somewhat oversized (Court 2011). This aspect of the transformer rating selection cannot be considered in isolation, but must be considered alongside other aspects, including prospective fault level, physical size, cost and the criteria for resilience and redundancy. It should also consider the level of harmonics present in the load and a sensible longer-term margin for load growth.

Sung *et al.* (2011) describe a 'whole-life total ownership cost' approach for different power distribution arrangements.

9.2.2 Optimising LV distribution arrangements

As well as optimising substation locations, the lengths of LV cables from the transformer to the main LV switchboard, and from the main LV switchboard to distribution equipment, motor control centres and other items, should be kept to a minimum to limit the losses. This will require attention to the distribution routes as part of the space planning exercises described in Chapter 12. It is also useful to consider the arrangement of LV distribution components in relation to both operational and embodied energy.

Distribution components used for LV mains and sub-mains power distribution – cables and busbars – can be represented by resistance of the conductors, plus, to a lesser extent, reactance. The resistance will reduce if the temperature is lower and will increase if the temperature is higher, so the I^2R power loss will increase as temperature increases. Therefore, a cable can carry more current in a lower ambient temperature and less current in a higher ambient temperature. To make the most efficient use of the cost and embodied energy in the distribution system, any factors that will limit the cable or busbar current-carrying capacity should be avoided. So, first, as a simple and fairly obvious measure, power distribution should be routed away from areas of high ambient temperature.

It is common practice to group power cables on cable ladders, cable trays, in ducts and so on, to make economic use of the cable management system and to reduce the space required. There are various standard installation arrangements for cables that are touching or spaced apart. To take account of the influence of heat emitted by adjacent cables on the rating of an individual cable, a group rating factor (always less than unity) is used as a multiplier to determine its current-carrying capacity. Thus two detrimental energy issues arise from a group of cables touching, or any other arrangement that increases the ambient temperature for cabling. First, the cable in question is likely to have a higher power loss per unit length; and second, the current-carrying capacity of all of the cables in the group will be reduced. Although these are interrelated, they are better seen as separate issues. The first is an operational energy issue and will increase carbon emissions per unit of useful energy consumed by the loads. The second is an embodied energy issue, as it will result in an unnecessary additional embodied energy (and capital cost) in the cabling system. In general, better energy utilisation can usually be achieved by spacing cables further apart.

A balance has to be made, however, between the additional one-off capital cost and embodied energy associated with an increase in materials for cable tray/ladder, and the ongoing operational energy impact. This is mainly a consideration for larger groups of larger-sized cables that will be carrying significant loads for long periods of time, where it is worth making an engineering judgement on the cable management arrangement. More generally, it is good design practice to keep loads balanced across phases and provide a symmetrical arrangement for single core cables.

There has been much recent interest in the energy benefits that might be available from adjusting the voltage level at the origin, or at other locations, in an LV distribution system through incorporation of 'voltage optimisation' equipment. While lowering the voltage could, potentially, save energy in certain types of loads in some legacy installations, it could give rise to risks and may not be the most appropriate energy reduction approach (Court 2011). Such measures always require careful technical assessment to assess their viability.

There has been relatively little research or monitoring on the proportion and pattern of energy losses arising from power distribution in buildings, but this is clearly a worthwhile area of research to inform design decisions.

9.2.3 Power factor correction and harmonic filtering

It is normally the case that the loads within buildings will have a variety of levels of reactance, and hence a variety of power factors. Some of the larger magnitude loads – such as those for the induction motors associated with chillers, pumps and fans – will be inductive and have lagging power factors. As a result, the overall power factor will tend to be lagging.

For power distribution losses to be minimised, power factors should be close to unity, so that the magnitude of current (and hence I^2R losses) is close to the theoretical minimum for the value of 'real' power flow. Power factor correction (PFC), using capacitor banks with automatic switching in stages, is a well-established technology that offers a simple way to reduce energy losses in a distribution system. Correction can be applied at main switchgear and/or at appropriate load centres to reduce current and thus I^2R power losses in cables, busbars and transformers. In reality, there are diminishing economic returns as power factors are corrected close to unity. While each case has to be assessed separately, there is often a strong environmental case for power factors to be kept at about 0.95 lagging. In Part L2A, PFC is recognised as an enhanced management and control feature.

In the UK, electricity suppliers normally encourage customers to maintain high power factors, typically no lower than 0.95, and customers can be charged for reactive power when the average power factor is less than 0.95 lagging. Reactive power changes are for excessive kVArh (typically based on a one month period). There is usually an 'availability' charge based on the contractual reserved (or authorised) supply capacity in kVA. The cost payback will vary depending on the load pattern; but it can be low, typically in the order of 1.5–2.0 years.

The benefits of reducing the kVA load are:

- lower energy costs and reduced carbon emissions, due to lower distribution energy losses;
- an increase in the efficiency of the supplier's distribution system due to better usage of the cost and embodied energy, and less need for infrastructure upgrade. This means that the consumer can prevent the potential business impact that could arise from insufficient service capacity.

Figure 9.1 shows typical locations for PFC equipment in an LV distribution system. Where multiple motors are fed from a motor control centre, but only a proportion of the motors will run at any one time, the most beneficial arrangement is likely to be common multistage PFC located at the motor control centre. Ideally it should be sized to provide correction for the maximum cumulative reactive power of the motors, with switching in equal stages to match the load variation. In these cases there would be no benefit in providing a separate PFC for each motor. For large individual motors, such as chiller compressors, a separate local PFC cubicle can be provided for each chiller machine (or this may be integral), sized specifically to provide the required correction and only operating when the chiller operates.

The selection of PFC equipment should not be considered in isolation, as it needs to take account of the presence of harmonic currents. The types of non-linear power loads in buildings that can give rise to harmonic currents are outlined in Chapter 11. Harmonics can have a detrimental carbon impact in two ways:

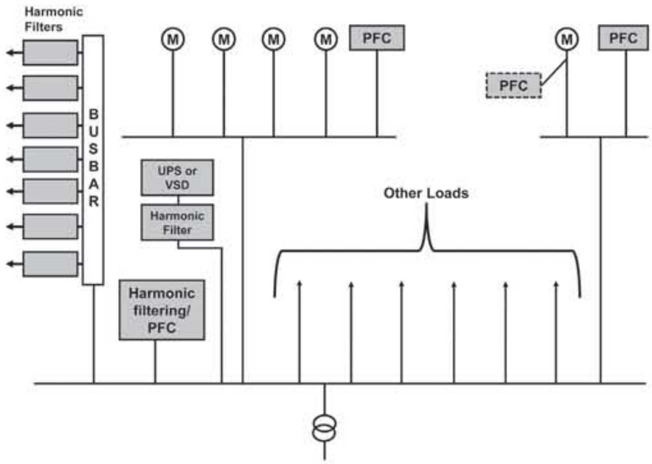


Figure 9.1 Typical locations for PFC and harmonic filtering equipment

- equipment will need to be sized for increased capacity, resulting in an increase in embodied energy (and cost);
- an increase in distribution energy losses in cables, busbars, switchgear and transformers.

The extent to which harmonics will have an impact will depend upon the magnitude and the harmonic pattern or signature. The most appropriate approach is to reduce the level of harmonics at source. There are methods for reducing the level of harmonics, including filtration equipment, that can (and in many cases should) be incorporated at suitable parts of an installation. It is always preferable to reduce harmonics rather than having to design oversized system components (with the resulting embodied energy and cost) to address their impact.

In the UK, regulations are in place to limit the impact of an electricity consumer on the power quality of the supply to other adjacent consumers. The limitations relate to the point of common coupling, which is the point in the public supply system nearest to the consumer (in the electrical sense), at which other customer loads could be connected. If a building has multiple LV supplies (as is sometimes the case for large buildings in city centres) each supply will have its own point of common coupling. Harmonics can cause problems with capacitors resulting in overheating, over-voltage and failure. If resonance occurs at a harmonic frequency (say 5th or 7th) the magnitude of the harmonic current (and hence voltage) will be magnified. Problems often arise from the magnitude of the 5th harmonic (ABB 2010). Therefore where non-linear loads are significant, PFC capacitors should be combined with harmonic filters.

Passive harmonic filters are normally selected so that they are de-tuned (i.e. the tuned frequency is below the frequency of the lowest order harmonic generated) so that the magnitude of 5th, 7th and higher harmonics are reduced (ABB 2010). This can improve the power factor. Active filters work on the principle of an active device generating harmonics that are equal and opposite in value to those generated by the non-linear load; and injecting these between the supply and the load. This results in cancellation, so that the current waveform from the supply to the point of filter connection contains the fundamental component only. This approach can also contribute to balancing the loads. Active and (de-tuned) passive filters are often used in combination (ABB 2010). Other solutions are available for different harmonic patterns, such as isolating transformers. These and other technical aspects of PFC and harmonic filtration selection require detailed assessment and reference to specialist equipment suppliers.

Figure 9.1 shows typical locations in a system where PFC and/or harmonic filtering are regularly used. It should be understood that, while the use of filters at the main LV switchboard might be necessary in order to meet regulatory criteria, it will only reduce energy losses on the supply side. Filters should be located as close to the load as possible to reduce losses in the internal LV distribution,. They can be provided for individual distribution boards feeding loads with significant harmonic content. Suitable space should be allocated in planning for the required PFC and/or harmonic filtering equipment. In cases where the nature of the load pattern is less certain, it can be prudent to allocate provisional space and undertake post occupancy measurements to determine the specific requirement. This can be particularly useful in situations such as multi-tenanted high rise buildings.

The widespread usage of variable speed drives (VSDs) (described in Section 9.3) is likely to reduce the need for PFC (as the drives will have power factors close to unity) compared with conventional drives. But it is likely to increase the need for active filters to counteract the harmonics arising from the drives.

9.3 Motor power for fans and pumps

In buildings with air conditioning or mechanical ventilation, the motors driving fans and pumps are likely to be responsible for a significant proportion of carbon emissions; they are therefore a major focus for energy efficiency. Because fans and pumps are components of HVAC systems, it is necessary to understand how both the mechanical and electrical aspects contribute to energy consumption, and identify the key measures that can reduce energy usage. It is useful to consider the whole-system approach, as outlined by Stasinopoulos *et al*. (2009).

Figure 9.2 shows a typical power balance Sankey diagram covering components from electricity generation to the fan or pump. There are serial efficiencies for each component that must be considered in determining the primary power requirement or energy to deliver power to the air or fluid from the fan or pump. This simplistic representation, with the whole of the electricity transmission and distribution losses conveniently lumped together (shown here for convenience as a transformer symbol), indicates that the primary power (which relates to the fuel input and hence CO_2 emissions) could be about five times the actual power imparted to the fluid stream. It should be noted that the efficiencies in this diagram could be considered to be optimistic, and in many older installations the overall efficiency could be much lower. Moreover, there will be additional losses in the fluid system that will further reduce the useful power delivered (von Weizsäcker *et al*. 1998). From this awareness, any improvements in the efficiency of motors can provide significant benefit. There are international classifications for LV motors, together with standard methods for calculating efficiency. A motor's efficiency can be defined as:

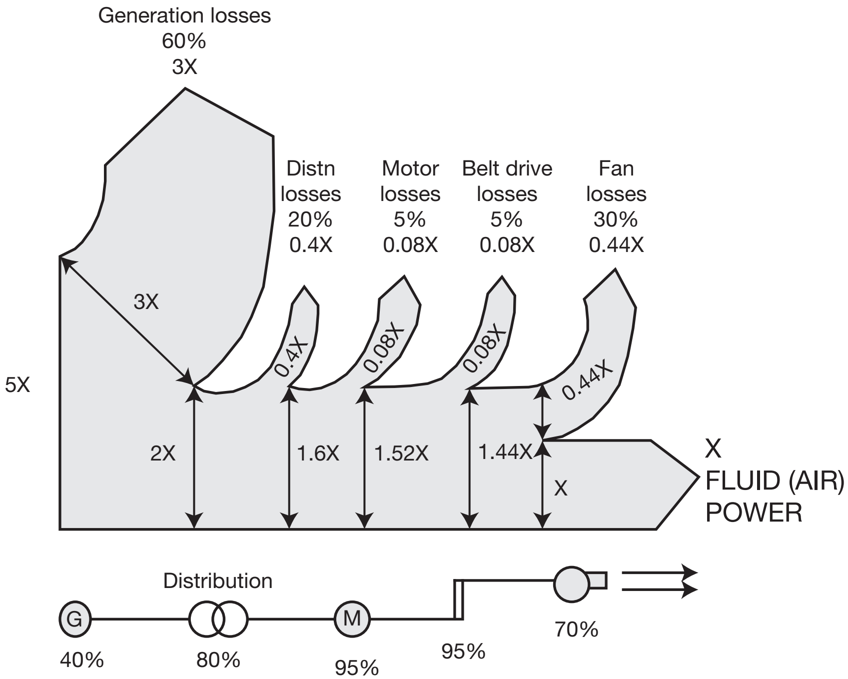


Figure 9.2 Sankey diagram for power to a fan or pump (not to scale)

$$\textit{Motor efficiency} = \frac{\textit{mechanical output power at the shaft}}{\textit{electrical power input to motor}} \tag{9.1}$$

The three international classes for the efficiency of motors are:

- IE1: standard efficiency
- IE2: high efficiency
- IE3: premium efficiency.

In the EU, proposed legislative changes under an EU directive on energy-related products will set criteria for the energy efficiency of circulating pumps and motors. This legislation will require that LV motors (of 2, 4 and 6-pole construction), within the range 0.75kW to 375kW must conform to IE2. Further improvements are due to be implemented in 2015, with IE3 required for fixed speed motors above 7.5kW; or IE2 if equipped with a VSD. Selection of the IE3 standard for a motor will provide the best efficiency, but should be considered in the context of cost and savings for the particular application, and may not always be justified.

The efficiency does not vary significantly between 50 and 100% of the load, but falls considerably below 25% of the load. The power factor also reduces at low loads. Motors should, therefore, not be significantly oversized for the required duty (CIBSE 2004a).

Hour	1	2	3	4	5	6	7	8	9	10	Average
Flow rate (%)	100	90	70	55	40	30	30	32	38	45	53·0
Energy consumption (%)	110·0	82·9	42·3	23·6	13·4	9·7	9·7	10·3	12·5	16·1	33·1
Energy saving (%)	−10·0	17·1	57·7	76·4	86·6	90·3	90·3	89·7	87·5	83·9	66·9

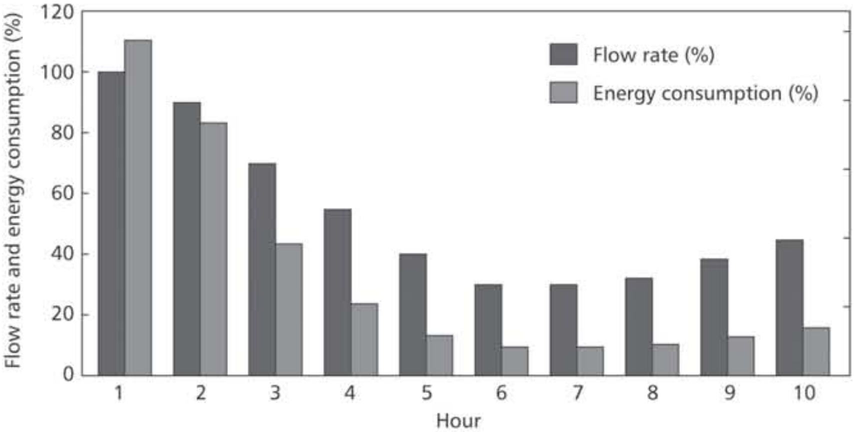


Figure 9.3 Typical savings from a variable speed drive pump

Source: reproduced from CIBSE KS14 (2009a) with the permission of the Chartered Institution of Building Services Engineers

The fluid power requirement necessitates that, as a minimum, fans and pumps should have high efficiency, plus appropriate and rigorous time control arrangements to suit occupancy, in order to manage the demand. The power requirement is the product of flow rate and pressure. Under the fan/pump laws, there is a cubic relationship between flow rate and motor power. Therefore, any reduction in the flow rate will significantly reduce the power consumption. Figure 9.3 shows a range of flow rate and energy consumption percentages for a pump for different hours of operation. This illustrates the considerable energy saving possible by reducing the flow rate. For example, it can be seen that by reducing the flow rate to 30%, the energy consumption can be reduced by 90%. VSDs using inverters have become a standard feature for variable flow systems. They eliminate the inefficiency of belt drives and improve overall efficiency by continually adjusting to balance flow rate against demand. VSDs sometimes have settings to optimise energy efficiency, and normally provide a high power factor at all loads (CIBSE 2004a), providing further improvements.

For certain applications, the power requirement could be reduced by using appropriate hydronic circuits and pumping arrangements, or a wider temperature difference, that allow the flow rate to be reduced. It can also be reduced by minimising system resistance. A simple solution is to reduce the length and complexity of ductwork or pipework systems, which can significantly reduce losses, and greatly reduce power requirements (CIBSE 2004a). This can be achieved through reducing the pressure drop arising from changes of direction, filters, fittings and attenuators; maintaining straight runs and suitable sizes; removing air and dirt from hydronic systems; minimising ductwork leakage; and other similar measures (von Weizsäcker *et al.* 1998).

Chapters 5 to 8 describe methods of reducing the energy for fans and pumps in specific HVAC systems. Motor power for lift drives and for fan coil units are covered in Sections 9.5 and 9.6, respectively.

9.4 Lighting

9.4.1 Design objectives

The overall objective for a lighting design is to achieve the desired lighting performance, in terms of creating a satisfying visual appearance and facilitating the functional performance within the space, with the minimum use of energy. Lighting represents about 33% of final energy consumption in retail buildings; about 17% of final energy consumption in commercial office buildings; and about 20% of final energy consumption for all buildings in the service sector (DECC 2012). It will, of course, represent a much higher proportion of carbon emissions in each case, due to the primary energy carbon factor for electricity, so it merits a strategic approach to minimise impact. Lighting can account for over 40% of electricity costs in naturally ventilated offices (CIBSE 2004a).

As with all active engineering systems, the first priority for the energy strategy is to reduce the demand. The primary requirement is, therefore, to seek a suitable level of daylight so that this can satisfy the lighting requirements for the optimum portion of time. The artificial lighting design should complement the daylighting provision. The energy efficiency of the artificial lighting will primarily be a function of the efficiency of the equipment; and controlling the usage of the equipment so that it matches the need at the times required for operation. As with the other engineering systems, the operation throughout its life will be the determining factor. As such, the engagement of the operational staff and occupants will be necessary. A key design challenge, therefore, is to understand the occupancy patterns and the need for flexibility; and then select the most suitable mix of automatic and manual controls to provide a practical solution.

Daylight potential can be optimised through liaising with the architect to influence decisions on the shape and orientation of the building at the initial design stage. So that daylight penetration can be maximised, floor plates should be narrow and glazing should extend towards the upper parts of walls, to make best use of ceiling reflectance. It is necessary to have suitable proportions of glazing with good light transmittance characteristics to achieve a high level of daylight in occupied spaces. Achieving good daylight levels also requires pale coloured wall, ceiling and floor finishes with high values of reflectance. The selection of suitable colours for internal finishes is a key criterion where the lighting designer can influence the architect. This is an important area of design coordination for energy efficiency that is often overlooked. The selection of the glazing proportion and characteristics will, of course have a major impact on the thermal performance of spaces, as well as on the acoustic performance. In most cases, improving the level of daylight will have a negative impact on the thermal and acoustic performance. So in seeking to maximise levels of daylighting, there is inevitably a compromise to seek an appropriate balance with the thermal and acoustic performance. There is also a need to ensure the design satisfies the requirements for compliance with relevant regulatory criteria.

Selecting a building shape with inner courtyards or light wells can be highly beneficial in this regard. For spaces where both the quantity and quality of light is of particular importance, glazing arranged to provide light from the north can be beneficial. This 'north light' provides a 'cool' colour source, without the detrimental impact of direct sunlight and solar gain. The locations, proportions and characteristics of glazing therefore require careful consideration as part of the interdisciplinary development of the envelope, as outlined at Chapter 3.

9.4.2 Design criteria

A key consideration for the artificial lighting system is to critically examine the design criteria. This is an area of building services design that can benefit most from exploring the potential relaxation of design parameters with a client, as outlined in Chapter 3. In particular, it is necessary to agree realistic and appropriate overall illuminance levels to meet the needs of the routine activities undertaken in the space, and avoid over-illuminating through an inappropriate and unnecessarily high level of illuminance. The same applies to the criteria for colour performance. The more demanding the colour performance, the higher the energy consumption is likely to be, as light sources providing better colour tend to have lower luminous efficacy than those with poorer colour.

While the primary focus will be on the general illumination for a space, the design approach should also consider the extent to which functional needs can be satisfied through lighting planned to satisfy illuminance of the task. This could be satisfied through the arrangement of the general lighting provision, or through a separate system of task lighting that supplements the lighting in the area where the task is undertaken. It is, obviously, beneficial in energy terms to use task lighting for localised demanding tasks, rather than increasing the level of general illuminance. The proposed usage pattern for the space should be determined at the briefing stage so that a suitable balance can be selected between task and general illuminance.

Design illuminance levels are defined as a maintained illuminance value, Em, in lux. This is the average value that the illuminance has fallen to at the time that maintenance has to be undertaken. The maintenance factor, MF, is defined as the ratio of maintained illuminance to initial illuminance (CIBSE 2002). The MF takes account of all the losses that contribute to a reduction in illuminance level over time:

$$\mathrm{MF} = \mathrm{LLMF.LSF.LMF.RSMF} \tag{9.1}$$

Where:

LLMF = lamp lumen maintenance factor
LSF = lamp survival factor
LMF = luminaire maintenance factor
RSMF = room surface maintenance factor

The higher the maintenance factor, the better the energy performance. Hence each term in the equation should be as high as possible. Two of these terms are functions of the lamp performance. The lamp lumen maintenance factor is an indication of the extent to which light output deteriorates with time; while lamp survival factor is an indication of lamp life expectancy. The selection of light sources should consider these aspects of lamp performance. The luminaire maintenance factor and the room surface maintenance factor are both related to the quality of the maintenance regime.

Lamp manufacturers usually provide rated LLMF figures for different periods of usage, such as 2,000 hours, 5,000 hours and up to 20,000 hours. For a T5 fluorescent lamp, typical LLMF ratings would be 0.96 at 2,000 hours, falling to 0.9 or below after 20,000 hours of operation. Rated lamp survival factors vary considerably between lamp families.

An unfortunate reality of lighting design, from an energy perspective, is that to achieve the required maintained illuminance level, spaces end up being over-lit for the majority of the life expectancy period of the lamps. Dimming controls can help to improve the overall energy efficiency for certain lamp types, as outlined below.

9.4.3 Energy efficient light sources

The energy efficiency of light sources will depend upon the luminous efficacy of the lamps, and the effectiveness of the luminaire in directing the lumen output towards the surfaces to be lit. In order to achieve energy efficient light sources, lamps should be selected with the highest luminous efficacy (lumens/watt) that is appropriate for the application, taking into consideration the colour rendering and colour appearance of the source. For any particular family of lamps, the luminous efficacy would usually increase with the power rating of the lamp. In addition, luminaires should have a good light output ratio (LOR), typically greater than 0.6. The Part L2A 2010 criteria for fixed lighting relate to the efficacy of the combination of luminaire and lamps, as outlined in Chapter 3. For offices, industrial and storage areas this requires an average initial efficacy of not less than 55 luminaire-lumens per circuit-watt. This relates to the total figure as averaged over the whole area of the relevant types of spaces in the building. This allows design flexibility to vary the LOR of the luminaires and the luminous efficacy of the lamps, and use different lamps and luminaires to meet the needs in different spaces.

A useful method for lighting energy targets is the lighting energy numeric indicator (LENI). This specifies the annual energy (rather than power density) per unit area, relating it to other aspects of the building design (so that it relates to a particular internal space); and could, together with other considerations for lighting energy efficiency, provide an improved target method, as outlined by Davies (2010).

Figure 9.4 shows the range of luminous efficacies for the main families of lamp types used in buildings. For internal lighting, fluorescent 'T5' linear fluorescent lamps used in luminaires with high frequency control gear have become the standard solution. These are available in a range of tube lengths and typically provide luminous efficacies of about 90–100 lumens per watt. Compact fluorescent lamps can typically provide luminous efficacies of 50–60 lumens per watt and are also used in a wide variety of spaces. As already stated, lamps with better colour rendering properties may have lower luminous efficacies. Metal halide lamps can typically provide luminous efficacies of 60–100 lumens per watt and are often used in spaces such as airports, sports halls, assembly halls and exhibition spaces, depending on the colour criteria. The selection of the lamp types will also need to consider whether dimming is proposed, as only certain lamps have a dimming capability.

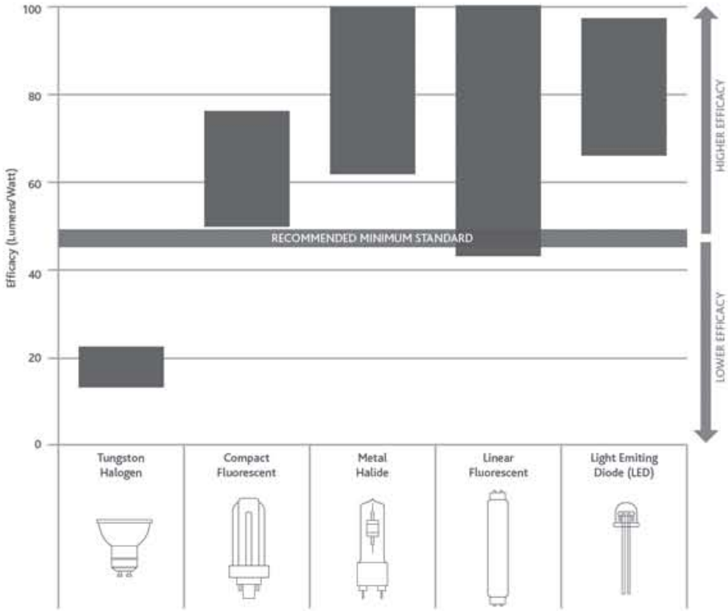


Figure 9.4 Luminous efficacies for the main families of lamp types

Source: courtesy of Hoare Lea

Figure 9.5 Example of a successfully lit and energy efficient office space: Microsoft Building 5, Reading, UK

Source: David Churchill Photography

The selection of the luminaire should not be determined by energy efficiency considerations alone, as it will involve design integration with the architectural layout and aspirations for the space, as well as the ceiling arrangement and finishes. Luminaires should, for the most part, provide good internal reflection and broad downwards distribution, including a modest proportion of upwards distribution where this is required. High efficiency luminaires can have LOR figures up to 0.8–0.85. Luminaires that provide narrow beams of downwards distribution – such as recessed downlights, often with low luminous efficacy lamps – can have high LOR figures, but poor overall luminaire-lumens per circuit-watt, and have more limited application. Figure 9.5 shows a successfully lit office space that utilises daylight from an atrium, together with a range of high efficacy light sources.

The rapid development of white LED technology provides future opportunities for using new energy efficient products in a variety of lighting applications. The range of LED lighting products available at present is particularly suited to more specialist aspects of lighting, such as architectural or accent lighting, rather than general purpose illumination (Jacobs 2011). A specific application that is likely to become the norm is the use of LED lighting in lift cars, as described in Section 9.5.

9.4.5 Lighting controls and management

The basic requirement is for the control system operation to provide acceptable lighting levels for occupants throughout the period of usage. The flexibility of the controls should match the anticipated usage pattern of the building. In many commercial premises, there is a considerable amount of energy wasted due to the continued usage of the lighting system outside of the main operational period. There is, of course, a practical need for partial usage for a proportion of the non-operational time, for example for cleaning purposes; and to a lesser extent for security. However, due to poor controls and management, energy usage is often well above the level required for these purposes (CIBSE 2002). From an energy perspective, the need can be satisfied with suitable controls that provide the required flexibility so that individual luminaires, or groups of luminaires, can be switched off when their light contribution is not required. Such controls should always have override facilities to allow usage for security or emergency purposes (CIBSE 2002). It is likely that the controls will be one or more of the types listed below, and could be a combination of these.

1 Local switching, through distributed groups of multi-gang switches located to control distinct zones or discrete spaces. This might be appropriate in some locations, provided it has a logical division and labelling. However, it has limited benefit as lighting does not switch off when people are absent.
2 Time switching, either based on fixed time schedules by room or zone; or pre-set values related to daily, weekly or annual usage patterns.
3 Automatic switching planned to respond to the occupancy patterns in spaces, used in conjunction with passive infrared (PIR) presence or absence detectors. Absence detection is preferred, in which the luminaires are switched off when the space becomes unoccupied, and switching on is manual. Presence detection switches the luminaires on when someone enters the space, and switches them off when the space becomes unoccupied. Such control systems should include time

delays to limit the switching operations. This will avoid the reduction in lamp life expectancy that can be a result of excessive switching. It will also avoid the nuisance to occupants of premature switching off. The time delay features should relate to the switching characteristics of the lamp for the run-up to full output, and the re-strike time.

4 Automatic switching with daylight-linking used in conjunction with photoelectric cells (PECs). This can be used for areas close to window-walls, with good daylight penetration; preferably to provide dimming, but it could just be for switching. Dimming not only reduces energy consumption but also allows flexibility for change of usage, although this may detract from the scope for energy efficiency.

To provide the best scope for energy reduction, it is preferable to locate PECs in zones corresponding to the areas of best daylight distribution.

It should be noted that the luminous efficacy of the lamp circuit would normally reduce as the lamp is dimmed, so the relation between reduction in illuminance and reduction in energy is not necessarily linear.

For many buildings, a mix of manual and automatic controls should be utilised to suit particular spaces. In some cases, a balanced choice will be required between traditional hard-wired switching, centralised control or localised stand-alone controls. As with most controls, it is often better to select for simplicity rather than technical sophistication.

Automatic controls as described at (3) and (4) above are most effective if they allow a degree of individual occupant control. Automatic systems of this type have the flexibility to allow for changes in the layout or usage of spaces. They can also have benefits in maintenance planning through monitoring of the system (CIBSE 2004a). Lighting control modules (LCMs), on the whole, are primarily lighting management features.

There is an anomaly in lighting performance versus design requirement that can be resolved through dimming controls (CIBSE 2002). This relates to the need to design to achieve maintained illuminance, which results in the initial illuminance level being much higher than the design illuminance, as outlined above. Modern fluorescent luminaires with dimmable high frequency control gear can vary the lighting level so as to correspond to the design maintained illuminance level. As the lamps age, the lumen delivery reduces. As a consequence, the level of dimming reduces with ageing and the power consumption increases (CIBSE 2002). At the time related to the requirement for maintenance attention, the power consumption will be at the maximum level, as designed to overcome the maintenance factor reduction (CIBSE 2002). One effect of this would be that the range of dimming achievable to respond to daylight levels would be reduced by its usage to offset the initial over-illuminance. Conversely, as the lamp ages, the effective range of dimming achievable will be higher. The accumulated energy consumption can be reduced by increasing the frequency of maintenance attention, which should be addressed in the operational regime (CIBSE 2002)

External lighting

External lighting is required in and around buildings for a mixture of safety, security and amenity purposes. The extent of the emergency lighting provision will depend upon the functions and numbers of buildings; and facilities for access, roads, car parking, pedestrian routes and amenity areas. As with internal lighting, the starting point should be to examine the brief and determine the specific functional requirements during times when daylighting is insufficient.

Because of the potential hours of operation, it is important to question whether external lighting is required throughout the night. If extensive operation is considered necessary, it is worthwhile discussing the needs with the client to explore the possibility of providing two or more levels or stages at different times, so that energy consumption levels can be reduced for a part of the time. It is also worth exploring whether lighting could be localised in certain areas, rather than providing an assumed widespread coverage. As with internal lighting, it is important to select efficacious lamp and luminaire combinations with appropriate colour rendering for all applications. There is a trend towards using white light sources, rather than high luminous efficacy discharge lamps with poor colour performance.

Consideration should be given to luminaire mounting heights in relation to the architectural and planning objectives, as well as the maintenance aspects. While mounting luminaires at increased heights can provide broader coverage, it also reduces the illuminance level, so may not result in a reduction in installed power. Figure 9.6 shows a successfully lit and energy efficient exterior space utilising a mix of column-mounted luminaires and recessed luminaires.

A key factor in the selection of luminaires and their locations is to avoid 'light pollution'. One aspect is 'encroachment' or 'trespass', which is light entering other properties and is both intrusive and a potential subject of conflict with neighbours, but also wasteful of energy. A different aspect of waste is 'sky glow', which is light

Figure 9.6
Example of a successfully lit and energy efficient external space: Highbury Square, London

Source: courtesy of Hoare Lea

directed upwards into the sky, rather than on the surfaces that require to be lit, and is also wasteful. A third aspect is glare. There are moves within society for legislation to address light pollution and encourage opportunities to appreciate the dark night sky.

9.5 Lifts

The planning of a lift installation forms an integral part of the building design process, and has a fundamental impact on the design development of the architecture and structural engineering solutions. The planning of the numbers, capacities and characteristics of passenger lifts is an outcome of a detailed analysis of passenger traffic performance to satisfy the design criteria. Through proper selection of the lift passenger installation parameters, the lifts should provide an efficient solution to the building's passenger traffic needs in terms of capital cost, space take (for lift shafts, lobbies and machine room space, if required), energy and running costs (CIBSE 2004a). The planning of lift shafts and lobbies is a fundamental consideration when designing the building's cores, as outlined at Chapter 12.

The energy consumption of lifts will vary considerably between different building types and patterns of vertical passenger movement; and will be most significant in tall buildings (Russett 2010). The energy consumption of lifts and escalators in some buildings can be 5 to 15% of total energy costs (CIBSE 2004a). However, the energy efficiency of lift installations has received little attention and has not featured directly in the UK regulatory framework, although this may change in the future. Lift installations can incorporate simple features that reduce energy consumption while having negligible effect on traffic performance.

Lifts use energy for these items:

- lighting in the lift cars (the single largest energy consumer)
- drive machinery
- control systems
- ancillaries.

The most significant energy efficiency improvement is likely to be the use of LED lighting in the lift car; and for lighting to be controlled in addressing the operational state, as outlined below.

For modern lift installations, the motor drives are normally of the variable voltage, variable frequency (VVVF) type, and can be regenerative. Regenerative drives have high levels of energy efficiency and recover energy from the out-of-balance condition by regeneration of power back into the mains electricity supply. However, existing, older lift installations have other types of motor drive that can be much less energy efficient.

The lifts in most buildings are mainly used for three relatively short periods during the day. However, in most multi-lift installations, all of the lifts normally remain in a continual operating mode throughout each 24-hour period, resulting in considerable wastage of energy. The key to reducing energy consumption in a lift installation is, therefore, to reduce the operational state of lift cars to a level consistent with the variable traffic level, as outlined by Barney (2006). This is a form of demand matching and covers two separate aspects:

1 *Reducing the number of lifts in service outside of the peak operational period.* Outside of the peaks, lift traffic is primarily inter-floor. Barney (2006) has suggested that the number of lifts in service could possibly be reduced, and still provide a satisfactory level of traffic performance in these periods of low traffic demand. This would reduce energy consumption from lift controllers, lighting and ventilation; and from the motor drives, due to overall reductions in motor starts and motor running time for the multi-lift group. Because individual car loading is likely to increase, lifts will operate closer to their optimum balanced operating condition, and therefore in a more energy efficient mode. As a minimum, one lift would be left in operational mode. Multiple lift installations require, therefore, suitable shut-down control protocols (Russett 2010) for programming lift management.
2 *De-activating energy consuming equipment in lifts that are idle, but still in service.* Barney (2006) has suggested that individual lifts in a multi-lift installation can be idle for considerable periods of time, possibly up to 60% of the time over a whole year. This provides an opportunity to switch off the car lighting and auxiliaries in these lifts after a predetermined period of idleness (say 5 minutes). Lift controllers consume energy in standby mode when a lift is idle. There is an opportunity to switch off the power side of controllers (isolation transformers and pre-energising motor winding power) while the electronic systems for control operation would remain in standby mode. For safety purposes, switching and timing arrangements would, obviously, have to be such that lighting would be operational prior to a passenger entering the car, as would any other safety-related features (Barney 2006).

9.6 EC/DC fan coil units

The factors that should be considered in the selection of an indoor climate control system are described in Chapter 6. While it may not be the preferred system in terms of energy performance, there is often a strong economic case to use a traditional fan coil unit solution, particularly in commercial offices. While fan coil units (FCUs) may not be the favoured choice for energy efficiency in most circumstances, they can be made much more efficient by using fan motors that are electronically-commutated (EC) instead of conventional single-phase motors. EC motors are also known as direct current (d.c.). In an EC/DC motor, power electronic devices create a rotating magnetic field in the stator winding. The motor contains a permanent magnet. For FCUs using this drive technology, carbon emissions can be reduced in these ways (Blackwell 2010):

- they are more efficient than an equivalent single-phase a.c. motor; typically up to 90% efficiency, compared to in the order of 50%;
- variable speed operation can be achieved without any reduction in efficiency, allowing matching of the motor speed to the required air flow rate at the commissioning stage;
- the fan speed can be varied in response to different load conditions, using suitable controls based on demand to provide variable volume operation;
- it does not incur the problem associated with heat transfer to the air from a less efficient motor in a conventional FCU. It thus avoids the increase in load on the cooling coil, and hence reduces the cooling energy requirement.

Therefore, EC/DC fan coil units should be the preferred choice for FCUs in areas with high cooling loads (Blackwell 2010), subject to the electrical design considerations described below.

9.6.1 Electrical design considerations

There are two electrical aspects of EC/DC fan coil units that require careful consideration in the planning of the electrical distribution system. The first is the poor power factor, which is typically about 0.6 (or above) for larger units, but decreases considerably under part-load conditions to 0.3–0.4 (Blackwell 2010). The second is the generation of harmonics from the power electronic devices. Such systems may require suitable PFC and/or harmonic filtering at relevant locations in the electrical distribution system. Where widespread use of an EC fan coil system is proposed for a refurbishment project, the impact on the existing electrical distribution system could be considerable. This might necessitate some upgrading of the distribution system, which could be a determining factor in the viability of this technology in some refurbishment projects.

9.7 Strategic decisions for electricity usage

The need to develop an energy strategy covering the wider decisions about the selection of fuel has been outlined in Chapter 3. It is useful, also, to have a strategy for electricity usage, because of its high carbon factor. This specifically relates to minimising carbon impact by avoiding electricity usage for heat generation; and avoiding the compounding effect of electrical heat gains in spaces requiring cooling, as outlined below.

Where the fuel factor for electricity is considerably above that for other fuels, it should be avoided as the fuel for heating purposes wherever possible. Examples are:

- Electricity should not be used for space heating unless it is the only, or most practical, solution, due to either location or intermittency of usage.
- Electricity should not be used for humidification generation if a less carbon intensive alternative is available, such as gas-generated steam.
- Electricity should only be used for domestic hot water services for dispersed provision, very occasional usage, back-up/top-up for gas, or where there is no alternative. Centralised hot water storage heated from a boiler system, or directly gas-fired, will nearly always be a lower primary energy option for high levels of usage. Reducing water demand should, of course, always be the first priority (through selection of low flow devices for showers, etc., to limit the amount of storage or heat-up energy required). For high density usage, solar hot water can be a viable alternative, as outlined in Chapter 8.
- For any usage of electricity in a heating context, the automatic time and temperature control settings (and response) should be set at suitable values to avoid unnecessary operation.

A key operational consideration is that the demand for cooling should be minimised by ensuring that there are no unnecessary heat gains to cooled spaces from electrical equipment. It is useful to consider the compounded carbon impact of unnecessary electric heat gains to a space that requires cooling to maintain its temperature criteria. Carbon emissions will arise from:

- electrical energy for the unnecessary electrical load
- electrical energy for the chiller to remove this heat gain
- electrical energy for the associated fans and/or pumps for heat rejection.

Consequently, it is essential to exercise rigorous demand management to avoid any unnecessary usage of electricity in spaces requiring cooling.

9.8 Process loads: small power equipment

The relevance of process loads to overall energy consumption has been described in Chapter 3. The use of personal computers (PCs), in particular, has a significant energy impact. There are various power-limiting features and settings, power management equipment and controls for PCs and other equipment to reduce energy consumption. Such features should be discussed with clients at the initial stage, alongside behavioural aspects, to address energy usage from process loads as part of the overall energy management strategy. Similar considerations apply to all other electrical and electronic process equipment. Such equipment often has a load that is non-linear, so it gives rise to harmonics, which can incur additional energy consumption; so policies to limit usage can play a useful part in carbon mitigation.

There is increasing focus on the wasted energy associated with electrical and electronic equipment that is not in active operation, but is in ‘standby’ mode. This relates to both business equipment and to consumer electronics in residential buildings. In some cases (particularly for older equipment), this can consume power at a rate that is a considerable proportion of the operating value. This represents an avoidable carbon impact which is compounded if, in turn, this leads to an additional cooling energy requirement. Proposed legislation will limit the standby load for a range of electronic equipment.

9.9 Process loads supported by UPS systems

Data processing and other loads supported by uninterruptible power supply (UPS) systems can represent a significant proportion of the energy consumption in certain types of buildings. Chapter 11 provides a brief outline of these systems in the context of load assessment. In order to provide the required level of redundancy, systems often comprise multiple parallel modules of equal size sharing the load. While module efficiencies could be, say, 96% at full load, they will normally reduce as the load reduces. This will result in an additional energy loss. While a client’s primary consideration for their UPS-supported load is likely to be the resilience, there is an increasing focus on the energy efficiency of such systems. The selection of the sizes and numbers of parallel modules sharing load to meet resilience criteria should, therefore, also consider the resultant energy efficiency and carbon impact.

9.10 Enabling energy management through controls, metering and monitoring

The need for rigorous demand management has been emphasised in Chapter 3. For all the active energy consuming systems described in this chapter, and in Chapters 5 to 8, a key design feature should be the inclusion of facilities to enable effective operation and energy management throughout the life of the building. This will provide the most appropriate automatic and/or manual control. It will also provide the operational engineering team with meaningful information on the performance so that they can understand where energy is being consumed, and thereby make suitable interventions to reduce consumption, as outlined at Chapter 3.

These facilities are not active energy using systems delivering a functional requirement, but the means through which the active systems can perform in an optimal way. So the starting point for developing the physical system requirements for the controls, metering and monitoring should be the energy management strategy and the proposed operational regime. As outlined in Chapter 2, this should be an early design consideration, to follow the energy strategy report; and should include a strategy for metering. While the controls and metering facilities are covered separately below, it is best to think of them together as an integrated system.

9.11 Controls and building energy management systems (BEMS)

When considering the requirements for the controls, it is, perhaps, tempting to commence with an engineering systems approach. This would typically cover aspects such as controllers (sometimes known as outstations); communications networks and interfaces; user interface (sometimes known as supervisor), and so on. Similarly, considerations for the controls systems objectives will often focus on the control of the comfort parameters and functional operation within the occupied spaces. These engineering aspects are, of course, essential and will need full consideration within the eventual controls provision.

From a perspective of focusing on energy optimisation, however, other factors need to be addressed within the wider initial objectives. It is necessary to stand back from the engineering perspective and consider what contribution the overall controls provision could provide, both in the shorter and longer terms. In this sense the controls requirement is integrally related to the energy management strategy and the wider operational strategy for the building as shown at Figure 3.10. It is best to think about what the facilities could provide, above and beyond mere control of the plant and equipment. The automatic and manual controls will be both the principal human–machine interfaces (HMIs) of the active (and, to a limited sense, passive) systems; and, in a BEMS, an information and data resource that is an essential requirement for allowing operators to monitor and improve performance.

In essence, the control facilities provide a mixture of automatic and manual control actions, and data allowing operator intervention, that can assist in optimising the energy performance. It will include a need to allow such moderate level of local manual intervention from occupants that is necessary to help adjust to suit localised conditions, and meet their psychological need to have some personal measure of control. This would be for selective aspects of systems, but can provide a beneficial sense of well-being, see Figure 9.7. However, the most effective energy management is

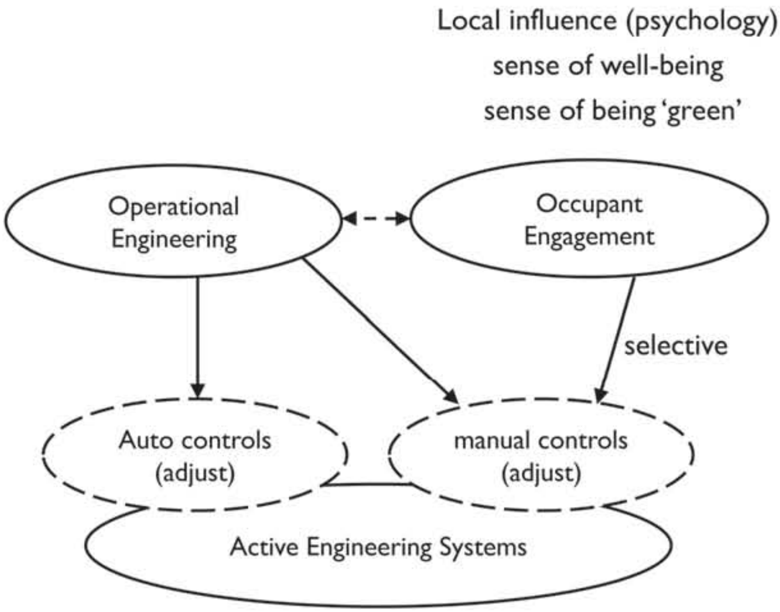


Figure 9.7 Concept for operator intervention

likely to be through the primary energy management controls being automated. The automatic controls for HVAC systems can have a major beneficial impact in reducing energy consumption, provided that they relate to practical spatial zone allocations and have appropriate levels of dynamic responsiveness. The emphasis is always on honing controls so that they can respond at a local level to match the varying needs at any point in time. This will then allow the central plant to adjust accordingly. Controls should be amenable to adjustment to suit the likely flexibility of space usage during operation.

There are obviously benefits from controls facilities that provide enhanced capability and flexibility, particularly in relation to lifetime adaptability and 'future-proofing'. However, it should always be recognised that greater so-called 'intelligence' and technological sophistication in the systems does not, by itself, contribute to energy efficient performance. It could, in some cases, be detrimental if the perceived complexity and/or the lack of user-friendliness prevent operators from intervening to the extent required. The key is always to select an appropriate and suitable controls capability through considered planning. There is no reason for controls to be any more complicated than required. Instead, the controls system should be of the simplest form and range of flexibility that can deliver the required level of operation, in an intuitive way, through the anticipated usage pattern of the building (CIBSE 2004a; Horsley 2010).

The key functional requirements for the control systems are:

1 The primary requirement is to regulate the various conditions in accordance with the design intention and maintain the condition of the controlled parameters. This is achieved by measuring and adjusting system variables, which will then

alter the system output through control loops incorporating the appropriate feedback arrangement.

2 Data collection from metering and other means to provide information on patterns of energy usage, with the facility to create a variety of outputs to represent meaningful aspects of energy performance.
3 A range of monitoring, alarm and control facilities specifically to restrict operation to within suitable parameter boundaries to maintain good energy performance, such as automated data collection and alarms.
4 A range of facilities to assist in the maintenance of active engineering systems. This is to ensure that suitable maintenance regimes can be instigated, such as planned preventative maintenance (PPM), requiring appropriate predictions and planning schedules.

These items can overlap and are integrally related to the metering provision.

To achieve the desired functionality will require suitable settings and adjustments, including timed switching profiles and schedules. Operational staff should be able to (and be encouraged to) fine tune settings (particularly time settings) to match active systems to the actual dynamic performance in practice. The same adjustments should apply to occupancy patterns in practice, so that there is continual matching. Together, these can reduce energy and carbon while maintaining comfort criteria as part of an active participatory plan. This can be of particular assistance in the settling-in and optimisation period, in line with the BSRIA Soft Landings Framework, Stages 1–5 (Bunn and Usable Building Trust 2009).

It should be understood that the building services designer is not responsible for the detailed software and engineering design for the building management system (BMS) and automatic control systems, control panels and controllers. Instead, the engineer creates the controls concept and provides an outline of the performance required. The appointed specialist contractor undertakes the detailed design, including the integration, interfaces and other compatibility aspects with the plant and equipment (Horsley 2010).

The scope and extent of controls provision is an important design decision. It is useful to discuss this with the client as part of the design development process. It might be appropriate in some smaller buildings just to use direct digital control (DDC) controllers on a stand-alone basis. This would be sufficient to effect the required controls function, but would not provide any information for management. The next level for extending the automatic controls capability would be to use a network of DDC controllers. This would allow sharing of data and, through a suitable user interface, would provide a facility for management intervention through monitoring and adjustments. The first level of integration would be to have a number of distributed DDC controllers linked together on a local area network (LAN) for sharing information (CIBSE 2005c). However, for most medium and large projects, it will be appropriate to utilise a full BEMS, often termed a BMS. A BMS provides the functions of both control and monitoring for the engineering systems via a networked system, with one or more user interfaces provided by operator terminals. A BMS has a multitude of beneficial functions, but its core usage can be described simply as a system with inherent intelligence that can control and monitor the engineering systems. By doing this it facilitates active energy management (CIBSE 2005c). It is also possible to have an energy monitoring system (EMS) alone, without any wider building management capability.

The main components of a basic BEMS network are shown in Figure 9.8. A BMS would usually have features such as PC-based graphical user interfaces connected to a communications network of DDC controllers. In a BMS, the linked-up DDC controllers will be connected to a central PC, usually known as a 'supervisor' or 'head-end', and will have suitable graphical capability for information displays and facilities for logging and recording. This will allow the operator to integrate the information; see records, fault reports and trends; and make adjustments to settings to improve performance. The system can be considered to have four levels: management (supervisor), network, control and field.

The communications system will usually comprise one or more LANs and/or wide area networks (WANs). This will allow adjustments to the control strategy to be made from the user interface and data to be logged and stored; and therefore extend the flexibility, and the potential range of interventions to improve the energy performance. A variety of network options exist, including structured cabling and wireless systems. Systems can be integrated (or converged) with other data systems, including communications, fire alarm and detection, and security (CIBSE 2005c). An early aspect of design integration is often with the communications systems designer. It is also possible to provide integration with other buildings and sites as part of the energy monitoring for an estate portfolio. Figure 9.9 shows a typical full network for a BEMS.

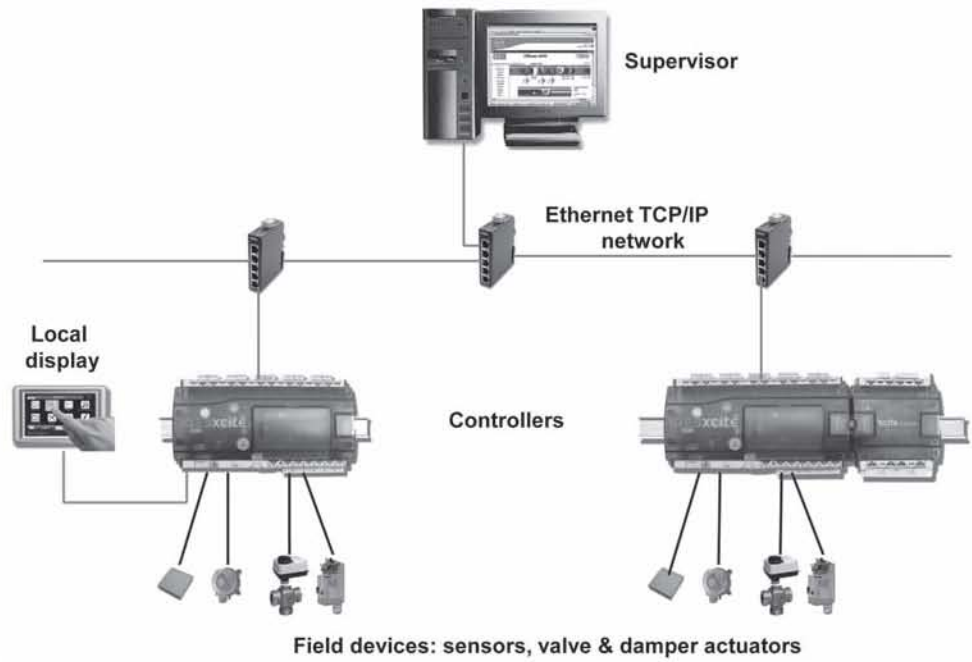


Figure 9.8 Components of a basic BEMS network

Source: by permission of Trend Controls Ltd

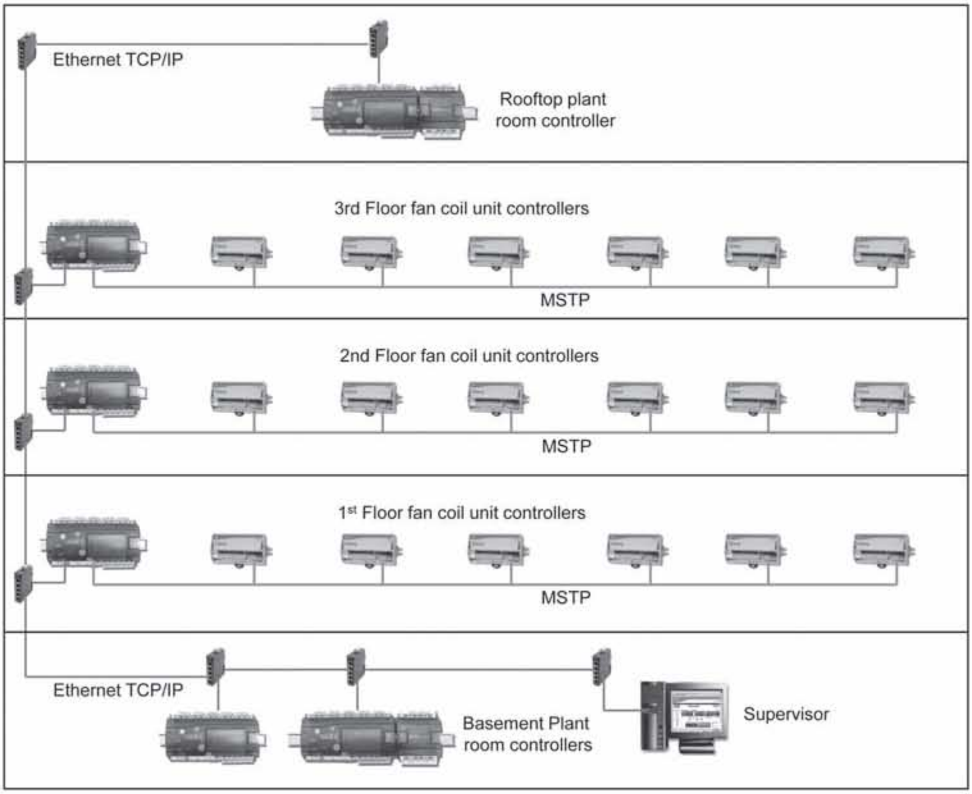


Figure 9.9 Typical full network for a BEMS

Source: by permission of Trend Controls Ltd

The core components are:

Controllers: These are intelligent devices using DDC. Controllers contain the embedded software programs and algorithms, and the required numbers of analogue and digital inputs and outputs. They can be programmed to undertake a variety of simple control functions, such as optimum start; temperature compensation; one, two or three-term PID (proportional, integral and derivative) feedback control; together with a range of monitoring functions. The controller size will vary depending on the number and range of plant items to be controlled, and hence the number of digital and analogue inputs and outputs. Most motor control centres will contain one or more outstations providing control of fan or pump motor drives. See Figure 9.10.

Operational devices: Control is effected through operational devices such as actuators for motorised valves for heating and cooling systems, and other field devices. There might be a need for other auxiliary devices, such as relays, to achieve the necessary interfacing.

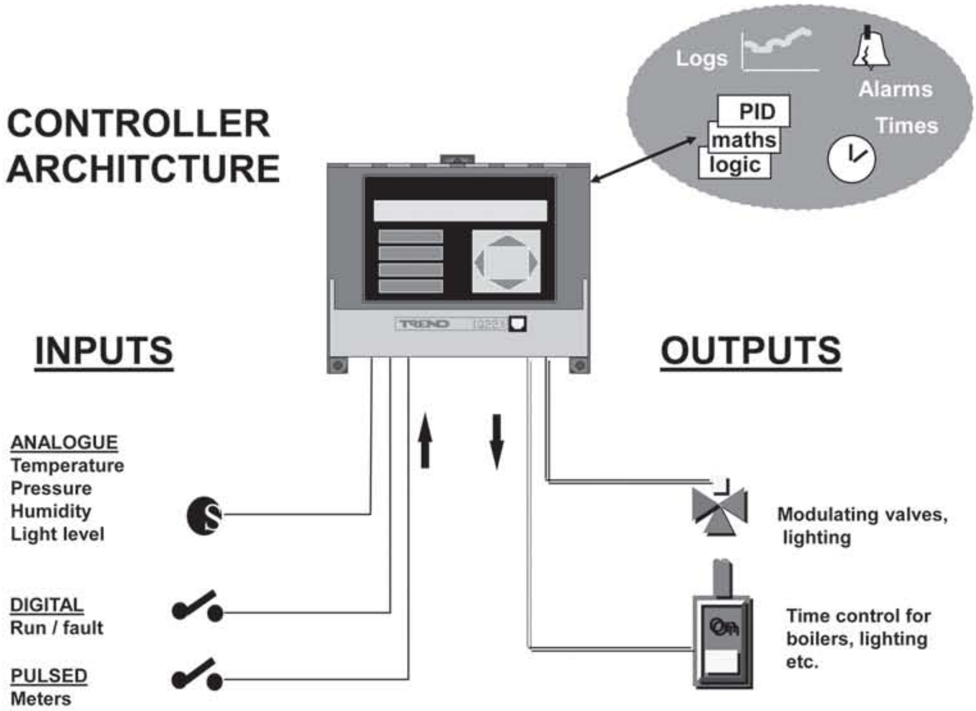


Figure 9.10 Typical controller architecture

Source: by permission of Trend Controls Ltd

It is normal for individual stand-alone items of equipment, such as boilers, chillers, generators, cooling towers, air-handling units and combined heat and power (CHP) plant, to be packaged with their own integral control panels and cabling. This allows pre-site testing of the controls operation at the manufacturers' works. The BMS would, therefore, only have to interface with the local control panel. Network interfaces allow the integration of other plant or systems, which can be 'seen' as another controller (Horsley 2010).

Sensors: These are used to provide signals for parameters such as temperature and humidity. Sensors should be of high quality and allow regular calibration to reduce the drifting of set-points. Control set-points should be monitored on a regular basis. Sensor locations must be selected so that they give a truly representative indication of the controlled parameter.

The control strategy should define the specific performance of each controller, sensor, actuator and all other control system devices in relation to all conceivable operating conditions and scenarios. Control loops should be selected to suit the required dynamic operation and tolerance required for the set point of the controlled parameter. Settings should take beneficial account of thermal lags, where this can reduce energy consumption (CIBSE 2004b, 2005c).

While a BEMS can provide facilities for a multitude of useful operational and management functions, the focus here is on the benefit that is provided for energy management to reduce fuel usage and carbon emissions. Consequently, as well as the BEMS capability to achieve and maintain the designed internal comfort conditions in all the spaces – itself a major contributor to reducing energy consumption – it can also provide direct energy management (Horsley 2010) through aspects such as:

- identifying and reporting faults. This allows corrective action to be taken to return plant to optimum operation;
- identifying unexpected conditions, including rises in energy usage in particular systems, or at particular locations;
- verifying the performance of systems, and allowing re-proving on a periodic basis;
- setting values for selected parameters, so that any parameter that goes out of range triggers an alarm.

Using information derived from the metering allows data logging by system, which could include:

- summated consumption for each type of fuel;
- status, operational mode or cycle for plant and systems;
- time periods and total running hours for all main items of plant;
- energy (kWh) delivered by all low and zero carbon (LZC) technologies;
- key parameters for LZC technologies, such as: CHP running time, accumulated number of starts, power/heat ratios, and key operating temperatures; peak power and daily energy generated by wind power and photovoltaics;
- data required for compiling statutory certification;
- logs of all alarms and faults.

9.12 Metering and monitoring

9.12.1 Usage for energy management

The concept for using metering and monitoring for energy management is shown in Figure 9.11. The operational engineering team need to engage with the occupants to jointly reduce energy consumption. However, at the outset of the project, they only have the theoretical knowledge of the building contained in the design information. Actual information on the true building performance comes from the data collected directly from the metering; and the monitoring derived from metering, showing trends and patterns. This information provides operational engineering personnel with dynamic knowledge. If properly contextualised, this information can improve awareness and thus allow operational and occupancy sides to collaborate as a management regime, as outlined in Section 3.6.

A metering strategy should be provided as part of the overall energy management strategy. It should be a consideration at an early stage in the design process, and thereafter developed as an integral part of the MEP systems design. Most important, it should be integrated with control systems planning. Metering provides essential information about the pattern of energy usage, without which management activities

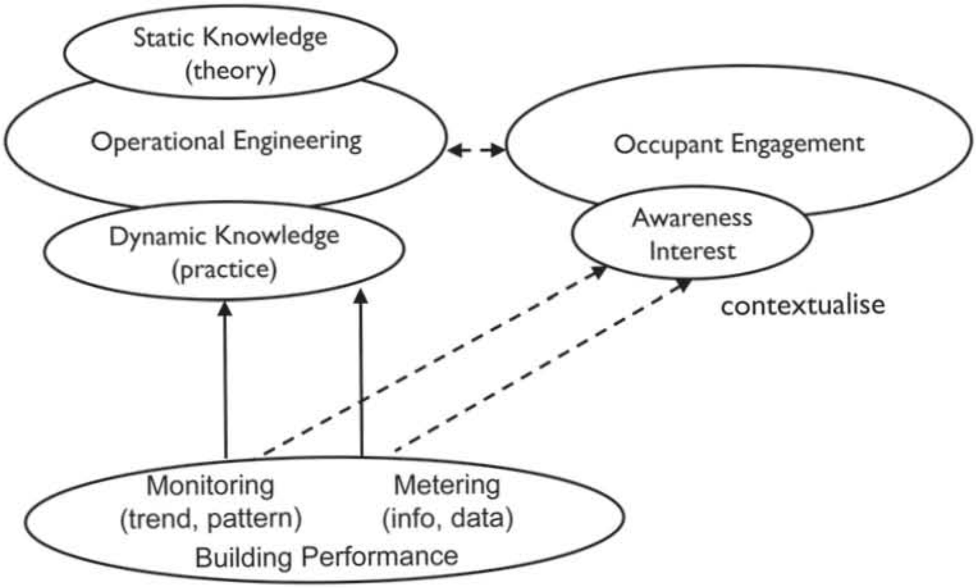


Figure 9.11 Metering and monitoring concept for awareness and engagement

would be hampered through being based only on assumptions. The ways in which metering data can be utilised for energy management should be established through agreement as part of the liaison with operational engineering; and should be set out in the building logbook. This information in itself will not save energy; however, suitable actions based on this information can form an important part of energy management strategies and can lead directly to considerable reductions in energy consumption. Metering is usually required to meet regulatory criteria and is specifically required to comply with Part L2 and the EU Energy Performance of Buildings Directive. At its simplest level, it can allow individual areas or end-use functions to be benchmarked against standard target consumption limits for comparison. By extending the information to convey an indication of the building's carbon impact and footprint, the metering strategy can provide a much wider benefit by stimulating occupant interest and involvement – and hence participation – in sustainability issues. In certain building types, it could also be used as an educational tool.

Case studies have shown that operational energy consumption can be reduced through behavioural change (CIBSE 2009b). The key to maintaining good energy performance is likely to be collection and logging of meter readings on an automatic basis. This needs to be in a suitable form for direct interpretation and can usually be provided via the BMS software (CIBSE 2004a). This would, ideally, be based on demand profiling derived from half-hourly data (CIBSE 2009b). The operational engineering regime should provide regular reviews of the collected data and ongoing intervention strategies to reduce carbon emissions.

9.12.2 Metering coverage

For metered information to be meaningful, a primary requirement is that it should accurately represent the consumed energy (in kWh) of each identifiable service or function at a particular location within the building. It is not necessarily the case that all services of interest need to be metered directly through fixed metering, as some energy consumption data could be obtained by calculation from other metered readings (CIBSE 2009b). Figure 9.12 shows a 'metering pyramid' with the variations in performance for different metering coverage. A further requirement is that the measuring arrangements for multiple meters should be synchronised, with all readings being taken at the same points in time (CIBSE 2009b). This is so that meaningful comparisons and relationships can be deduced from the output information. In some cases, the fixed metering could be supplemented by portable meters where continuous readings are not so important.

For most buildings, metering should be considered for the following functions, which include aspects described in Part L Guidance (DCLG 2010a, 2010b):

1 In tenanted areas, it is likely that regulatory criteria will determine the requirements for sub-metering for billing purposes. In addition, for energy purposes metering should be provided for electricity for areas above 500m^2, together with heating and cooling provision where appropriate.
2 At least 90% of each service by end-use; or so that at least 90% of the estimated annual energy consumption of each fuel can be assigned to the relevant end-use function.
3 All major items of equipment.

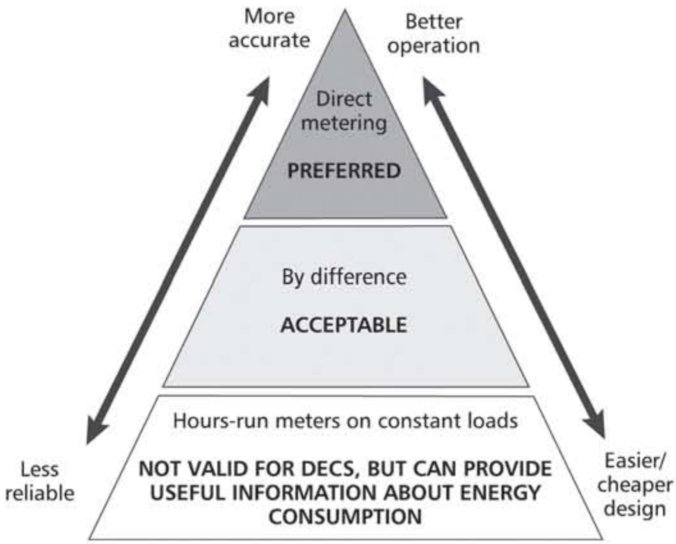


Figure 9.12 Metering pyramid

Source: reproduced from CIBSE TM39 (2009b) with the permission of the Chartered Institution of Building Services Engineers

4 The output from LZC technologies, including CHP. This is so that their individual contribution and performance can be monitored, which will aid the process of optimising performance.
5 District heating and cooling distribution.
6 Electric humidifiers, above about 10kW.
7 Dedicated lighting distribution boards and lighting controllers.
8 Particular usages that might need to be subtracted so that consumption in other areas can be evaluated in relation to relevant benchmarks.
9 For areas above 1000m^2, automatic reading and data collection.

It is also worth considering extending the coverage for particular buildings and systems:

- data processing and ICT systems, such as data centres, main and secondary equipment rooms, including loads supported by UPS systems;
- small power systems, specifically in areas where particular attention is merited to monitor the pattern of usage to help control energy consumption;
- specialist lighting where the function is beyond general illumination and is of relatively higher power density, such as in retail and display areas;
- for lighting management systems, logging of the dimming levels and the running hours to allow calculation of consumed energy related to the installed load (DCLG 2010b);
- external lighting, particularly for car parks and floodlighting;
- all catering installations. It is worth considering sub-metering of separate sections of a catering facility or large items of equipment with high energy usage;
- other process loads related to the business function;
- all significant load centres, switchgear and distribution boards;
- other identifiable services or functions with the potential for high energy usage without management intervention.

A judgement always needs to be made between the benefit and the economics of extending metering coverage. It is highly unlikely that metering will be of benefit in final circuits from distribution boards, where occasional use of portable meters is more appropriate (CIBSE 2009b).

9.12.3 Metering types

The type of metering should be selected to suit the most appropriate usage of the data, and this will often require a mixture of manual reading meters and automatic meters. Automatic meters can have three main types of output data: pulsed output, typically 0–10V; analogue output, typically 4–20mA; or a communications output that can be used with open protocol systems (CIBSE 2009b; Horsley 2010). The facilities should be planned so that output data is in a form that can be connected to a BMS, or to another collection system. This information can then be used for the automatic monitoring and targeting of energy data.

9.12.4 Smart metering

A development in metering technology that is likely to provide further potential for carbon reductions in the UK is the widescale introduction of 'smart metering'. There has been some debate about the extent to which this might actually reduce energy consumption; and some concerns about the major capital investment that would be required. There are also concerns about the security of information about consumers and their lifestyles that could be derived from load profiles and patterns. However, the IET and RAEng (IET 2009) have jointly indicated their strong support for the deployment of smart meters as an important step toward a more flexible and more efficient supply infrastructure for energy. They have suggested that proposals for smart meters should be part of the overall plan to introduce 'smart energy grids'. It is recognised that to introduce such a system would require an extensive supply side infrastructure so that data could be collected, aggregated as required, distributed and processed to provide meaningful information.

It is envisaged that smart energy meters would have output interfaces to drive local displays or instruct the operation of designated appliances within a building or site. They would also have suitable network interfaces to allow remote access. Data would be transmitted to and from the operator of the network or system, and the energy supplier (IET 2009).

Numerous ways have been identified in which smart meters could help to reduce carbon emissions (IET 2009). These include the management of peak energy demand, and management of imbalances in supply and demand in the short term. Smart meters should also allow energy systems to be operated more efficiently and more securely. For electricity, this should allow the security of the supply to be improved by facilitating adjustments to reserve and reactive power, and frequency response. It should also assist the management of energy networks. By educating customers about energy usage, it should allow them to become engaged, through seeing their direct interrelationship with the supply and demand of energy.

In the UK, the government has proposed that every home should be offered smart meters by 2020, on a voluntary basis. The foundation stage of this process commenced in 2012, and the mass roll-out is due to commence in 2014 (Energy Saving Trust).

9.13 Renewable electricity generation

9.13.1 Renewables in perspective

The need to develop a logical energy strategy, in which renewable energy is the third priority in the hierarchy, was outlined in Chapter 3. The measures outlined in the preceding sections, covering a mixture of demand management and energy efficiency, will directly reduce energy consumption and carbon emissions and should, therefore, be seen as a higher priority than the incorporation of renewable electricity generation.

For renewable technologies in general, it is important to recognise that there are often other more appropriate, and less costly, measures for reducing carbon. Incorporating building-integrated renewables usually involves most of the issues listed in Section 3.4.2, which is not the case with routine energy efficiency measures. The viability of renewables should always be assessed in the wider context of the range of potential carbon reduction measures.

The two main renewable technologies for electricity generation for buildings – wind power and photovoltaics – are often, respectively, the most favoured and least favoured in the renewable assessment hierarchy when based on the cost per unit of carbon reduction. Both of these technologies have potential hazards that must be addressed within the design, and as part of the designer's obligations under CDM as outlined in Chapter 2. These two technologies are discussed below. The other main renewable technologies are covered in Chapters 5 and 6.

Wind power

A: RENEWABLE ENERGY AVAILABILITY AND GENERATION TECHNOLOGY

It is estimated that the proportion of the planet's incident solar radiation that is used to maintain winds is only about 1% (Coley 2008). Wind power is a form of kinetic energy and can reach much higher power densities than solar irradiance, so it has high potential as a renewable energy source (Quaschning 2005). Winds arise from variations in the solar heating in different locations, resulting in differences in pressure in the atmosphere and hence movement of air masses (Boyle 2004). Wind patterns are influenced by geographical location, elevation and terrain. In coastal locations, the potential wind resources are usually much higher than for locations that are deep inland. Sea breezes are generated due to the variation in heat capacities of the land and sea. Because of its lower heat capacity, the land heats up quickly in the daytime, but cools more quickly at night. Cooler air flows from the sea to the land in daytime, replacing warm air rising from the land. At night, cooler air flows from the land to the sea, in a reverse relationship (Boyle 2004). Thus a regular feature in coastal location is 'compensating' winds from the sea to the land during the day, and from the land to the sea during the night. Winds can move easily across the relatively smooth surface of the sea, which offers little surface resistance compared with the land. In a coastal area, mean wind speeds are typically about 6m/s. In inland areas, mean wind speeds are often less than 3m/s. Mountainous regions also provide good wind conditions. In mountain valleys winds travel upwards during the day, and downwards at night, driven by similar differential heating and movement of air masses (Boyle 2004).

The British Isles include locations with some of the EU's higher mean wind velocities (Boyle 2004). For the UK, studies have indicated that wind power – both offshore and onshore – is likely to have both higher potential and lower costs than other renewables (Boyle 2004). More generally, wind power is likely to become more economically viable in the next few decades (Boyle 2004). Historically there has been little wind generation in the UK; however, within the past decade wind farms have expanded significantly. Large-scale wind turbines are a tried and tested technology, but planning issues have limited the growth of wind generation. Although there are many rural wind farms in the UK, major generation projects are mainly in offshore locations, where there are fewer restrictions. Some other European countries, including Germany, Spain and Denmark (Boyle 2004), have extensive wind generation capacity. It should be recognised, however, that as wind speeds are variable and can be still for prolonged periods, wind power is an intermittent resource. This has a major bearing on its viability for both on-site generation, and larger-scale contribution to the grid, as it means that wind energy has minimal impact in addressing maximum demand aspects, its primary benefit being reduction in energy consumption (Boyle 2004). The estimated 'energy payback ratio' for wind power has been estimated as 80:1, which is much higher than for fossil fuel power stations; however, this figure is somewhat artificial, as it does not make allowance for the necessary back-up generation to address intermittency (Coley 2008).

The power generated by a turbine is proportional to the cube of the wind velocity, so the predicted annual energy generation can be severely reduced if the incidence of the mean wind speed is overestimated. The power generated is also directly proportional to the swept area of the blades, so is proportional to the square of the radius (or diameter) of the blades. These cubic and square relationships mean that the best viability will be for large turbines in locations with high wind speeds.

The mean wind speed alone does not fully describe the intermittent nature of wind on a site, but it is relatively easy to obtain and is often used as the measure of site quality or availability. Wind speed frequency distribution (ideally measured for a whole year) provides better information, but is time-consuming and costly to record. Figure 9.13 shows a typical wind speed frequency distribution format. If wind speed is measured at wide intervals, this can result in incorrect estimates of the frequency of wind speeds (Quaschning 2005). Measurements are usually taken at a height of 10m, corresponding to the hub height of a typical small-scale horizontal axis turbine.

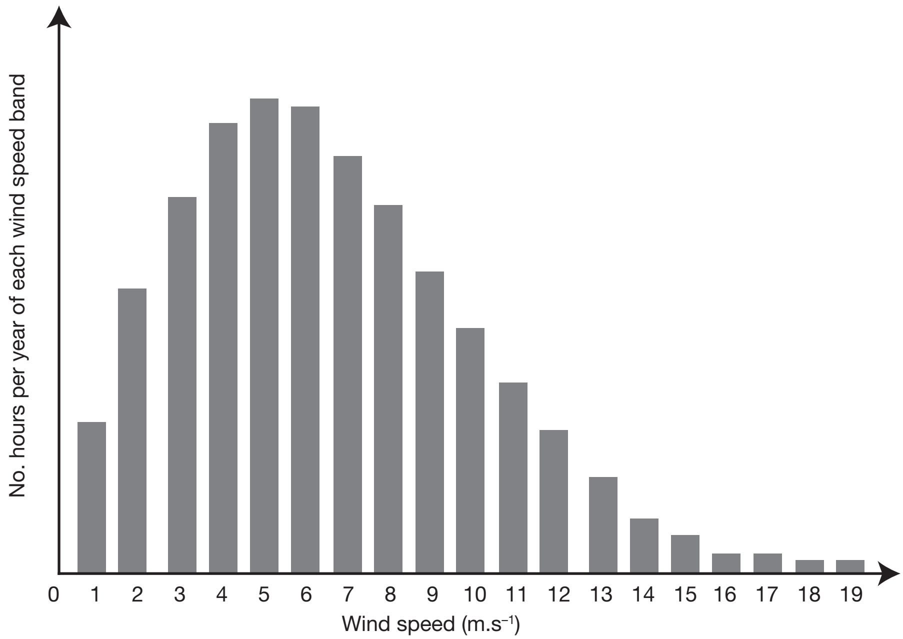


Figure 9.13 Typical wind speed frequency distribution

Source: derived from Boyle 2004: Figure 7.30

The maximum power of a wind, P, is given by (Quaschning 2005):

$$P = 0.5\ \rho\ A\ v^3 \tag{9.2}$$

Where:

ρ = density of air in kg per cubic metre
A = swept area of the blades in metres
v = velocity in metres/second

As air density varies with altitude and temperature, the power generated will also vary with altitude and temperature.

Most horizontal axis wind turbines are three bladed. This arrangement is considered to be slightly more efficient than two-bladed versions (Quaschning 2005). As the number of blades on a turbine increases, they tend to produce higher levels of noise (Boyle 2004).

The velocity reduces as wind passes through a turbine. The turbine utilises the power difference between the wind speeds on either side, while the mass flow rate of air passing through a wind turbine remains constant (Quaschning 2005). However, a wind turbine can only usefully extract a proportion of the total power content of the wind (Coley 2008). This utilisation capability is called the power coefficient of a turbine, Cp, and is defined as:

$$Cp = \frac{P_T}{P_O} \tag{9.3}$$

Where:

P_T is the power used by the turbine
P_O is the power content of the wind

The theoretical maximum value for Cp is about 0.6. In practice, good quality wind turbines usually have power coefficients of about 0.4–0.5 (Coley 2008).

So the power generated by a turbine, Pgen, will be:

$$Pgen = 0.5\ Cp\ \rho\ Av^3 \tag{9.4}$$

To obtain a good energy yield, it is necessary to have high mean wind speeds at the turbine height. Wind speeds can be influenced significantly by terrain, including change in elevation. Wind speed will therefore increase with height. Wind is slowed down by the surface features that determine the roughness of the ground. The wind can also be slowed down considerably by obstacles in its path, such as buildings, trees or hills (Quaschning 2005). In this 'boundary layer', the energy of the wind is dissipated, creating turbulence, making the available wind power highly sensitive to height and location (King 2010b). If the total rotor area is more than three times the area of an obstacle, this usually causes no problem, although this depends on the distance between the turbine and the obstacle (Quaschning 2005). As a result, it is far less appropriate to locate wind turbines in built-up areas or in areas with significant tree cover or other obstructions. Due to the low mounting height of most small-scale and micro turbines, the wind power can reduce to about 12.5% of that available in open countryside, and there would be a further reduction in city centres (King 2010b). Small-scale and micro turbines mounted on buildings in urban and suburban locations therefore provide minimal energy contribution and their usage is questionable. The best viability is large-scale wind power in unobstructed rural locations with high levels of annual wind velocity distribution; but located close to the load.

B: ENERGY YIELD IN PRACTICE

When considering wind generation for a building project or site development, the key issues are location and likely energy yield. The site location will determine the wind pattern and hence the potential for wind generation. The proposed built form and planning considerations will influence the potential locations within the site for wind generation, using either free-standing or building-mounted turbines, and the acceptable rotor height and blade diameter. It will be necessary to consider the potential impact on the site and occupants. Apart from visual impact, turbines create noise, and can cause electromagnetic interference and other environmental impacts (Boyle 2004; Coley 2008). Planning approval can be a major obstacle. All wind turbine proposals require careful assessment to address these issues. The likelihood of new structures being erected in the vicinity, and their potential effect on performance, should also be considered (Roe 2011).

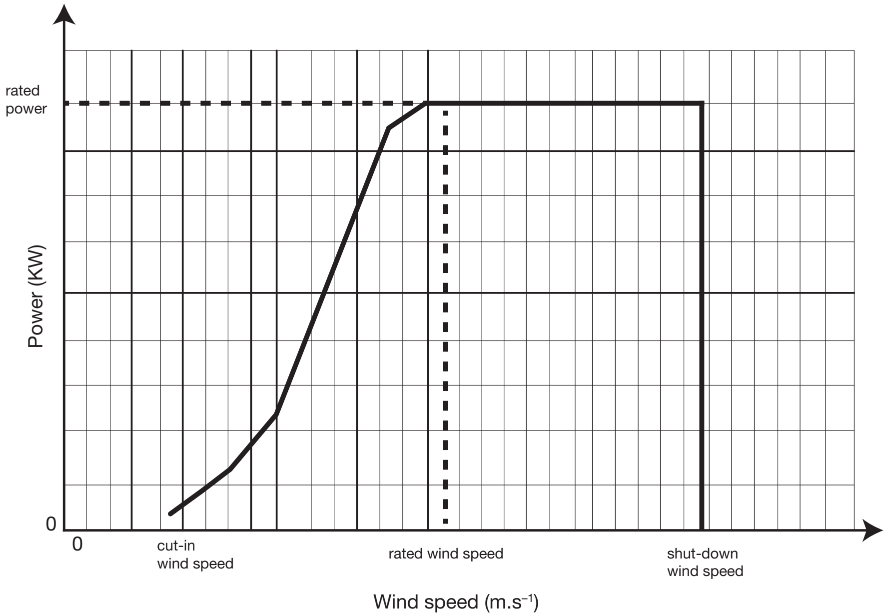


Figure 9.14 Typical format of a wind turbine wind speed power curve

Source: derived from Boyle 2004: figure 7.29

The performance of an individual wind turbine will be represented by a wind speed power curve, in the form shown in Figure 9.14. A wind turbine only provides useful output power within an operational velocity band. Below a predetermined cut-in velocity, the power generated is negligible and operation is prevented. Similarly, operation is prevented above a predetermined high wind speed, or shutdown velocity, in order to protect the turbine from damage. The power generated is often poor at low operational velocities. The wind turbine provides maximum efficiency at the design wind speed, and generates rated power at the rated wind speed (Quaschning 2005).

The typical operational velocity ranges are (Quaschning 2005):

cut-in wind speed: 2.5–4.5m/s
design wind speed: 6–10m/s
nominal wind speed: 10–16m/s
shutdown wind speed: 20–30m/s

The wind speed frequency distribution, in the form shown in Figure 9.13, can be used in conjunction with a wind speed power curve to provide the wind energy distribution. This can then show the summated energy production in relation to the band of operational velocities. There could be inconsistencies between the power curves of different manufacturers' products, as the test procedures may not be standardised (Roe 2011). At the lower end of the power output scale, turbines rated up to about 50kW output have often failed to deliver the predicted energy yield, particularly in urban environments (King 2010b).

The d.c. output generated by the turbine must be converted to a.c. at the required frequency via an inverter. The selection of the inverter should seek the optimum efficiency taking account of the range of operating power levels. The inverter's power loss must be included when assessing the delivered energy from the turbine. There will also be a power loss for distribution from the turbine to the inverter, and from the inverter to the point of connection on the LV distribution system; therefore the locations should be selected to minimise cable lengths.

Where the power generated is above the level of usage within the building or site, the excess can be exported to the grid, in which case the appropriate protection, metering and approvals would be required.

C: PRACTICAL CONSIDERATIONS FOR BUILDING INTEGRATION

For roof-mounted wind turbines the selection of the location on the roof area must consider installation and maintenance requirements. The need to provide the necessary clear space can cause limitations in the planning of other roof-mounted services. Suitable structural support will be required, so design liaison with the structural engineer should commence at an early stage, as transmission of vibrations to the structure can be an issue.

Connecting wind turbines to power systems can cause voltage fluctuations, which can be perceived as changes in the luminance of certain types of lamps (Quaschning 2005). As a general rule, the higher the power rating of the turbine, the more likely that such disturbances and fluctuations would become problematic to occupants. This is more likely to be the case where the grid-derived supply has a high source impedance (Quaschning 2005); although it will depend, to some extent, on the point in the system where the supply from the turbine is connected.

There are other potential issues related to the integration of wind turbines into building projects, due to daylight interference caused by shadows and reflections.

Photovoltaics (PVs)

A: RENEWABLE ENERGY AVAILABILITY AND GENERATION TECHNOLOGY

Solar radiation does not strike the upper atmosphere equally, and is not spread equally at the Earth's surface as it is dependant on latitude and cloud cover; the average net incoming radiation for the planet is 240W/m^2 (Coley 2008). However, this varies considerably with location, so information on the average accumulated radiation over a period of time is required to determine the potential viability of PV generation. Figure 9.15 shows a map of the UK with the variation in average annual total solar radiation per unit area.

A PV or solar cell is a large area semiconductor that uses the 'photovoltaic effect' to absorb the energy of the sun and cause current to flow between two oppositely

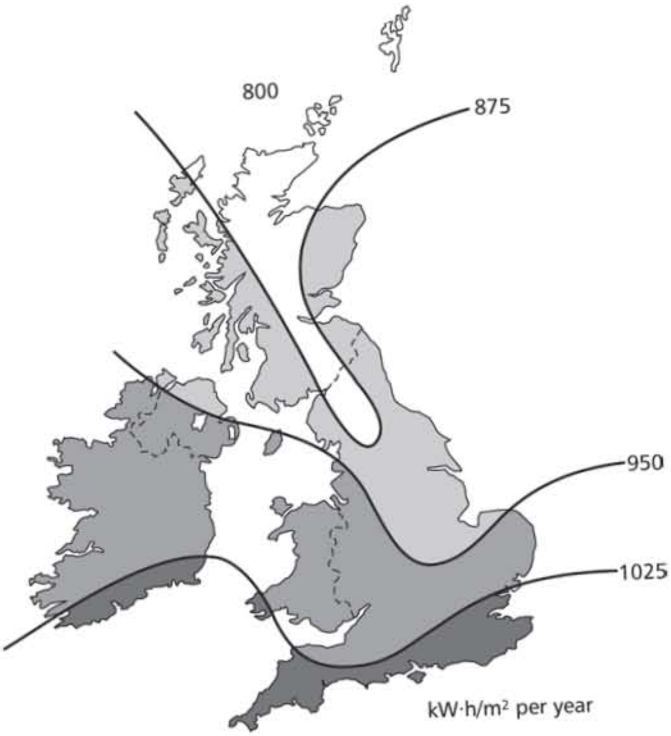


Figure 9.15 UK average annual solar radiation on a horizontal surface

Source: reproduced from CIBSE TM25 (2000b) with the permission of the Chartered Institution of Building Services Engineers charged semiconductor layers. A PV cell is, in effect, a semiconductor junction, usually formed from two differently ‘doped’ crystals of silicon (IET 2007). One half will be an n-type layer, or negatively doped, with a surplus of electrons compared with holes. The other half is a p-type layer, or positively doped, with an excess of holes compared to electrons. A voltage is created in a boundary layer at the junction (IET 2007). The current generated varies with solar intensity, while the d.c. voltage remains constant. The upper p-type layer is translucent to sunlight, and has an anti-reflection surface on the covering of dielectric material (IET 2007; Quaschning 2005). A monocrystalline cell is formed from a single crystal and is considered to be efficient and reliable, but is relatively expensive. A polycrystalline cell is formed from several crystals and is less efficient, but more economic; while thin film cells are more costly with lower efficiency, but use fewer materials (CIBSE 2000b: IET 2007). Cell efficiencies are about 13–17% for monocrystalline cells, and about 12–15% for polycrystalline cells, with module efficiencies a little lower (CIBSE 2000b). The semiconductor technologies are continually changing and this is a major area of research, particularly related to new thin film devices.

The duty of PV devices is expressed as peak power output, Wp. Individual cells would typically generate a voltage of about 0.5–0.6V and have a power rating of about 1.5Wp. The most practical way to protect the cells and harness energy is to form them into modules, typically containing 30–70 cells connected in series and embedded into plastic (CIBSE 2000b; IET 2007). The front surface is glass, while the back is made of glass or plastic. The typical module characteristic is an open circuit voltage of about 20V, with a short circuit current of about 5A, but this can vary (CIBSE 2000b). A module would typically have a rating of up to 100Wp. The usual arrangement is to have an array of modules. Modules are connected in series as a string, the number in the string being that required to provide the desired voltage level. The number of strings that are connected in parallel will determine the current. If just one cell in a module is shaded, the module performance can be significantly reduced as the cell can act as a load and dissipate heat (CIBSE 2000b). Each module usually has a bypass diode to provide protection, which is more economic than a separate diode for each cell (CIBSE 2000b); and each string usually has a blocking diode to prevent reverse current flow.

In its simplest sense a PV system can be considered in a block form as shown at Figure 9.16. The PV array generates d.c. power, and this is converted to a.c. in a power conditioning unit which also contains control and protection equipment (CIBSE 2000b). The system will require the necessary protection equipment for grid connection to ensure disconnection on loss of mains, and d.c. and a.c. isolation devices; and should not result in disturbance beyond established limits (CIBSE 2000b). Where appropriate, suitable meters register the amount of energy imported or exported. PVs are an established technology that is reliable and requires minimal maintenance as the modules are largely self-cleaning. They have widespread usage for local power applications in remote locations, such as for communications, control, data logging, sensing and monitoring equipment. Small-scale panels have become a familiar sight alongside railway lines. Their use in buildings, and in stand-alone PV generation facilities, is growing.

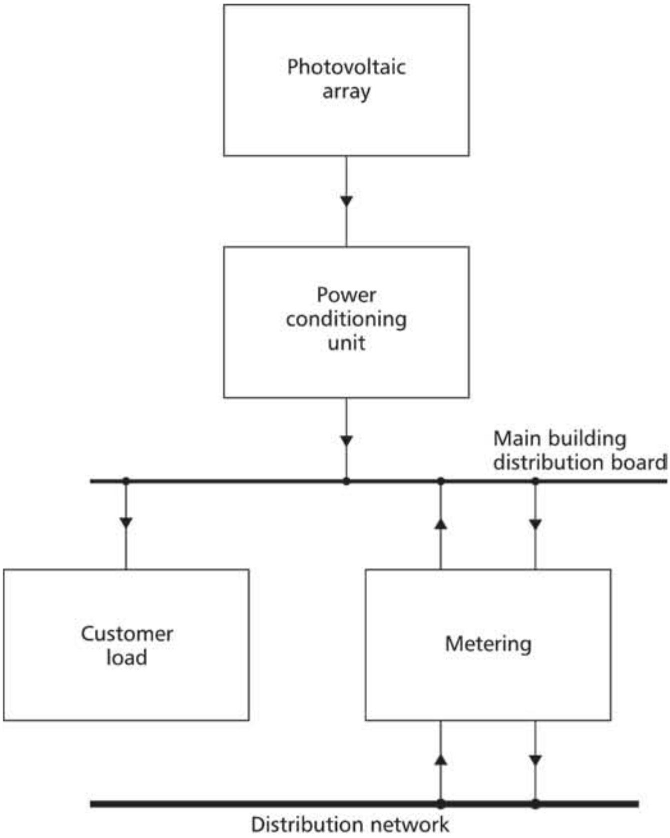


Figure 9.16 Block diagram of a grid-connected PV system

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B: ENERGY YIELD IN PRACTICE

To assess the annual energy yield of a PV system it is necessary to consider the theoretical yield, and then the likely yield in practice. The theoretical energy yield of an array, E, in kWh is given by:

$$E = A.n.H \tag{9.5}$$

Where:

A is the area of the active part of the array in m^2
n is the efficiency of the array
and H is the annual solar irradiation per unit area in kWh (Quaschning 2005)

So, for a PV array with an inclined area of 25m^2, an efficiency of 14%, and an annual solar irradiation of 950kWh/m^2, the theoretical annual energy yield of the array would be:

$$E= (25).(0.14).(950) \text{ kWh} = 3325 \text{ kWh} \tag{9.6}$$

The actual energy yield will be lower in practice, due to shading, dirt on the modules, installation factors and operating temperature (Quaschning 2005). A system might have losses of about 15–20% for these aspects. So, in the above example, a realistic annual energy yield might be:

$$E = (3325).(0.8) = 2660 \text{ kWh} \tag{9.7}$$

There will be additional losses external to the array due to the inverter, transformer (if required) and distribution cabling. Coley (2008) notes these figures for losses for an example application in the UK:

Multiplier to account for losses from cables: 0.98
Efficiency of inverter: 0.85

The resultant annual energy yield would then be:

$$E = 2660 \times 0.98 \times 0.85 = 2216\text{kWh} \tag{9.8}$$

There are useful guidance figures on energy yield related to either module area or peak output. Boyle (2004) states that UK tests have indicated annual yields of 700–100kWh/kWp, and 22–120kWh/m^2 for unshaded optimal orientation; and that a practical assumption in the UK would be 750kWh/kWp per year for crystalline cells. ‘Rules of thumb’ for the UK of 90–110kWh/m^2 per year for crystalline cells with reasonable tilt, orientation and system efficiency; and 700kWh/kWp per year for a roof-mounted grid-connected system, have been provided by CIBSE (2000b).

In the UK, the best power densities are about 120–140W/m^2. To achieve optimum performance, cells should be orientated from south-east to south-west, and tilted at about 30–45 degrees above horizontal. The exact orientation is not too critical to the output. If an array is vertical, orientated between south-east and south-west, and unobstructed, it will receive about 70% of the available maximum annual energy (CIBSE 2000b). The location for the PV modules should be selected so that shadowing (by buildings, parts of buildings, equipment and so on) is avoided. Photovoltaic power generation continues even when skies are overcast or cloudy, but the power generated reduces, so it is an intermittent resource.

Key issues with PV viability relate to the area required for a meaningful level of power generation in relation to the total building electrical load; and, most of all, the very high cost (per unit of carbon offset) of PVs compared with other renewable technologies, or other carbon reduction measures. Cost payback is often in the order of 70–80 years (and sometimes longer), although this can be reduced considerably if grants are available. The lifespan of PV cells is usually estimated at about 25 years. The average embodied energy for PV modules varies from 1,305MJ/m^2 for thin film devices to 4,750MJ/m^2 for monocrystalline devices (Hammond and Jones 2011). It has been estimated that the energy payback period is about two to five years in European conditions (Boyle 2004). In the UK, the economic case related to exporting surplus energy to the grid is complicated due to the changing policies for feed-in tariffs.

It should be noted that the situation described here is for the UK. The energy yield, and hence the viability, would be quite different in countries with higher average solar intensities and longer annual hours of sunshine, and/or where different grant arrangements may apply. PVs usually provide the most benefit in remote locations where establishing a power connection would be prohibitively expensive. This has led to their widespread usage in locations such as alongside railway lines to provide independent stand-alone, small-scale power supply, in conjunction with suitable capacities of battery storage.

C: PRACTICAL CONSIDERATION OF BUILDING INTEGRATION

There has been considerable development of the forms of PV module to improve the options for integration into the envelopes of buildings. This includes glass modules; modules used in curtain-wall cladding systems; roofing tiles; brise soleils and other types of canopy. Where the PV format integrated into the building replaces the need for a conventional element of construction material, this can help to make an economic case. An example would be where a canopy of PV modules also provides solar control shading. There are issues related to available south facing space, particularly at roof level, which might also be in demand for other MEP equipment. The installation should be such that the rear of the cells is properly ventilated to remove heat generated.

Special equipment is required to integrate with a.c. systems (inverter, controls, protection, etc.) (CIBSE 2000b). For connection to a building's a.c. grid-connected system, an inverter is required to convert the module's d.c. output to a.c. power at the required mains voltage and frequency. The grid-commutated inverters must operate the PV generator at the optimal operating point so that maximum power is generated. To do this, the inverters are often combined with a d.c./d.c. converter, known as an MPP (maximum power point) tracker (CIBSE 2000b; Quaschning 2005). The selection of the inverter should take account of the dynamic nature of the operation during changing levels of solar irradiance. It should be recognised that the inverters will operate at their rated power for just a few hours each year. For most of the time, they will be operating at part-load, so it is important for the inverter to maintain good efficiency levels for low loads. Inverters should not be oversized; should have minimal losses; and should be switched off during hours of darkness (Quaschning 2005). The majority of inverters used for PVs generally have an efficiency of about 90%, for an inverter with about 1kW rating, and this efficiency is maintained even down to loads of about 10% of the inverter rating. Higher rated inverters can have an efficiency of up to 96–97% (Quaschning 2005). The lengths of d.c. and a.c. cabling should be kept short to limit distribution losses.

9.14 Summary

In many countries, electricity has a high primary energy carbon factor; furthermore, electrical systems feed both direct electrical system loads and motive power for HVAC systems. Therefore, the efficiency of power distribution can be an important measure for achieving a low-carbon building. Efficiency can be optimised through the appropriate selection of substation disposition and transformer characteristics in relation to the load profile; together with cabling and cable management arrangements to minimise operational and embodied energy impact. Power factor correction and harmonic filtering can reduce energy losses in distribution components in many systems. The efficiency of internal lighting can be addressed through optimising the usage of daylighting, together with attention to design criteria; use of energy efficient lamp and luminaire combinations; and the application of suitable lighting controls and management. Features for energy effectiveness in motor drives, lift installations and other electrical systems have been outlined. Strategic decisions should be made on electricity usage, noting its potential carbon impact. Process loads might give rise to significant energy consumption, so should also be considered in carbon reduction strategies.

Energy management for all active systems can be enabled through suitable controls and building management systems. Such systems should be considered alongside metering systems to provide monitoring to inform an energy management regime.

Where appropriate, wind power and photovoltaics can provide a useful renewable energy contribution, but the viability will be dependent upon the costs, potential energy yield and the practical aspects of integration; and should be a lower priority than reducing demand and improving efficiency.

Chapter 10

Building thermal load calculations

10.1 Introduction

Building heating and cooling load calculations can only be undertaken if the heat transfer mechanisms between the building walls and the internal and surrounding environment are identified. Heat transfer through building walls is caused by a difference in temperature between the exterior and interior surfaces of the wall. During the day, solar radiation strikes the exterior wall surface. A small portion of this energy is reflected while the remainder is absorbed, thereby increasing the wall surface temperature. Because of the higher outer surface temperature of the wall, convection also takes place between the wall and the outdoor air. Heat received at the exterior wall surface is then transferred by conduction through the various material layers in the wall to the interior surface. It should be noted that the nature of this process is strongly affected by the number of wall materials involved, the thickness of each layer and the properties of each material, namely thermal conductivity, density, thickness and heat capacity.

The thermal interaction between the building and the environment is illustrated in Figure 10.1. At the interior surface of the wall, some of the heat is transferred to the room air by convection, while the remainder is radiated to the surfaces of other walls, floors, ceilings and furnishings in the room. At each surface which receives this radiant heat, a proportion is then transferred, through convection, to the room air, conducted into the material mass and stored, or re-radiated to other surfaces in the room. By the repetition of these processes over time, most of the original heat which entered through the wall is eventually transferred to room air.

Since the space heat gain by radiation is partially absorbed by the surfaces and contents of the space, it does not affect the temperature of the room air until sometime later. It follows therefore that the rate at which heat must be removed from the room air to maintain its temperature constant is not the same as the instantaneous rate of heat gain. In air-conditioning systems design, it is therefore important to differentiate between related but distinct heat flow rates, each of which varies with time.

It is the radiant component of the total heat gain that falls on the internal surfaces of the building, and is partly absorbed into the structure as the surfaces are warmed, that appears as a cooling load through convection after a time delay.

The radiant component of the heat gain takes two forms, namely short- and long-wave radiation. Short-wave radiation is due to solar irradiation and part of the electric light spectrum, and long-wave radiation resulting from the rest of the electric light spectrum, people and warm objects such as electrical equipment.

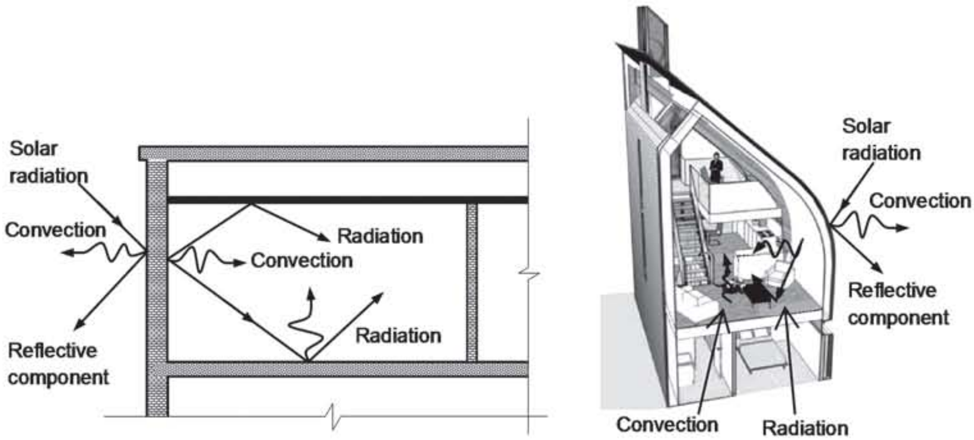

Figure 10.1 Thermal interaction between the building and the environment

The heat gain due to convection within the indoor air volume takes place without time delay and is known as the heat gain to the air node and the heat gain due to the solar or thermal (long-wave) radiation is considered to take place to the environmental node, which is partly due to long-wave heat exchange between indoor surfaces.

Various heating and cooling load calculation techniques are in use; however, the emphasis here will be on the methods recommended by the UK Chartered Institution of Building Services Engineers (CIBSE).

10.2 The cyclic dynamic model and the admittance procedure

This method is based on the calculation of the thermal response of a building using the admittance procedure. It provides a manual method of calculating cooling loads of buildings by assuming a sequence of identical days when the external conditions repeat every 24 hours. This procedure estimates the proportion of the total heat gain that is absorbed by the internal surfaces of the building and therefore reduces the peak cooling load. Figure 10.2 represents the way in which heat energy is interacting with the building structure, and the way 'thermal latency' and 'thermal storage' affect the conversion of heat gains to cooling loads.

The conversion from heat gain to cooling load for a building is illustrated in Figure 10.3, where a building of a random structure is selected and the relation between the heat gain and the cooling load is plotted. It is clear that the component of heat gain that is stored in the building structure causes the peak cooling load to be lower than the peak heat gain.

In Figure 10.3, the upper curve shows the solar heat gain and the lower curve represents the actual cooling load with a constant space temperature during the operating period of the equipment. The horizontally shaded areas represent the heat stored in the building structure and furnishings, while the vertically shaded areas represent the stored heat, which was released to the building space. Since, for a cyclical 24-hour operation, all the heat entering the structure must be removed, the two shaded areas

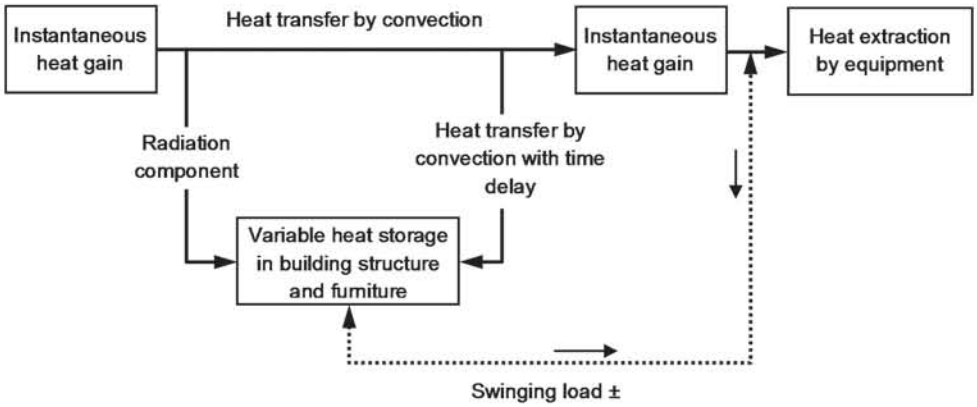

Figure 10.2 Difference between space heat gain and its cooling load

must be equal. It can be seen that the peak load is lower than the peak heat gain and occurs after the peak heat gain has occurred by a noticeable time (time lag). The time lag depends on the building construction, the external walls, floor, ceiling, internal walls or partitions and internal finishes.

From fundamental heat transfer theory and for one-dimensional non-steady heat conduction through a homogeneous material of uniform thermal conductivity, the temperature distribution is given by:

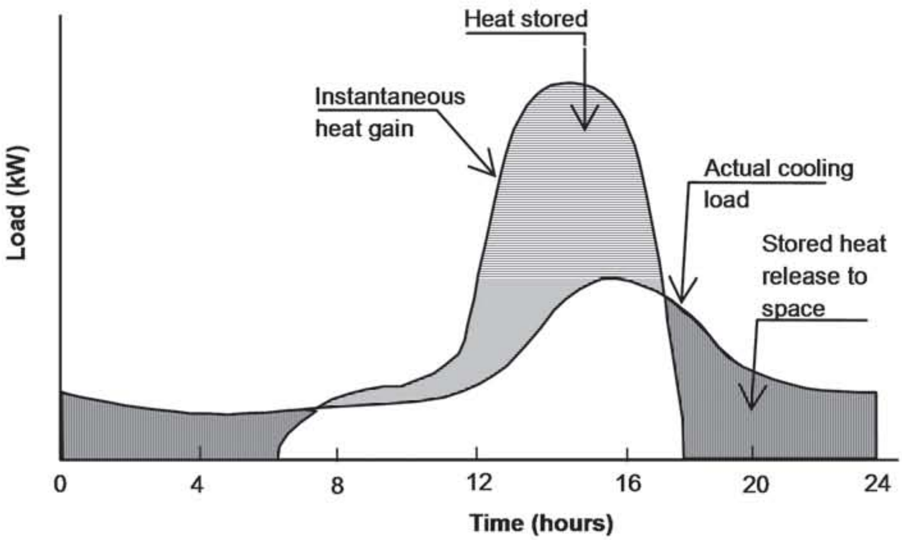

Figure 10.3 The relationship between the heat gain and the cooling load of a building

$$\frac{\delta\theta}{\delta\tau} = \alpha \frac{\delta^2\theta}{\delta x^2} \tag{10.1}$$

Where:
- θ temperature
- x distance
- τ time
- α thermal diffusivity $\left(\frac{k}{\rho c}\right)$
- k thermal conductivity
- ρ density
- c specific heat

The above equation has to be solved in the admittance method for sinusoidal variations. For practical building components such as multi-layered walls with materials containing differing thermal properties, the analytical solution of this equation to sinusoidal variations is complex and cannot be solved easily by manual calculations. The solution requires computer calculation of the resulting matrix algebra or the use of numerical methods such as finite differences. For details of the mathematical solution of the equation for sinusoidal temperature variations you can refer to BS EN ISO 13786 (1999), or Appendix A6 in Section 3 of the CIBSE Guide A (2006) which also includes the mathematical derivation of thermal admittance.

The steps followed to calculate building cooling loads using the admittance procedure will be detailed in a later section, but first the various types of building heat gains will be explained.

10.3 Building heat gains

The various types of building heat gains, illustrated in Figure 10.4, are:

- heat gain through building fabric (sensible gains);
- solar gains through windows and blinds (sensible gains);
- heat gain due to air infiltration and ventilation (sensible and latent gains);
- internal heat gains (sensible and latent gains).

10.3.1 Heat gain through the building fabric

The heat transmission through external walls, internal walls, roofs and a part of the heat transmission through the glazing take place due to conduction of heat through solid structures and is calculated using the concept of the sol-air temperature.

The sol-air temperature is defined as the outside air temperature that, in the absence of solar radiation, would give the same temperature distribution and heat gain through the wall or roof as that which exists with the actual outdoor temperature and the incident solar radiation.

The sol-air temperature θ_{eo} is calculated from the following formula:

$$\theta_{eo} = \frac{\alpha I_t}{h_{so}} + \theta_{ao} \tag{10.2}$$

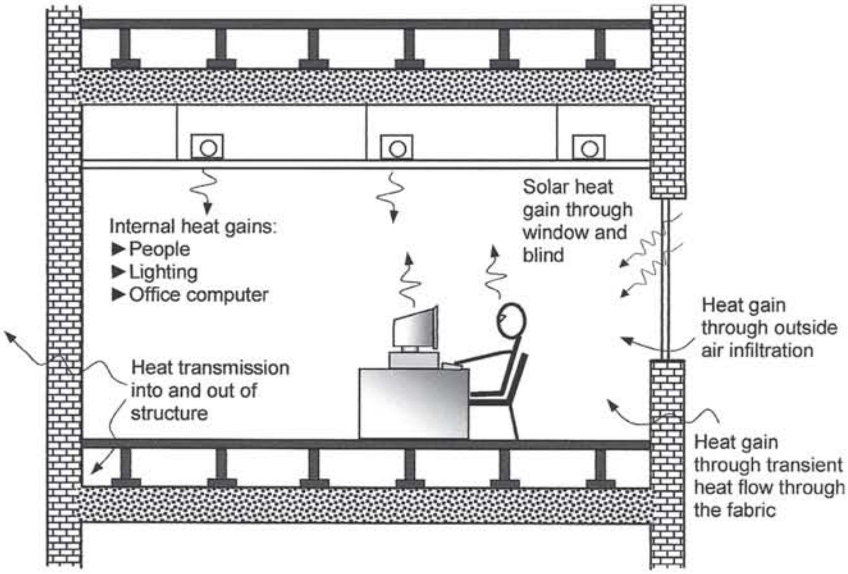

Figure 10.4 Heat gains to a conditioned space

Where

α absorption coefficient for solar radiation
I_t incident short-wave solar radiation
h_{so} outside surface heat transfer coefficient
θ_{ao} outside air temperature.

Sol-air temperatures for three cities in the UK (London, Manchester and Edinburgh) can be found in CIBSE Guide A (2006a) tables 2.34–2.36.

The solar energy incident on an external wall or roof is periodic and the variation in sol-air temperature is also periodic. The degree by which the amplitude of the external temperature variation is dampened at the internal surface is a function of the decrement factor, *f*.

The decrement factor is defined as 'the ratio of the rate of heat flow through the structure due to variations in the external heat transfer temperature from its mean value with the environmental temperature held constant, to the steady state conduction' (CIBSE 2006a) (see Section 10.5).

Figure 10.5 illustrates the temperature cycles induced by sinusoidal temperature variation at the outside surface. The external fluctuations give rise to temperature cycles of smaller amplitude which decay in an exponential way through the wall. There is also a time delay as the temperature wave passes through the wall.

In the cyclic dynamic model, the structural heat gain comprises both mean and alternating components of heat gains through opaque and glazed areas and heat gains through internal partitioning walls, where temperature differences exist across them.

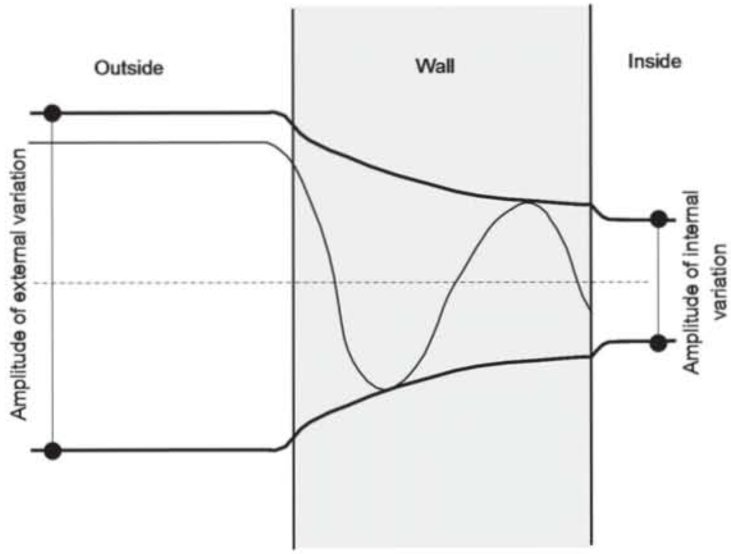

Figure 10.5 Temperature cycles induced by sinusoidal temperature variation at the outside surface

Heat gain through opaque and glazed areas

A heat gain through opaque and glazed areas consists of mean and alternating heat gain components.

The mean heat gain through the fabric at the internal operative temperature is obtained by summing up the mean structural heat gains through the opaque and glazed surfaces:

$$\bar{Q}_f = \Sigma A_n U_n (\bar{\theta}_{eon} - \bar{\theta}_c) + \Sigma A_{gn} U_{gn} (\bar{\theta}_{ao} - \bar{\theta}_c) \tag{10.3}$$

Where:

$\bar{Q}_f$ =	the mean fabric heat gain
$\Sigma A_n U_n$	the sum of the products of the opaque surface areas and corresponding thermal transmittances
$\bar{\theta}_{eon}$	the 24-hour mean sol-air temperature for the wall element *n*
$\Sigma A_{gn} U_{gn}$	the sum of the products of the glazed surface areas and corresponding thermal transmittances
$\bar{\theta}_{ao}$	the 24-hour mean air temperature
$\bar{\theta}_c$	the 24-hour mean internal operative temperature
n	number of wall elements on a particular facade
gn	number of glazed elements on the same facade.

The operative temperature, θ_c in a real room, is defined as the air temperature in a hypothetical room such that an occupant would experience the same net energy exchange with the surroundings (the heat gains to the body equal the heat losses from it). At low air velocities, the operative temperature can be used as an index temperature for thermal comfort.

The operative temperature combines air and mean radiant temperatures into a single index temperature, as follows:

$$\theta_c = \frac{\theta_{ai}\sqrt{10v} + \theta_r}{1 + \sqrt{10v}} \tag{10.4}$$

Where:

θ_c the operative temperature (°C)
θ_{ai} the inside air temperature (°C)
θ_r the mean radiant temperature (°C)
v the air speed (m/s)

For indoor air speeds below 0.2m/s, and when the mean radiant and air temperature difference is less than 0.4°C, the operative temperature becomes the average of the air temperature and the mean radiant temperatures:

$$\theta_c = 0.5\,\theta_{ai} + 0.5\,\theta_r \tag{10.5}$$

For differences smaller than 0.2°C, the operative temperature becomes so close to the air temperature that the two can be used interchangeably without an appreciable error.

The alternating heat gain through the fabric is obtained by summing up the alternating structural heat gains through the opaque and glazed surfaces:

$$\tilde{Q}_f = \Sigma f_n A_n U_n \tilde{\theta}_{eon} + \Sigma A_{gn} U_{gn} \tilde{\theta}_{ao} \tag{10.6}$$

Where

$\tilde{Q}_f$ the alternating fabric heat gain
f_n the decrement factor for the opaque surface, n
$\tilde{\theta}_{eon}$ the alternating component of sol-air temperature for the corresponding opaque surface
$\tilde{\theta}_{ao}$ the alternating component of air temperature.

The alternating component of sol-air temperature is given by:

$$\tilde{\theta}_{eon} = \theta_{eon} - \bar{\theta}_{eon} \tag{10.7}$$

Where θ_{eon} is the sol-air temperature at the particular time the heat gain is determined. If the time is τ, θ_{eon} refers to $(\tau - \phi)$ where ϕ is the time lag.

The alternating air temperature is obtained in the same way, setting the time lag to zero. Thus, the alternating component of air temperature is given by:

$$\tilde{\theta}_{ao} = \theta_{ao} - \overline{\theta}_{ao} \tag{10.8}$$

The values of decrement factors and time lags for typical walls and roofs can be found in CIBSE Guide A (2006): tables 3.49–3.55.

Heat gains through internal partitions

When an air-conditioned space is adjacent to a space which is maintained at a different temperature, heat transfer takes place with heat flowing from the hotter to the colder space through the partition materials. The heat gain can then be calculated taking into account the steady state conditions which exist in both spaces. The rate of heat transfer (heat gain or loss) to or from the conditioned space is given by:

$$Q_i = U\,A\,(\theta_{bi} - \theta_{ai}) \tag{10.9}$$

Where:

U overall heat transfer coefficient (W/m²K)
θ_{bi} temperature of air in adjoining space (°C)
θ_{ai} room air temperature (°C)

Example 10.1 Heat transfer through wall

Location	London 51.7°N
Wall construction	105mm dark-coloured brickwork 50mm air gap 100mm dense concrete 13mm dense plaster
Wall area	30m × 3m
Orientation	Facing south-east (SE)
Internal air temperature	21°C, held constant
Time	August at 9.00, 11.00, 13.00, 15.00, 17.00, 19.00

Assume: the indoor mean radiant temperature, $\theta_r = \theta_{ai}$. Then $\theta_{ai} = \theta_c$

Solution:

Calculation of heat transfer through wall (data)

Item	*Reference*	*Value*	*Unit*
Date		August	
Orientation		SE	
U (thermal transmittance)	CIBSE table 3.49 (No 7a)*	1.77	W/m²
f (decrement factor)	CIBSE table 3.49 (No 7a)*	0.34	
ϕ (time lag) CIBSE table 3.49 (No 7a)*		8.1	hours
$\theta_{sol\text{-}air}$ (24-hour mean)	CIBSE table 2.34(h)*	28.2	°C
Wall area	30 x 3	90	m²

Source: *CIBSE Guide A (2006a)

Heat transfer through wall					
Time of heat gain into room, τ (hour)	*Time at which sol-air temperature should be considered, τ − φ (hour)*	*$\theta_{sol\text{-}air}$ at $\tau - \varphi$ (°C)*	*24-hour mean heat gain (W)*	*Alternating heat gain component (W)*	*Total heat gain (W)*
9.00	1.00	13.2	1147	–812	335
11.00	3.00	11.7	1147	–894	253
13.00	5.00	11.1	1147	–932	215
15.00	7.00	35.9	1147	417	1564
17.00	9.00	53.9	1147	1392	2539
19.00	11.00	53.9	1147	1392	2539

Note: It should be noted that to calculate the heat gain into the room at a given time, e.g. 5pm, the external sol-air temperature that occurred 8 hours earlier is used in the calculation, i.e. 9 am, as there is a time lag of 8 hours, before the temperature wave passes through the wall.

10.3.2 Solar gains through windows and blinds

The response of a space to solar radiation transmitted through and absorbed in the glazing system is characterised by two parameters, the mean solar gain factor and the alternating gain factor. These are further divided into factors relating the heat gain to the room environmental node (causing an increase in the environmental temperature) and the room air node (causing an increase in the air temperature). The latter is used only where internal blinds are fitted. This is because increased convection from blinds significantly changes the proportions of long-wave and convective heat from the surface.

The environmental temperature is a hypothetical temperature determined from heat flow into a room surface by convection from the room and radiation from the surrounding surfaces. This temperature is traditionally given by:

$$\theta_{ai} = {}^{1}\!/_{3}\, \theta_{ai} + {}^{2}\!/_{3}\, \theta_{r} \tag{10.10}$$

a) The mean solar gain factors for the environmental and air nodes are given by (CIBSE 2006a):

$$\bar{S}a = \frac{\textit{Mean solar gain at air node per m}^2 \textit{ of glazing}}{\textit{Mean solar intensity incident on solar facade}} \tag{10.11}$$

$$\bar{S}e = \frac{\textit{Mean solar gain at air environmental node per m}^2 \textit{ of glazing}}{\textit{Mean solar intensity incident on solar facade}} \tag{10.12}$$

b) The alternating solar gain factors for the environmental and air nodes are given by (CIBSE 2006a):

$$\tilde{S}a = \frac{\text{Instantaneous cyclic solar gain at air node per } m^2 \text{ of glazing}}{\text{Instantaneous cyclic solar intensity incident on solar facade}} \tag{10.13}$$

$$\tilde{S}e = \frac{\text{Instantaneous cyclic solar gain at air node per } m^2 \text{ of glazing}}{\text{Instantaneous cyclic solar intensity incident on solar facade}} \tag{10.14}$$

Where no shading devices are used, the alternating gain usually lags the solar intensity by between zero and two hours. The lag time depends on the surface factors (characteristics) for the internal surfaces. High surface factors (e.g. 0.8) give rise to delays of about one hour; low surface factors (e.g. 0.5) give rise to delays of about two hours (the surface factor is defined in Section 10.5)

Typical values of solar gain factors for various glazing configurations are given in Table 10.1. Glazing manufacturers do not usually provide values of these solar factors for their products but the factors can be determined from fundamental principles and the properties of the glazing materials.

One or more for the following properties are normally provided by manufacturers:

- properties at normal incidence (see Appendix 5.A7, CIBSE Guide A 2006);
- shading coefficients;
- total solar energy transmittance ('G-value').

The shading coefficient 'S_c' can be defined as:

$$S_e = \frac{\text{Solar gain through glass and blind at direct normal incidence}}{\text{Solar gain through reference glass at direct normal incidence}} \tag{10.15}$$

The solar gain can be considered to mean the short-wave, long-wave or the total component of the two. The shading coefficient can therefore refer to any of the three gains but in all cases the solar gain through the reference glass at normal incidence can be taken as 0.87 (CIBSE 2006a).

After determining the above solar gain factors, the solar heat gains can be calculated as follows:

Mean solar heat gains

Solar gains through glazing consist of solar radiation, which is absorbed in the glazing and transmitted to the environmental node, and also the transmitted solar radiation, which is absorbed at the internal surfaces of the room and appears at the environmental node.

Table 10.1 Solar gain factors and shading coefficients for various glazing/shading configurations

Description (inside to outside)	*Solar gain factor at environment node*†			*Solar gain factor at air node*		*Shading coefficient S_c*	
	$\bar{S}e$	$\tilde{S}el$	$\tilde{S}eh$	$\bar{S}a$	$\tilde{S}a$	*Short-wave*	*Long-wave*
Single glazing/blind combinations:							
• glass	0.76	0.66	0.50	–	–	0.91	0.05
• absorbing glass	0.61	0.54	0.44	–	–	0.53	0.19
• absorbing slats/clear	0.43	0.44	0.44	0.17	0.18	–	–
• reflecting slats/clear	0.35	0.32	0.31	0.12	0.12	–	–
• 'generic' blind/clear	0.34	0.33	0.29	0.11	0.11	–	–
Double glazing/blind combinations:							
• clear/clear	0.62	0.56	0.44	–	–	0.70	0.12
• clear/reflecting	0.36	0.32	0.26	–	–	0.37	0.08
• low emissivity/clear	0.62	0.57	0.46	–	–	0.62	0.18
• low emissivity/absorbing	0.43	0.38	0.32	–	–	0.36	0.15
• low emissivity/clear/'generic' blind	0.15	0.14	0.11	–	–	–	–
• absorbing slats/clear/clear	0.34	0.36	0.37	0.18	0.21	–	–
• absorbing slats/clear/reflecting	0.19	0.19	0.19	0.12	0.13	–	–
• absorbing slats/low emissivity/clear	0.33	0.35	0.35	0.21	0.23	–	–
• absorbing slats/low emissivity/absorbing	0.22	0.22	0.22	0.16	0.17	–	–
• reflecting slats/clear/clear	0.28	0.29	0.26	0.15	0.16	–	–
• reflecting slats/clear/reflecting	0.17	0.16	0.16	0.10	0.10	–	–
• reflecting slats/low emissivity/clear	0.28	0.27	0.26	0.18	0.20	–	–
• reflecting slats/low emissivity/absorbing	0.18	0.17	0.17	0.14	0.15	–	–
• 'generic' blind/low emissivity/clear	0.29	0.29	0.27	0.17	0.18	–	–
Triple glazing:							
• clear/clear/clear	0.52	0.49	0.40	–	–	0.55	0.17
• clear/clear/absorbing	0.37	0.35	0.29	–	–	0.33	0.15
• clear/clear/reflecting	0.30	0.28	0.23	–	–	0.30	0.09
• clear/low emissivity/clear	0.53	0.50	0.42	–	–	0.50	0.21

Source: CIBSE Guide A 2006a

Note: † For $\tilde{S}e$, subscripts 'l' and 'h' denote thermally 'lightweight' and 'heavyweight' buildings, respectively.

The mean solar heat gain to the internal environmental node, $\bar{Q}_{se}$, is given by:

$$\bar{Q}_{se} = \bar{S}_e \bar{I}_t A_g \tag{10.16}$$

Where

$\bar{I}_t$ the mean total solar irradiance (W/m^2)

The solar irradiance I_t is the sum of the beam, I_{DV}, and diffuse, I_{dv}, solar radiation given by:

$I_t = I_{DV} + I_{dv}$

A_g the area of glazing (m^2)

For the case of internal shading (i.e. blinds), part of the solar gain will enter the air node and part will enter the environmental node.

The mean solar heat gain to the air node is:

$$\bar{Q}_{sa} = \bar{S}_a \bar{I}_t A_g \tag{10.17}$$

Swing in solar heat input

The swing in solar gain to the environmental node is given by:

$$\bar{Q}_{se} = \tilde{S}_e (\hat{I}_t - \bar{I}_t) A_g \tag{10.18}$$

and that to the air node by:

$$\tilde{Q}_{sa} = \tilde{S}_a (\hat{I}_t - \bar{I}_t) A_g \tag{10.19}$$

Where

$\bar{Q}_{se}$ the alternating solar gain to environmental node
$\tilde{Q}_{sa}$ the alternating solar gain to air node
$\hat{I}_t$ the peak total solar irradiance (W/m^2)
$\bar{I}_t$ the 24-hour mean total solar irradiance (W/m^2)

There will be a time delay between the occurrence of the gain and the appearance of the solar cooling load due to the admittance of the room surfaces. This delay is one hour for spaces having a ‘slow’ response and zero for ‘fast’ response spaces.

Example 10.2 Calculate the peak solar heat gain and the solar heat gain at 17.30 for the following glazing configuration:

Location	Edinburgh
Glazing type	Reflecting slats (internal) with single clear glass
Window size	10m × 2m
Orientation	Vertical glazing facing south-west (SW)
Time	August
Space	Lightweight

Solution: The solution is detailed in the following tables

Item	Reference	Value
Date		4 August
Orientation		SW
Glass area	$A_g = 10 \times 2$	20m²
$\bar{S}_a$ Mean solar gain factor air node	CIBSE, table 5.7*	0.12
$\tilde{S}_a$ Alternating solar gain factor air node	CIBSE, table 5.7*	0.12
$\bar{S}_e$ Mean solar gain factor environmental node	CIBSE, table 5.7*	0.35
$\tilde{S}_e$ Alternating solar gain factor environmental node, light weight space	CIBSE, table 5.7*	0.32

Source: *CIBSE 2006a

(a) Peak solar heat gain through the glazing

Item	Reference	Value	Unit
Time for peak heat gain	CIBSE, table 2.32	13.30	
I_{Dv} (peak) – beam	CIBSE, table 2.32	444	W/m²
I_{dv} (peak) – diffuse	CIBSE, table 2.32	220	W/m²
$I_{t,\ max}$ (peak)	$I_{Dv} + I_{dv}$	664	W/m²
$I_{t,mean}$ Mean solar radiation (24 hours)	CIBSE, table 2.32	187	W/m²
Mean solar gain at air node $\bar{Q}_{sa}$		448	W
Alternating solar gain at air node $\tilde{Q}_{sa}$		1144	W
Peak air node solar heat gain Q_{sa}	$\tilde{Q}_{sa} + \bar{Q}_{sa}$	1592	W
Mean solar gain at environmental Node $\bar{Q}_{se}$		1310	W
Alternating solar gain at environmental Node $\tilde{Q}_{se}$		3052	W
Peak environmental node solar heat gain Q_{se} @ 13.30	$\tilde{Q}_{se} + \bar{Q}_{se}$	4362	W
Total solar heat gain @ 13.30 Q_s		5954	W

(b) Solar heat gain through the glazing at 17.30

Item	Reference	Value	Unit
Time		17.30	
I_{Dv} (peak) – beam	CIBSE, table 2.32	116	W/m²
I_{dv} (peak) – diffuse	CIBSE, table 2.32	109	W/m²
$I_{t,\ max}$ (peak)	$= I_{Dv} + I_{dv}$	225	W/m²
$I_{t,mean}$ Mean solar radiation (24 hours)	CIBSE, table 2.32	187	W/m²
Mean solar gain at air node $\bar{Q}_{sa}$		448.8	W
Alternating solar gain at air node $\tilde{Q}_{sa}$@ 17.30		91.2	W
Air node solar heat gain Q_{sa}@ 17.30	$\tilde{Q}_{sa} + \bar{Q}_{sa}$	540	W
Mean solar gain at environmental node $\bar{Q}_{se}$	$\bar{S}_e \bar{I}_t A_g$	1309	W
Alternating solar gain at environmental node $\tilde{Q}_{se}$ @ 17.30	$\tilde{S}_e (\hat{I}_t - \bar{I}_t) A_g$	243.2	W
Environmental node solar heat gain Q_{se} @ 17.30	$\bar{Q}_{se} + \tilde{Q}_{se}$	1552.2	W
Total solar heat gain @ 17.30	$Q_{sa} + Q_{se}$	2092.2	W

Note: The above calculation assumes that there is no shading of the glass area from external overhangs or deep window reveals, etc. In practice the shaded area of the glass would be calculated from the solar altitude and azimuth and deducted from the total area before the heat gain is calculated.

10.3.3 Heat gain due to air infiltration and ventilation

Infiltration is the uncontrolled flow of air through cracks and other openings around windows and doors and through floors and walls. Ventilation is the intentional displacement of indoor air by the air-conditioning system or through specified openings such as windows and doors. The rate of infiltration or natural ventilation is a function of the pressure difference across the building envelope. This pressure difference is caused either by:

- wind pressure;
- difference in density between the indoor and outdoor air, often called the chimney or stack effect;
- pressure generated by a mechanical ventilation system.

In recent years, several techniques for calculating infiltration rates have been developed. These are outlined in ASHRAE *Handbook of Fundamentals* (2009) and CIBSE Guide A (2006).

A simplified estimate of the instantaneous heat gain due to infiltration or ventilation to the air node of a building is given by:

$$Q_v = C_v\,(\theta_{a0,\tau} - \theta_c) \tag{10.20}$$

Where:

Q_v heat gain due to air infiltration/ventilation
C_v the infiltration/ventilation conductance (W/K) and is given as:
$C_v = \rho c_p NV$

Where N is the number of room air changes for air entering the space at the outside air temperature (per hour) and V is the room volume (m^3). Values for N for various building types can be found in tables 4.13 to 4.21 in CIBSE Guide A (2006). Converting the number of air changes per hour to air changes per second and using, $\rho c_p \approx 1200$ J/m^{3}K, the following relation for the ventilation conductance in SI units becomes:

$$C_v = \frac{1200\,NV}{3600} = \frac{NV}{3} \tag{10.21}$$

Where:

$\theta_{a0,\tau}$ outside air temperature at time, τ (°C)
θ_c indoor operative air temperature (°C)

Equation 10.20 can be used for simple calculation of infiltration gains. For more precise infiltration/ventilation heat gain calculations, the alternating component of the heat gain needs to be considered. Therefore, by the admittance procedure method, the mean and the alternating components of the infiltration/ventilation heat gains need to be calculated as follows:

The mean infiltration/ventilation heat gain component:

$$\bar{Q}_v = C_v (\bar{\theta}_{ao} - \bar{\theta}_c) \tag{10.22}$$

The alternating infiltration/ventilation heat gain component:

$$\tilde{Q}_v = C_v \tilde{\theta}_{ao} \tag{10.23}$$

Where: $\tilde{\theta}_{ao} = \hat{\theta}_{ao} - \bar{\theta}_{ao}$; $\hat{\theta}_{ao}$ is the air temperature at peak hour

The total infiltration/ventilation heat gain can then be estimated from:

$$Q_v = \bar{Q}_v + \tilde{Q}_v \tag{10.24}$$

10.3.4 Internal heat gains

Internal heat gains arise from the heat released by the following elements into the environmental node within the considered space:

- occupants
- lighting
- equipment.

Occupants give out heat and moisture in the conditioned space. The rates at which the heat and moisture are released depend on the different states of activity of the people in the conditioned space. Typical values of sensible and latent gains for various activities, adapted from the ASHRAE *Handbook of Fundamentals* (2009) are given in Table 10.2.

Lighting

The heat gains from lighting are partly due to convection and partly due to radiation which is first absorbed by the building structure and furnishings before it is released to

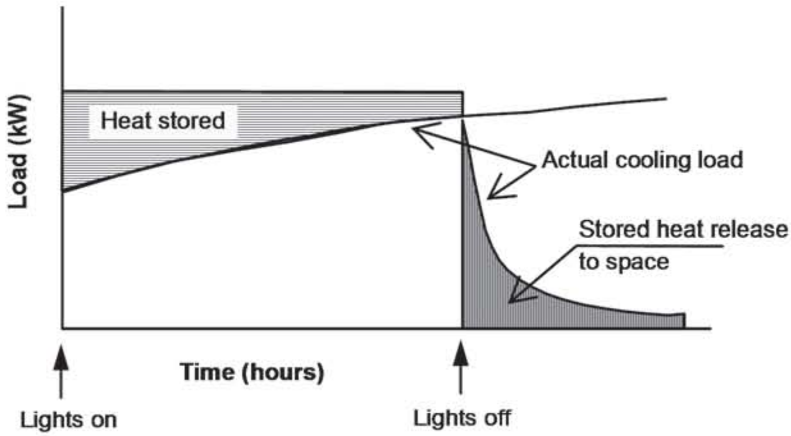

Figure 10.6
Influence of radiant energy from lighting on cooling load

Table 10.2 Rates of sensible and latent heat gains from occupants for different levels of activity.

Degree of activity	*Typical building*	*Total rate of heat emission for adult male (W)*	*Rate of heat emission for mixture of males and females (W)*			*Percentage of sensible heat that is radiant heat for stated air movement /(%)*	
			Total	*Sensible*	*Latent*	*High*	*Low*
Seated at theatre	Theatre, cinema (matinee)	115	95	65	30	–	–
Seated at theatre, night	Theatre, cinema (night)	115	105	70	35	60	27
Seated, very light work	Offices, hotels, apartments	130	115	70	45	–	–
Moderate office work	Offices, hotels, apartments	140	130	75	55	–	–
Standing, light work: walking	Department store, retail store	160	130	75	55	58	38
Walking; standing	Bank	160	145	75	70	–	–
Sedentary work	Restaurant	145	160	80	80	–	–
Light bench work	Factory	235	220	80	140	–	–
Moderate dancing	Dance hall	265	250	90	160	49	35
Walking; light machine work	Factory	295	295	110	185	–	–
Bowling	Bowling alley	440	425	170	255	–	–
Heavy work	Factory	440	425	170	255	54	19
Heavy machine work: lifting	Factory	470	470	185	285	–	–
Athletics	Gymnasium	585	525	210	315	–	–

the conditioned space. This creates a time lag, so that part of the absorbed energy is radiated back to the space after the lights have been switched off, as shown in Figure 10.6.

Table 10.3 provides typical values of the convective and radiant heat outputs from various lamp types.

Table 10.3 Energy heat output from different types of lamps

Lamp type	*Heat output (%)*		
	Radiant	*Conducted/convected**	*Total*
Fluorescent	30	70	100
Filament (tungsten)	85	15	100
High pressure mercury/sodium, metal halide	50	50	100
Low pressure sodium	43	57	100

Source: CIBSE *Code for Lighting* 2002

* The power loss of ballasts should be added to the conducted/convected heat

Equipment

The heat gains from the various types of equipment need to be taken into account when calculating internal heat gains. In buildings such as data centres and restaurants, equipment heat gains form the largest heat gain of the building. Typical values for heat gains from various office equipment are given in Table 10.4.

For building services engineers it is normal practice to specify internal heat gains (including occupants, lighting and equipment) in the form of watts per square metre (W/m²). Typical values of these heat gains for different building types are given in Table 10.5.

Table 10.4 Typical heat gains from office equipment

PCs Nature of value		Value for stated mode (W)	
		Continuous	Energy saving
Average		55	20
Conservative		65	25
Highly conservative		75	30
PC monitors			
Monitor size		Value for stated mode (W)	
		Continuous	Energy saving
Small (13–15 inch)		55	0
Medium (16–18 inch)		70	0
Large (19–20 inch)		80	0
Laser printers			
Printer size	Value for stated mode (W)		
	Continuous	1 page/min.	Idle
Small desktop	130	75	10
Desktop	215	100	35
Small office	320	160	70
Large office	550	275	125
Photocopiers			
Copier size	Value for stated mode (W)		
	Continuous	1 page/min.	Idle
Desktop copier	400	85	20
Office copier	1100	400	300
Fax, scanner and dot matrix printer			
Device		Value for stated mode (W)	
		Continuous	Energy saving
Fax machine		30	15
Scanner		25	15
Dot matrix printer		50	25

Source: Wilkins and Hosni (2000)

Table 10.5 Internal heat gains in typical buildings in W/m²

Building type	Use	Density of occupation (person/m²)	Sensible heat gain (W/m²)			Latent heat gain (W/m²)	
			People	Lighting	Equipment†	People	Other
Offices	General	12	6.7	8–12	15	5	–
		16	5	8–12	12	4	–
	City centre	6	13.5	8–12	25	10	–
		10	8	8–12	18	6	–
	Trading/dealing	5	16	12–15	40+	12	–
	Call centre floor	5	16	8–12	60	12	–
	Meeting/conference	3	27	10–20	5	20	–
	IT rack rooms	0	0	8–12	200	0	–
Airports/stations‡	Airport concourse	0.83	75	12	5	4	–
	Check-in	0.83	75	12	5	50	–
	Gate lounge	0.83	75	15	5	50	–
	Customs	0.83	75	12	5	50	–
	Immigration						
	Circulation spaces	10	9	12	5	6	–
Retail	Shopping malls	2–5	16–40	6	0	12–30	–
	Retail stores	5	16	25	5	12	–
	Food court	3	27	10	†	20	§
	Supermarkets	5	16	12	†	12	§
	Department stores:						
	• jewellery	10	8	55	5	6	–
	• fashion	10	8	25	5	6	–
	• lighting	10	8	200	5	6	–
	• china/glass	10	8	32	5	6	–
	• perfumery	10	8	45	5	6	–
	• other	10	8	22	5	6	–
Education	Lecture theatres	1.2	67	12	2	50	–
	Teaching spaces	1.5	53	12	10	40	–
	Seminar rooms	3	27	12	5	20	–
Hospitals	Wards	14	57	9	3	4.3	–
	Treatment rooms	10	8	15	3	6	–
	Operating theatres	5	16	25	60	12	–
Leisure	Hotel reception	4	20	10–20	5	15	–
	Banquet/conference	1.2	67	10–20	3	50	–
	Restaurant/dining	3	27	10–20	5	20	–
	Bars/lounges	3	27	10–20	5	20	–

Source: CIBSE Guide A 2006a

Notes: The internal heat gain allowance should allow for diversity of use of electric lighting coincident with peak heat gain and maximum temperatures. Lighting should be switched off in perimeter/window areas (up to say 4.5m) and no allowance account for any dimming or other controls.
† Equipment gains do not allow for heavy-duty local equipment such as heavy-duty photocopiers and vending machines.
‡ The exact density will depend upon airport and airplane capacity, the type of gate configuration (open or closed) and passenger throughput. Absolute passenger numbers if available would be a more appropriate design basis. Appropriate building scale diversities need to be derived based on airport passenger throughput.
§ Latent gains are likely but there are no benchmark allowances and heat gains need to be calculated from the sources, e.g. for meals, 15W per meal served, of which 75% is sensible and 25% latent heat (ASHRAE 2005).

In accordance with the admittance procedure, the total internal heat gain consists of the mean and alternating components as follows:

$$Q_{int} = \bar{Q}_{int} + \tilde{Q}_{int} \tag{10.25}$$

Where:

$$\bar{Q}_{int} = \frac{\sum_i^n \bar{Q}_{int,n}\, t_n}{24}$$

and $\tilde{Q}_{int} = \hat{Q}_{int} + \bar{Q}_{int}$

n refers to the heat gain source and t_n to the duration of the source (hours of operation). The internal gains can be a combination of convective Q_{con} and radiant Q_{rad} gains.

10.4 Total building heat gain

The total heat gain has two components: mean and alternating. These two components contribute to the air and environmental nodes as follow:

Mean heat gain into the environmental and air nodes

This is the mean value over 24 hours and is given as follows for the air and environmental nodes:

Environmental note: $\bar{Q}_{te} = \bar{Q}_{se} + \bar{Q}_{int} + \bar{Q}_f$ (10.26)

Air node: $\bar{Q}_{ta} = \bar{Q}_{sa} + \bar{Q}_v$ (10.27)

Alternating heat gain into the environmental and air nodes

This, for the air and environmental nodes, is given as follows:

Environmental note: $\tilde{Q}_{te} = \tilde{Q}_{se} + \tilde{Q}_{int} + \tilde{Q}_f$ (10.28)

Air node: $\tilde{Q}_{ta} = \tilde{Q}_{sa} + \tilde{Q}_v$ (10.29)

10.5 Building classification and thermal response

Buildings are classified as having either a slow or a fast response to heat transfer. The response of a space to thermal input depends upon:

- type of thermal input
- surface finishes

- thermal properties of the construction
- thickness of the construction
- furnishings within the space.

The heat input to the surfaces will be in the form of:

- short-wave radiation (solar radiation and energy from electric lights); or
- combination of long-wave radiation (from surfaces and other emitters) and convective exchange with the air.

The thermal response of a building is affected by:

- the thickness of the building structural materials;
- the properties of the structural materials (i.e. thermal conductivity, density and specific heat capacity);
- the relevant positions and orientations of the various construction elements of the building.

To determine the thermal response of a building, the following three parameters need to be known.

The admittance

Denoted by *Y*, this is the most significance parameter when using the admittance procedure. It is defined as 'the rate of flow of heat between the internal surfaces of the structure and the environmental temperature in the space, for each degree of deviation of the space temperature about its mean value' (CIBSE 2006a) and it has the same unit as that of the heat transfer coefficient (*U*):

$$Y = \frac{\hat{q}_i}{\hat{\theta}_i} \tag{10.30}$$

Where:

Y thermal admittance (W/m^{2}K)
$\hat{q}_i$ amplitude of heat entering the surface
$\hat{\theta}_i$ amplitude of variation of temperature.

The associated time dependency of the thermal admittance takes the form of a time lead denoted by ω. The admittance equals the *U*-value of a building structure if this structure is thin (less than 100mm in thickness) and consists of a single layer of material with time lead equal to zero. In multi-layered constructions it is the *inside* surface layer which primarily determines the admittance.

Decrement factor (f)

The decrement factor as described in Section 10.3.1 is 'the ratio of the rate of heat flow through the structure due to variations in the external heat transfer temperature from its mean value with the environmental temperature held constant, to the steady state conduction' (CIBSE 2006a). The time dependency, associated with f takes the form of a time lag denoted by ϕ. $f = 1$ and $\phi = 0$ for thin structures of low thermal capacity value. With increasing thermal capacity of structure materials, f decreases as ϕ increases.

Surface factor (F)

The surface factor is defined as 'the ratio of the variation of radiant heat flow (from short-wave sources) about its mean value readmitted to the space from the surface, to the variation of heat flow about its mean value incident upon the surface. The associated time dependency takes the form of a time lag denoted by ψ' (CIBSE 2006a). The surface factor value decreases and its time lag increases with increasing thermal conductivity but both remain virtually independent of the material thickness.

The physical process involved is that short-wave radiation is absorbed at the surface, which, after a delay due to thermal storage, causes the temperature of that surface to rise. Heat is then transferred to the space in the form of long-wave radiation and convection. The effect is to raise the internal heat transfer temperature (i.e. environmental temperature). The response of a space to changes in environmental temperature is characterised by the admittance of the surfaces, which depends upon the long-wave emissivity, the surface heat transfer coefficient and the thermal properties of the structure.

There are therefore two time delays associated with the thermal response of the space, one which applies to short-wave radiation and the other due to surface-to-surface and surface-to-air heat exchanges. Thus, it is possible for a space to be lightweight in terms of its response to solar radiation but heavyweight in terms of the change in temperature arising from other sources of heat input.

Buildings are categorised as fast or slow, with regards to their thermal response to short-wave radiation as follows:

Fast:	surface factor, $F = 0.8$ with a delay, ψ of 1 hour
Slow:	surface factor, $F = 0.5$ with a delay, ψ of 2 hours

Response to the changes in the environmental temperature is characterised by the response factor, f_r, given by:

$$f_r = \frac{\Sigma AY + C_v}{\Sigma AU + C_v} \tag{10.31}$$

Where

f_r	is the response factor
$\Sigma(AY)$	is the sum of the products of surface areas and their corresponding thermal admittances (W/K)

Σ(AU) is the sum of the products of surface area and corresponding thermal transmittance of surfaces through which heat flow occurs (W/K)

C_v is the infiltration/ventilation conductance (W/K) (see Equation 10.21)

Taking the response factor into account, buildings can then be classified as follows:

High thermal response ($f_r > 4$) → Slow response building (*heavyweight*)
Low thermal response ($f_r \leq 4$) → Fast response building (*lightweight*)

Nominal building classifications according to the response factor and values of the three parameters, Y, f_r and F for buildings with slow or fast thermal response are provided in Table 10.6.

10.6 Building cooling load calculations using the admittance procedure

The admittance procedure for cooling load calculation recognises that a person's feeling of thermal comfort depends on the heat exchanges between the body of a person to the indoor environment by convective heat loss to the indoor air and by radiant heat loss to the indoor environment.

Operative temperature

To assess the cooling loads using the admittance procedure, the concept of *operative temperature* as defined in Section 10.3 is used.

The mean operative temperature for a fixed ventilation rate is given by:

$$\bar{\theta}_c = \frac{\bar{Q}_{ta} + F_{cu} Q_{te}}{C_v + F_{cu} \sum AU} \tag{10.32}$$

Table 10.6 Typical amplitude values of the admittance (Y), decrement factor (f) and surface factor (F) with time lag/lead values

Thermal response	*Typical features of construction*	*Response to short-wave radiation*			
		Response factor, f_r	*Average surface factor, F*	*Time delay, ϕ (h)*	*Time lead for admittance, ω (h)*
Slow	Masonry external walls and internal partitions, bare solid floors and ceilings	> 4	0.5	2	1
Fast	Lightweight external cladding, de-mountable partitions, suspended ceilings, solid floors with carpet or wood block finish or suspended floors	≤ 4	0.8	1	0

Source: CIBSE Guide A 2006a

Where:

$\bar{Q}_{ta}$ mean total heat gain at the air node, from Equation 10.27
$\bar{Q}_{te}$ mean total heat gain at the environmental node, from Equation 10.26
C_v the ventilation conductance (W/K)
$\Sigma(AU)$ the sum of the products of surface area and corresponding thermal transmittance over surfaces through which heat flow occurs (W/K)
F_{cu} mean room conductance factor with respect to operative temperature. Using standard heat transfer coefficient and emissivity values, F_{cu} is given by (CIBSE 2006a):

$$F_{cu} = \frac{3(C_v + 6\sum A)}{\sum AU + 18\sum A} \tag{10.33}$$

The alternating value of the internal operative temperature caused by the building thermal storage is given by:

$$\tilde{\theta}_c = \frac{\tilde{Q}_{ta} + F_{cu}\tilde{Q}_{te}}{C_v + F_{cy}\sum AU} \tag{10.34}$$

$\tilde{Q}_{ta}$ and $\tilde{Q}_{te}$ can be obtained from Equations 10.29 and 10.28, respectively. F_{cu} is the room admittance factor with respect to operative temperature and is given by:

$$F_{cy} = \frac{3(C_v + 6\sum A)}{\sum AY + 18\sum A} \tag{10.35}$$

$\Sigma(AY)$ is the sum of the products of surface area and corresponding thermal admittance (W/K).

The peak value of the internal operative temperature can then be calculated from:

$$\hat{\theta}_c = \bar{\theta}_c + \tilde{\theta}_c \tag{10.36}$$

Building overheating risk is detailed in CIBSE Guide A (2006).

Building cooling load for a convective cooling system

The cooling load is influenced by the characteristics of the heat emitter in the space and the temperature used for the control of the system. The section below outlines the method of cooling load calculation for a convective cooling system. Equations for the calculation of cooling loads for a radiant or a combined convective and radiant system are given in chapter 5 of CIBSE Guide A (2006).

For a convective cooling system (zero radiant component), the total sensible cooling required to control the operative temperature in a space is given by:

$$Q_k = \bar{Q}_a + \tilde{Q}_a + Q_{sg} + Q_v \tag{10.37}$$

Where:

Q_k = total sensible cooling load (W)
$\bar{Q}_a$ = mean convective cooling load (W)
$\tilde{Q}_a$ = alternative component of convective cooling load (W)
Q_{sg} = cooling load due to windows and blinds (W)
Q_v = cooling load due to air infiltration or ventilation (W).

Mean convective cooling load

The mean convective cooling load can be calculated as follows:

$$\bar{Q}_a = \bar{Q}_{fa} + F_{cu} 1.5\ \bar{Q}_{rad} + \Sigma\bar{Q}_{con} - 0.5\ \bar{Q}_{rad} \tag{10.38}$$

Where:

$\bar{Q}_{fa}$ mean fabric gain at air node (W) given by: $\bar{Q}_{fa} = F_{cu}\bar{Q}_f$
$\bar{Q}_f$ and F_{cu} can be determined from Equations 10.3 and 10.33 respectively
$\bar{Q}_{rad}$ daily mean radiant gain (W)
$\bar{Q}_{con}$ daily mean convective gain (W)

Alternating component of convective cooling load

The alternating component of the convective cooling load is calculated from the following:

$$\tilde{Q}_a = \tilde{Q}_{fa} + F_{cy} 1.5\ \tilde{Q}_{rad} + \Sigma\tilde{Q}_{con} - 0.5\ \tilde{Q}_{rad}$$

Where:

$\tilde{Q}_{fa}$ alternating component of fabric gain at air node, which is calculated from: $\tilde{Q}_{fa} = F_{cu}\,\tilde{Q}_f$
$\tilde{Q}_f$ and F_{cy} can be determined from Equations 10.6 and 10.35 respectively
$\tilde{Q}_{rad}$ alternating component of radiant gain (W)
$\tilde{Q}_{con}$ alternating component of convective gain (W)

Cooling load due to windows and blinds

The cooling loads due to windows and blinds can be determined in a simplified manner using tables 5.19–5.24 in CIBSE Guide A (2006). These tables apply to certain locations in the United Kingdom as follows:

- tables 5.19 and 5.20 (SE England)
- tables 5.21 and 5.22 (NW England)
- tables 5.23 and 5.24 (NE Scotland)

The CIBSE Tables also assume:

- constant internal temperature with cooling plant operating 10 hours per day (7.30–17.30);
- sunny spell of 4–5 days duration;
- *fast response (lightweight)* buildings, see Table 10.6 for characteristics.

For *slow response (heavyweight)* buildings, correction factors included at the end of tables 5.19–5.24 in CIBSE Guide A should be used.

Using these factors the cooling load due to glazing can be determined from:

$$Q_{sg} = C_f C_c Q_{st} A_g \tag{10.40}$$

Where:

Q_{sg} = cooling load due to solar gain
C_f = correction factor for building response
C_c = correction factor for air temperature control
Q_{st} = cooling load given in tables
A_g = glazing area

Cooling load due to air infiltration (ventilation)

The sensible cooling load due to infiltration/ventilation, Q_V is calculated from Equation 10.22.

The latent heat load due to infiltration/ventilation, Q_{VL} can be calculated

$$Q_{VL} = \rho \frac{N}{3600} V(g_{ao.\tau} - g_{ai})\, h_{fg} \tag{10.41}$$

Where:

ρ = density of air
N = air changes per hour
V = room volume

$g_{ao.\tau}$ and g_{ai} are moisture content of external and internal air respectively at the time of load calculation
h_{fg} = latent heat of evaporation of water.

If the values of ρ and h_{fg} are assumed to remain approximately constant with changes in ambient and room conditions, Equation 10.41 becomes.

$$Q_{VL} \approx 0.8\, NV\, (g_{ao.\tau} - g_{ai})\, (W) \tag{10. 42}$$

Where: room volume is in m^3, and moisture content in grams of water vapour per kilogram of dry air (g_w/kg_{da}).

The above calculations for the cooling load are based on controlling the internal operative temperature. For control of the air temperature, the above equations can be used after substituting the following:

- The operative temperature, θ_c is replaced by indoor air temperature, θ_{ai};
- F_{cu} and F_{cy} are replaced by F_{au} and F_{ay}, room conductance and admittance factors respectively for air temperature (°C) and are given by:

$$F_{au} = \frac{4.5 \sum A}{4.5 \sum A + \sum (AU)} \tag{10.43}$$

$$F_{ay} = \frac{4.5 \sum A}{4.5 \sum A + \sum (AY)} \tag{10.44}$$

10.7 Building heating load calculations

If used to calculate heating loads, the admittance procedure described in the previous section for cooling load calculations can cause an under-sizing of heating systems and a delay in achieving the building design internal operative temperature (or internal air temperature).

To avoid under-sizing of heating systems, the CIBSE Simple Model is recommended for heating load calculations.

CIBSE Simple Model for heating load calculations

According to this model, the heating load has the same value as the total of heat losses through the building, Q_h, which is the sum of the heat losses through the building fabric and losses due to ventilation/infiltration. It is calculated as follows:

$$Q_h = [F_{1cu} \sum AU\, (\theta_c - \theta_{ao}) + F_{2cu}\, C_v]\, (\theta_c - \theta_{ao}) \tag{10.45}$$

Where:

Q_h total building heat loss (W)
θ_c the operative temperature (°C)
θ_{ao} the outside air temperature (°C)
F_{1cu} and F_{2cu} factors related to the heat emitter sources given by:

$$F_{1cu} = \frac{3\,(C_v + 6\sum A)}{\sum AU + 18\sum A + 1.5R\,(3C_v - \sum AU)} \tag{10.46}$$

$$F_{2cu} = \frac{\sum AU + 18\sum A}{\sum AU + 18\sum A + 1.5R\,(3C_v - \sum AU)} \tag{10.47}$$

R is the radiant fraction of the heat emitter source (typical values are given in Table 10.7)

As the F_{1cu} and F_{2cu} values are close to 1, it is an acceptable engineering approximation to estimate the total building heat losses through the fabric and ventilation/infiltration from:

$$Q_h = \sum AU\,(\theta_c - \theta_{ao}) + C_v\,(\theta_c - \theta_{ao}) \tag{10.48}$$

It should be noted that when the spaces surrounding the considered space are at different temperatures, heat transfer (losses or gains) will occur. Equation 10.4 can still be used but with a modified U-value, U', as follows:

$$U' = \frac{U\,(\theta_c - \theta'_c)}{(\theta_c - \theta_{ao})} \tag{10.49}$$

where θ'_c is the operative temperature of the opposite side of the partition.

Note: It is common for building services engineers to neglect solar and internal heat gains when calculating heating loads. The reason for this is to allow the selection of heating systems capable of providing the required heating loads under extreme conditions.

Table 10.7 Typical values for the radiant fraction of the heat source

Emitter type	*Proportion of emitted heat*	
	Convective	*Radiative (R)*
Forced warm air heaters	1.0	0
Natural convectors and convector radiators	0.9	0.1
Multi-column radiators	0.8	0.2
Double and treble panel radiators, double column radiators	0.7	0.3
Single column radiators, floor warming systems, block storage heaters	0.5	0.5
Vertical and ceiling panel heaters	0.33	0.67
High temperature radiant systems	0.1	0.9

Source: CIBSE Guide A 2006a

10.8 Summary

In this chapter, ways of calculating building heat gains and losses and cooling and heating loads arising from these gains have been explained. The concept of building admittance has been introduced and its use to determine the thermal behaviour of buildings has been highlighted. The CIBSE admittance procedure outlined in the chapter is detailed in CIBSE Guide A (2006) which also provides the data tables required for its application in cooling and heating load calculations. The CIBSE Simple Model for the calculation of heating loads has also been introduced.

Chapter 11

Building electric power load assessment

11.1 Introduction

This chapter provides an introduction to simple methods of load assessment for electric power systems in buildings. The need for load assessment as part of the design development process has been outlined in Chapter 2. It is also a necessary step in the selection of an energy strategy to minimise carbon emissions, as outlined in Chapter 3. A brief overview provides the context for some of the key issues for power system infrastructure design related to selection of equipment locations in buildings. The specific requirements for load assessment are outlined, together with a review of the nature of load patterns and profiles for electricity in buildings. The main methods for load assessment are described, including guidance on applying diversity factors. In practice, early estimation is usually based on load per unit area, or unit of accommodation. Typical load densities are provided for a range of systems and types of functional spaces in buildings. In commercial or public buildings, the electric power load is usually dominated by the main items of mechanical plant in the heating, ventilation and air-conditioning (HVAC) systems. Simple methods of early stage load assessment are described for the main items of mechanical plant, together with methods for some of the more problematic electrical loads, such as process loads. An introduction is provided for the more complex data processing loads and those supported by uninterruptible power supply (UPS) systems. The relevance of day, night, summer and winter load variations is outlined. A sample tabulation method is provided to illustrate a simple initial load assessment. Most electrical systems have a considerable proportion of non-linear load that gives rise to harmonics. This chapter concludes with a brief discussion on the impact of harmonics on equipment sizing and capacities.

Thermal load assessment has been covered in Chapter 10. Thermal loads are directly related to the thermal performance of the building envelope, and to internal gains and occupancy levels within the building. Electric power loads are more directly related to floor area, and are also a function of the HVAC systems that address the thermal loads; and occupancy levels and processes. So an electric power load assessment cannot be undertaken without suitable information on the HVAC systems proposals. Electric power loads can be best understood on a system-by-system basis. It should be emphasised that load assessment is about power load flow at a point in time, and should be clearly distinguished from energy demand, which is about accumulated energy consumption over a period of time.

It should be noted that the approach shown here is based on certain assumptions and simplifications, as outlined in 11.12. As this section relates to load assessment, for the purposes of simplicity the diagrams have largely been kept as indicative only.

11.2 Basic elements of power system infrastructure

Load assessments should be related to the relevant parts of a power system infrastructure. Similarly, the planning of a power system needs to take account of the locations and magnitudes of the main loads; so power system planning and load assessment are inextricably linked as outlined in Chapter 2, Section 2.5.1. It is useful, therefore, to start by reviewing those aspects of infrastructure that are most relevant to a load assessment.

Nearly all major power distribution networks operate with alternating current (a.c.) and consist of a multitude of interconnected items of generation, transmission and distribution equipment. In the UK this is known as the ‘grid’ or ‘National Grid’. The a.c. frequency is 50Hz (with close tolerances). The grid provides a reliable and stable supply of electricity. The UK transmission system comprises numerous dispersed power stations feeding an extensive transmission system, which in turn feeds local distribution to consumers. Transformation of a.c. power is the basis of modern interconnected grid systems, and extensive local distribution. Distribution in cities and towns is typically at 11,000V. This is usually defined as being within the ‘medium voltage’ (MV) band, although building services engineers will often refer to this as ‘high voltage’ (HV); and sometimes use both terms interchangeably. The term HV is used here. The generation, transmission and distribution systems are planned to meet the relevant identified load, and to some extent the anticipated future load at each location, with equipment capacities selected accordingly. Inevitably different parts of the distribution infrastructure will have different levels of spare capacity as the load pattern changes over time. In some locations the additional load required for a proposed new development might require reinforcement of the local network, to a greater or lesser extent. It is often the case that the developer of the site will incur some or all of the associated costs for the extent of reinforcement works that are required.

Figure 11.1 shows a fictitious 11,000V ring main, as might be used in a part of a town or city to feed a variety of consumers – buildings or other facilities – or could be used for a single site with a significant load. This chapter relates to the load assessment for individual buildings or developments, but it is important to understand that the same principles apply further into each ‘upstream’ part of the system, i.e. towards transmission network and the source of supply. In the case of a ring main as shown, the individual building estimated maximum demand figures will each be relevant, but should be considered in relation to the specific load patterns, and when the anticipated maximum demands occur for each building. It should be evident that there are considerable differences in the daily (diurnal) and seasonal load patterns for these building types. For example, the office building will have its highest load during the daytime, with a considerable reduction in the early morning and evening; while the hotel is likely to have its highest load during the early morning and evening, with a much reduced load during the day. The college building is likely to have minimal load during the summer. The design of the 11,000V infrastructure will relate to the

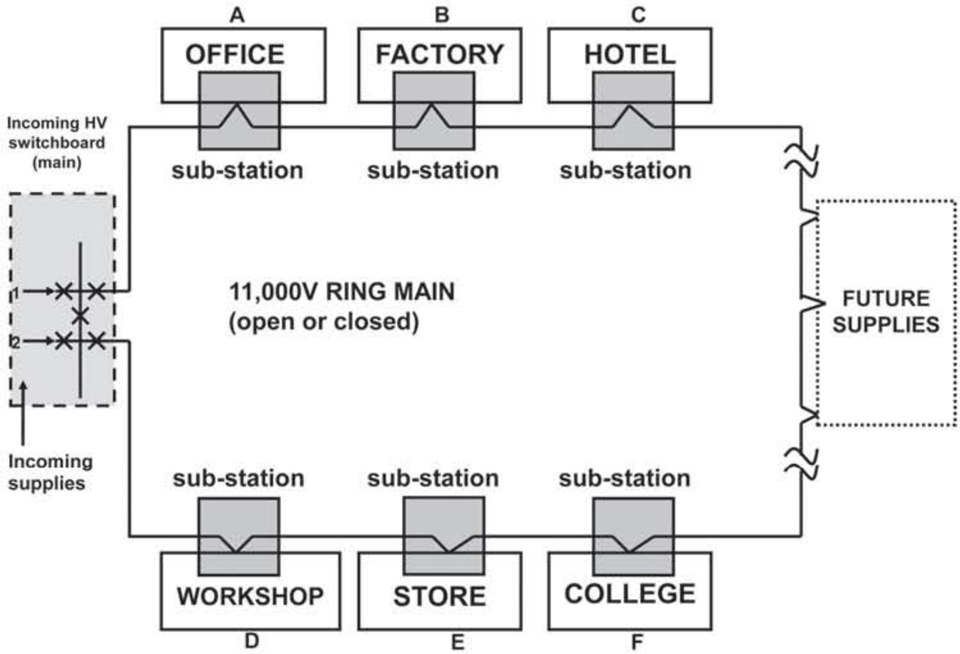

Figure 11.1 Simplified HV power system

anticipated maximum demand and load pattern for the ring main, and should include a suitable allowance for future spare capacity and expansion.

Figure 11.2 shows a much simplified low voltage (LV) power system schematic as might be used in an office building. The system has been shown with a substation, with a transformer fed from a ring main unit (RMU) on the HV side; an LV switchboard, rising main busbars and various distribution boards, motor control centres (MCCs) and other equipment. Load assessment is required at all parts of a system, in order to size all items of equipment, but is of particular importance in relation to the capacity of the LV switchboard, transformers and the capacity of incoming supply. The actual ratings of equipment will, of course, be part of the design development process covering all the necessary regulations and criteria (BS7671 2008), of which the load assessment is only one aspect, albeit an important aspect.

11.3 An introduction to load assessment

Load assessment is required for a number of reasons. Its primary reason is so that decisions can be made for the power system design, the capacities for plant and equipment, and the incoming supply provision based on the maximum predicted load (BS7671 2008; CIBSE 2004b). Assessment of the load profile is required for design decisions affecting the strategy for minimising carbon emissions, such as assessing the viability of co-generation (together with thermal load profiles) and the relative contribution for renewable electricity generation.

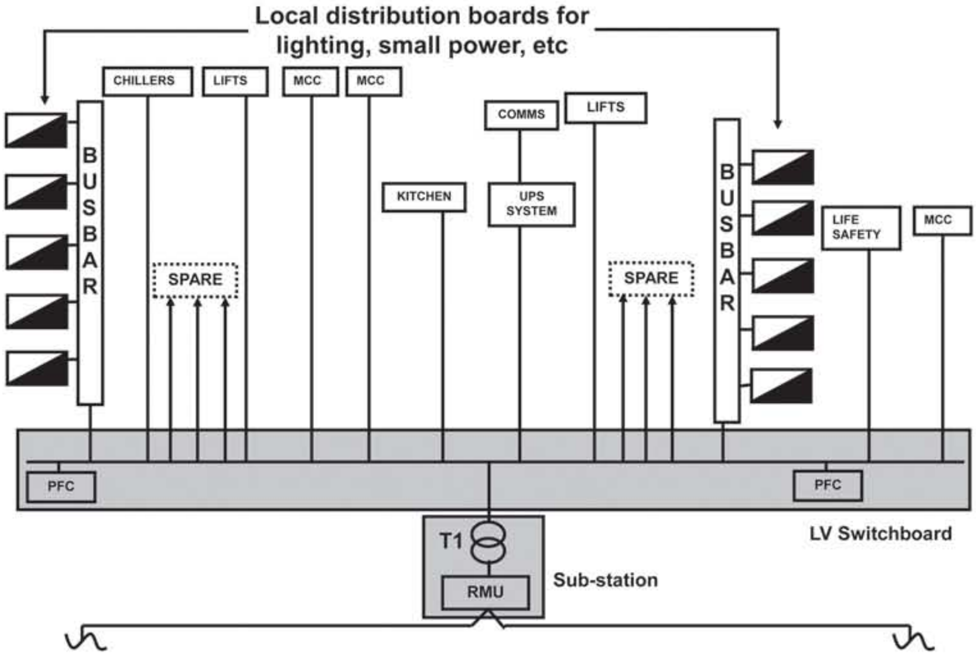

Figure 11.2 Simplified LV power system schematic

The key requirement is to determine the maximum demand of a system, or individual parts of a system. The load figure for the whole building is usually called the 'estimated maximum demand' (EMD) or the 'assessed maximum demand' (AMD). This assessment will be used to:

- determine the capacity of the components in a power system (and hence the physical sizes, so it will therefore be used in space planning);
- allocate a suitable capacity of incoming electricity supply, and determine the associated availability of service capacity and the energy costs from the utility supplier.

The design decisions based on load assessment must consider the likely usage of the installation (CIBSE 2008a). As these parameters are fundamental to the initial infrastructure design, they need to be made at an early stage, when very little information is available. It is therefore necessary for engineers to be able to apply suitable techniques so that they can make basic initial estimates, and exercise suitable judgement, at the early stage of a project; and then update and amend the assessment as the design develops with a greater level of detail and certainty. This is highly relevant to the design brief development, and iterative design development, outlined in Chapter 2.

For an undertaken load assessment to be meaningful, it is necessary to understand the nature of the individual loads, and how these contribute to summated loads for 'upstream' parts of the system, towards the source of supply. An important factor is that electric power loads are dynamic. At any point in a system, it is necessary to establish the ‘worst-case scenario’ for power demand. This may not necessarily be just a simple summation of the maximum load for each individual circuit. The potential impacts of incorrect load assessment need to be fully understood because they illustrate the importance of obtaining a realistic estimate for maximum demand at an early stage.

If the demand estimate is oversized, several issues could potentially arise:

- unnecessary capital cost and a waste of resources
- inefficiency and hence additional energy cost and carbon emissions
- waste of space, and hence cost
- increased maintenance cost
- increased tariff cost and service charge penalty.

If the demand estimate is undersized, several issues could potentially arise:

- design does not meet relevant codes
- safety issues, such as overheating failures, faults or fire
- inadequate space for plant (substation, switchrooms, risers, etc.)
- the system cannot satisfy demand, with business implications.

Furthermore, if the load assessment data in W/m^2 is used for calculating internal gains, errors could affect HVAC equipment sizing, and hence efficiencies. If the anticipated load profile is incorrect it could have a misleading influence on decisions made for the building/site energy strategy.

It should be recognised that considered engineering judgement is necessary, ideally based on experience from previous projects of a similar type. However, it should also be recognised that load estimation is not an exact science. Historically, engineers have tended to adopt a cautious approach. There is much experience of predicted loads not materialising in practice, perhaps as a result of an overcautious approach and a lack of insight and dialogue with the client regarding the likely operational pattern. Alongside the need to understand loads in existing buildings, and avoid being overcautious, it is necessary to make suitable provision for future flexibility, and for potential changes in building usage; although this aspect is beyond the scope of this book.

11.4 Load patterns and profiles

Load estimation would be relatively easy if all electric power loads were of fixed magnitude, purely resistive, and switched on and off for known periods of time. But, in reality, most of the loads in buildings are dynamic:

- variable in magnitude (to some extent)
- partly reactive
- often non-linear, sometimes with significant harmonic content
- switched on and off for known or unknown periods of time
- sometimes transient.

Unfortunately, to make the assessment more complicated, the largest loads in buildings can often be the most difficult to estimate at the early stage, thereby requiring a particular focus in initial estimates. It should be noted that load estimation deals with steady state conditions, so transient conditions can be ignored. Two particular aspects of load variation should be appreciated – diurnal (i.e. through the course of the day) and seasonal. These aspects are, of course, relevant also to thermal systems.

Figure 11.3 shows a typical load profile for an office building, with approximate load variation through a 24-hour period. It can be seen that the peak period lasts for about 10 hours. For approximately eight hours during the night, the load is at about 20% of the peak; this represents the base load. A full assessment would include further 24-hour profiles to show the seasonal variations. In the case of a site development with a number of buildings, while each building's power infrastructure would, of course, be required to satisfy its own load profile, the infrastructure for the whole site would have to satisfy the accumulated profile.

A useful way to understand load build-up for an individual building is to look at the typical breakdown of the EMD load in terms of systems. It should be noted that this is different from a breakdown of the annual energy consumption. Figure 11.4 shows the diversified loads for a typical office building on a business park (Building A), with the mechanical services dominant at 44%, followed by lighting and small power as the other significant system loads. Figure 11.5 shows a comparative breakdown for a typical healthcare building. The generally less intensive HVAC systems, and the significant loads for catering and medical equipment, result in a smaller proportion for the mechanical services, while lighting represents a higher proportion.

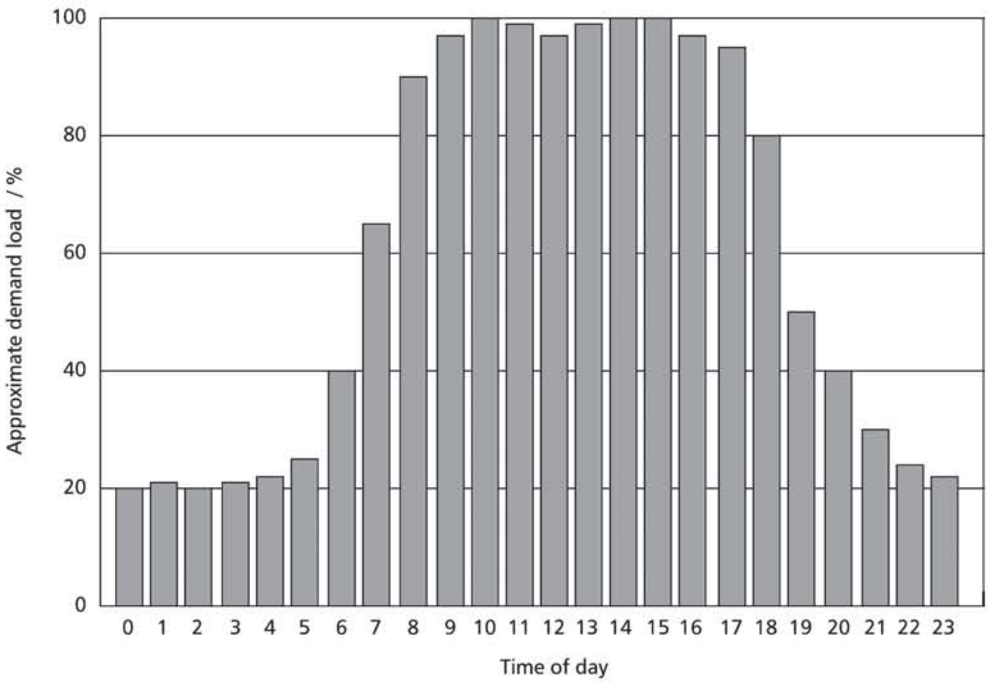

Figure 11.3 Typical load profile for an office building

Source: reproduced from CIBSE Guide K (2004b) with the permission of the Chartered Institution of Building Services Engineers

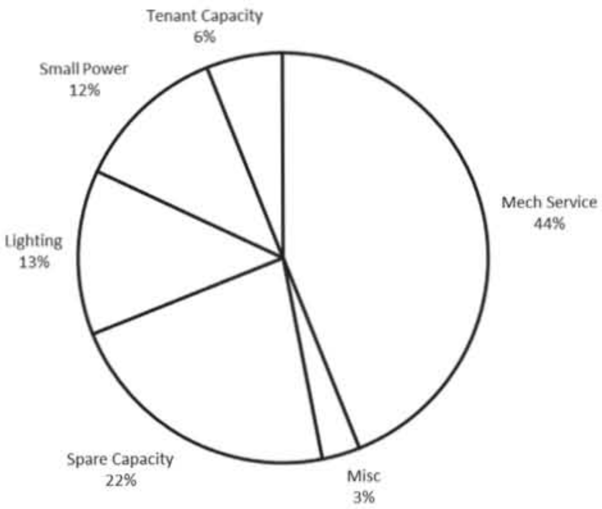

Figure 11.4 Maximum demand breakdown example: business park office Building A

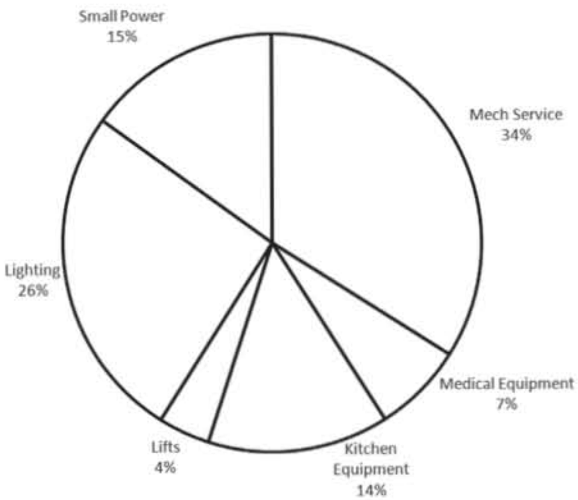

Figure 11.5 Maximum demand breakdown example: healthcare building

As we attempt to estimate loads it is worth noting that, even at the completion stage for a project, it is difficult to determine the whole load with any degree of certainty. The load pattern will only emerge with full occupation and usage (in accordance with the design brief), hence the importance of post occupancy feedback and monitoring to inform the design. If an example of a simple distribution board is taken, as shown at Figure 11.6, it can be seen that, while the loads might be known for lighting circuits and fixed items of equipment, the load for small power ring circuits, future and spare items cannot be known with any certainty.

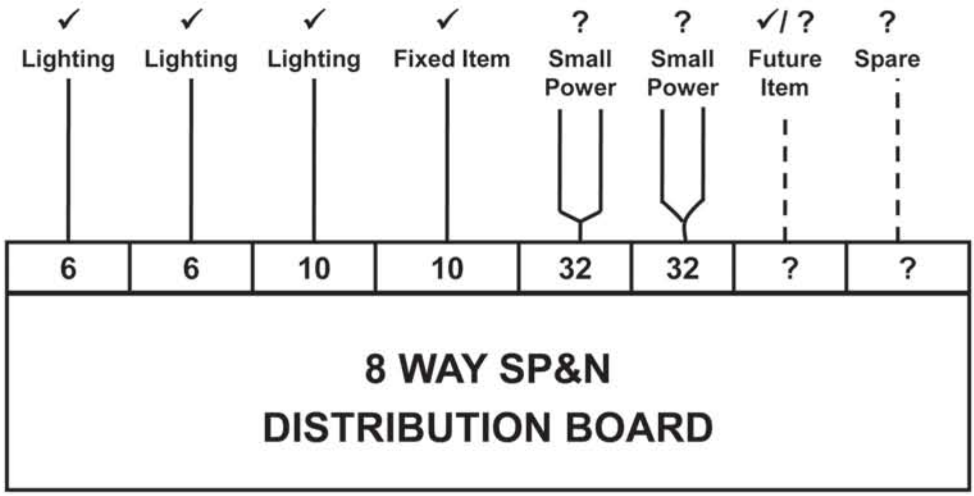

Figure 11.6 Load assessment issues for a simple distribution board

It is clear that some circuit loads are easy to estimate, while others are not. But to size equipment it is necessary to make an objective assessment of the unknown factors, using engineering judgement.

11.5 The main methods of load assessment

Various methods are available to assess loads, either separately or in combination. Some of these are only applicable when the design has been well developed. Examples are:

- 'Rules of thumb', or other guidance using typical load densities for types of buildings, types of areas within buildings, or types of systems (CIBSE 2004b; DOH 2007; Hawkins 2011);
- applying diversity to estimated design loads or connected loads;
- detailed calculation;
- client guidance;
- manufacturers' information;
- information from the mechanical systems designer;
- information from specialists.

Most assessments will require a mixture of these methods at different stages of the design. Because initial assessment is required at an early stage, it usually involves applying 'rules of thumb' and diversity. As the Building Regulations in England and Wales provide certain limiting design criteria (DCLG 2010a), these can also be useful for assessing loads.

Table 11.1 shows some useful 'rules of thumb' load density figures for whole buildings or groups of buildings. These are typical average figures for use at the earliest stage of a project, when there is limited information on the facilities to be included. In each case the figures assume that there is no electric heating. The figure for residential accommodation relates to average loads for typical sizes of standard quality accommodation. Higher figures would, of course, apply to larger properties, luxury houses and apartments, and properties with air conditioning, large audio-visual systems, or other power consuming features. All load assessment figures should be reviewed and updated as the brief and design develop with more certainty, and the specific equipment is determined.

11.6 Diversity

The numerous items of electrical equipment in a power system will each have their own pattern of operation, but, when the overall load is examined the pattern will be seen to be diverse, with different items reaching their peak loads at different times. This is known as diversity of operation and is applied in load assessments where the overall EMD at any point in the system is a lower figure than the sum of the individual maximum connected loads.

The key factors that give rise to diversity are:

- multiplicity of similar items which are unlikely to be used concurrently;
- disposition of spaces on a site or in a building, which are used at different times;
- usage pattern, operation or process, including control features to minimise energy consumption;
- time of day (diurnal variations);
- seasonal influence.

The application of diversity can be understood by reference to the hypothetical LV distribution system shown in Figure 11.7, which has been drawn to illustrate the point. This shows ten items of distribution equipment, or load centres, with the main switchboard identified as item 10. It is necessary to assess the load at each item of distribution equipment, as well as for the main incoming supply. If we take the distribution board labelled 1, then each circuit might have design currents I_A, I_B, etc, as shown. While it would depend upon the nature of the loads, the maximum demand for the distribution board, I_1, is likely to be less than the sum of the individual circuit design currents, as they would not necessarily all occur at the same time. So there

Table 11.1 Typical unit loads by building type

Type of building	*Typical load density*
Office building (air conditioned)	90W/m^2 to 110W/m^2
Hotel (air conditioned)	4000W/room (*)
School	35W/m^2
Warehouse (standard)	25W/m^2
University	30 W/m^2 to 40W/m^2
Residential accommodation	1.0–1.7kW/dwelling (*)

Note: * These figures could be diversified for large multiples

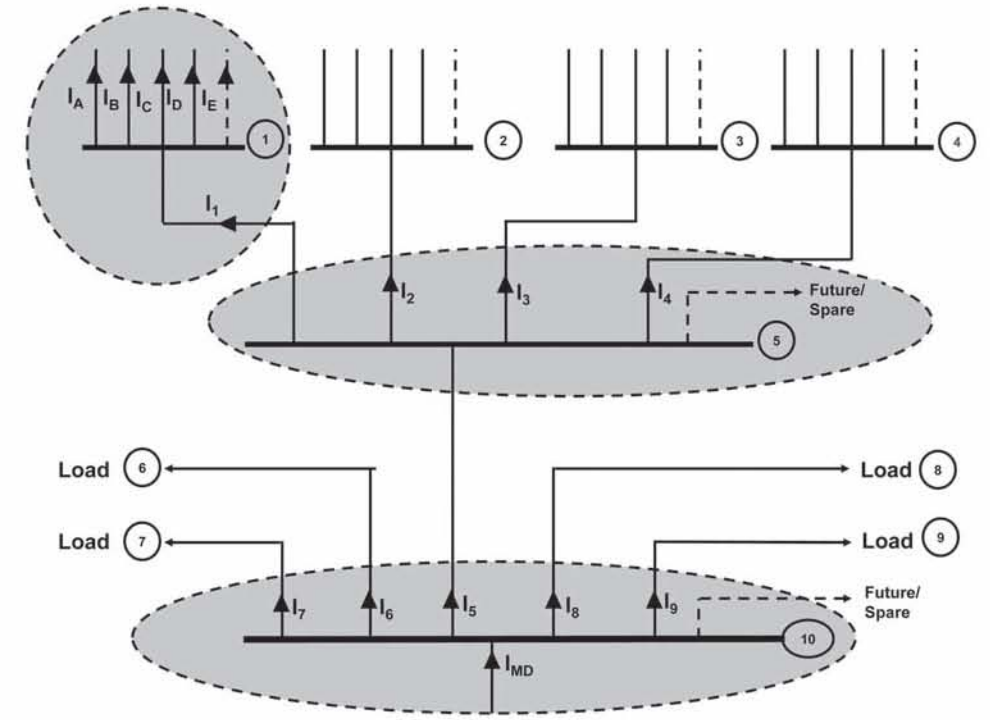

Figure 11.7 Loads for distribution centres

would be some diversity, perhaps small in this case, say 0.95. It would be necessary to allocate some spare capacity for the spare circuit(s) allocated, and some future load growth, say 15%. Therefore, the total load, I_1 would be:

$$I_1 = (Ia + Ib + Ic + Id + Ie).(0.95).(1.15) \tag{11.1}$$

The distribution boards 2, 3 and 4 might be similar to distribution board 1 and might have similar loads. However, when we assess the load at switchboard 5, this might not be the sum of the maximum currents for I_1, I_2, I_3, I_4 and the future/spare provision, as they might not all have their maxima at the same time. Thus there will be some further diversity. In this case it might be considered that the most appropriate diversity factor is 0.8 and future and/or spare allowance should be 20%, thereby, the maximum demand for switchboard 5 would be:

$$I_5 = (I_1 + 1_2 + I_3 + I_4).(0.8).(1.2) \tag{11.2}$$

The same approach will apply in assessing the total load at switchboard 10, which represents the building's maximum demand 1_{MD}; and to further upstream parts of the system. There is no exact science to the application of diversity factors, which relates more to engineering judgement based on an understanding of likely patterns of operation.

11.7 Load assessment by system

Lighting and small power loads tend to be evenly distributed within buildings, and are fairly simple to assess using a load density approach. However, the key loads that need to be assessed require more careful consideration. Guidance on these load assessments is included in the following sections.

Catering equipment loads will be dependent on the specific brief; proportion of electric to gas equipment; and the electric equipment selection. These can be of considerable magnitude, and are usually associated with high ventilation air flow rates, so the total load related to catering facilities can be considerable.

11.8 Lighting

Assessing the load for a general illumination lighting system is relatively easy compared with other systems. However, it is important to recognise that a lighting load:

- varies with time due to the occupancy pattern;
- varies with control usage, i.e. through the use of dimming, time switching, daylight-linking or other lighting management features. This is an important energy efficiency feature, as described in Section 9.4.

The most well-known application factors are related to conventional office buildings, where load density is often taken as 11W/m², and diversity as 90% (0.9). While these figures are useful for initial assessment, it is important to only use them where appropriate. In particular, task lighting should be included, where applicable. This is often supplied from separate distribution boards and would, therefore, be allocated as a small power load to the appropriate part of the distribution system. A broad guidance on the target range of power densities is given in Table 11.2, which shows average installed power densities for different lamps and illuminance levels. These figures relate to efficient lamps and luminaires, in good quality installations with high surface reflectances and a high degree of installation maintenance (CIBSE 2002).

It is important when applying lighting W/m² figures to be aware of the key factors that will increase the power density compared with a conventional arrangement. These include: increased mounting height; increased illuminance levels; less satisfactory maintenance; and a design requirement for better colour rendering. Each of these

Table 11.2 Typical average lighting power densities for different lamps and illuminance levels

		Lamp type		
		Fluorescent triphosphor	*Compact fluorescent*	*Metal halide*
Task illuminance lux	300	7W/m²	8W/m²	11W/m²
	500	11W/m²	14W/m²	18W/m²
	750	17W/m²	21W/m²	27W/m²

Source: derived from CIBSE (2002): table 2.5

factors will increase the power density figure, and a combination of these factors could result in a considerable increase in W/m^2.

The load for external lighting should only be included in the overall maximum demand assessment where its usage will coincide with periods of worst-case demand. For buildings such as sports stadia and entertainment centres that can have their peak activities in the evening, this is likely to be concurrent with their maximum demand period.

11.9 Small power

Small power systems mainly consist of socket outlets and therefore have a variable load; although they can also contain fixed items of equipment with a predictable load. There is no precise method of estimating the load for circuits with socket outlets. The nature of the circuits is to allow flexibility of usage to suit user requirements, so the load will vary accordingly. However, the load will nearly always be only a relatively small proportion of the circuit capacity. The best approach is to understand the likely usage through discussion with the client; observation of usage in similar locations; or, preferably, data logging of metered power usage in similar areas.

Small power usage will vary depending on the type of functional space. In some spaces there might be a considerable number of sockets, but their usage might be primarily for cleaning purposes outside the main occupancy period. In such cases the load contribution will barely feature in a maximum demand assessment. Examples would be sports halls, foyer or circulation areas and classrooms. Careful consideration should be given to those areas where the sockets provide power to continuous functional facilities as part of the business process. This would include offices, but also spaces such as laboratories. For offices it is necessary to know the types of desk-based equipment such as PCs and monitors, and ancillary equipment such as printers and photocopiers. It is also necessary to know the density of occupation and the intensity of equipment usage. Many offices have underfloor power distribution via busbars to floor boxes with multiple outlets, providing high flexibility and the potential to connect a dense coverage of equipment. Some sense of the occupancy density and intensity of usage will assist in the assessment, which could be based on a unit area or a watts per person basis.

As with most other electrical equipment, the actual average power consumed by PCs, monitors and other office equipment is usually well below the nameplate rating. It might be the case that the anticipated nameplate equipment loads in a localised area might total to $30–45W/m^2$, and some designers use these figures. It is often the case that $10–15W/m^2$ will be sufficient for non-intensive general office areas, perhaps rising to $15–20W/m^2$ for more densely populated spaces. However, it is sometimes the case that a figure of $15W/m^2$ would suffice when applied to the whole floor area, including circulation areas. The exceptions would be for highly intensive use, such as dealers' rooms, where loads of 350–550W per desk, or $50–75W/m^2$, can be applicable in localised areas.

It is important to understand that load assessment figures may be quite different from the capacity provision. An example is where the installed systems and their power infrastructure require capacity ratings to satisfy industry sector body standards, such as recommendations of the British Council of Offices.

As stated in Section 7.4.1, task lighting loads should be allocated where fed from distribution boards for small power.

11.10 Mechanical plant

For most modern commercial or public buildings with HVAC systems, the mechanical plant will normally provide a dominant proportion of the maximum electrical power demand. It is therefore essential that the engineering systems are designed in a coordinated manner, with close liaison and clear communication between the mechanical and electrical systems designers. The largest loads are normally chillers (and their ancillary equipment), fans and pumps; all of which are motor loads, and hence are inductive loads. The overall figure for an air-conditioning system will depend on many factors, including the cooling load, occupancy levels and type of system selected. Typical power loads for these systems can be in the range of 55–70W/m^2.

11.10.1 Cooling systems

Chillers are regularly the largest items of load in the electrical distribution systems for air-conditioned buildings. It is most important for the electrical designer to understand the details of the cooling equipment, and all the other components in the cooling system, so that the correct total electrical load figures can be applied. The mechanical designer will describe chillers in terms of maximum thermal power, i.e. kW or MW of cooling capability, sometimes written as kWc or MWc. Electrical designers must not confuse this with electric power, sometimes written as kWe or MWe. The relationship between the two is described by the coefficient of performance, COP, where:

$$\text{COP} = \frac{\text{Cooling power output (at evaporator)}}{\text{Electrical power input (to compressor motor)}} = \frac{\text{kWc (thermal)}}{\text{kWe (electrical)}} \qquad (11.3)$$

The higher the COP, the better the performance or energy efficiency ratio (EER) of the cooling production process. The COP will vary with the type of cooling equipment. It will also vary with the operating conditions and the proportion of load, so part-load and seasonal aspects need to be addressed.

Typical COP ranges for chillers are:

Air-cooled heat rejection: COP of 2.8–3.2
Water-cooled heat rejection: COP of 3.2–3.8

For example, for a 1200kWc water-cooled chiller, with a COP of 3.6:

$$\text{Electrical power} = 1200\text{kWc}/3.6 = 333\text{kWe} \qquad (11.4)$$

Chiller plant will usually be associated with auxiliary equipment for heat rejection, such as condenser water pumps and/or condenser fans, depending on the specific cooling and heat rejection arrangement. Chillers operate with capacity control to satisfy system demand at part-load, and this should be addressed in load calculations.

Seasonal part-load operation may have a lower COP, so this should be taken into account, where appropriate.

Once the power input has been established for each chiller, it is necessary to understand how the overall cooling system works, so that the concurrent loads can be determined. Figure 11.8 shows the central plant in a typical chilled water system schematic. The questions that should be addressed are:

- How many chillers operate together?
- Are they at full load?
- Do they have integral pumps?
- What is the arrangement for any separate heat rejection, in terms of condenser fans or cooling towers and pumps?
- How many primary pumps and secondary pumps run together?

The electrical load pattern can only be understood by understanding the dynamic operation of the mechanical system to meet the cooling demand, and determining the worst-case concurrent electrical load and the time at which it occurs.

11.10.2 Heating systems

The only items requiring electric power in conventional gas-fired heating systems are the boilers (for the burners and ancillaries) and the pumps. Power requirements for boilers will be a function of the equipment rating and characteristics. Power requirements for heating pumps in multiple boiler systems will require the same considerations as outlined above for the primary and secondary pumps in multiple chiller systems.

If electricity is used as the fuel for all or part of the heating for a building, the electric power load assessment will be provided by the relevant thermal heating load assessment.

There are other items of electric heating equipment that can be included in HVAC systems which often have significant loads. These include frost coils (located in the air

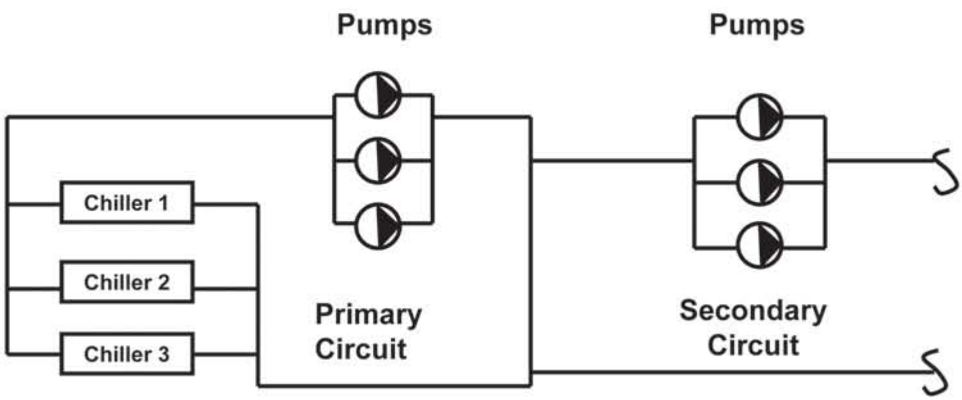

Figure 11.8 Example chilled water system

intake to air-handling units to prevent freezing of filters) and heater batteries (which might be present in close control air-handling units, for example in computer rooms). It is important not to overlook these in the load assessment.

11.10.3 Heat pumps

Where heat pumps are used, similar considerations apply to electrical power input as described above for chillers. While for reverse cycle heat pumps, the load assessment should use the relevant COP figures when in cooling mode and heating mode.

11.10.4 Fan coil units and other distributed equipment

HVAC equipment can often be in the form of distributed items that are either standalone, or part of a system that includes central plant. Examples are fan coil units and fan assisted terminal boxes for VAV systems. In all cases the electric power loads should be sought from the mechanical designer, together with an indication of the operating mode, and hence the load figure that will be concurrent with other worst-case figures. It should be noted that VAV terminal boxes can have heating coils that are electric, or use the LPHW heating system. If the heating coils are electric this can have a major impact on the load. As outlined in Chapter 9, EC/DC fan coil units have different power characteristics from conventional FCUs.

11.10.5 Fans and pumps in HVAC systems

The absorbed motor power associated with fans and pumps will depend on the specific parameters of the air and hydronic systems respectively, and the relevant operating points on the fan or pump characteristic curves. The mechanical designer will advise the power ratings, and it is important to understand how the systems work, so that the individual operational loads and the concurrent loads can be determined accordingly. The electrical power input to the fan or pump will take into account the serial efficiencies of the fan or pump, the motor and the drive arrangement. Table 11.3 shows the range of typical plant efficiencies for fans and pumps.

For example, for a large pump operating at 50kW, fed from a variable speed drive, and with efficiencies at the upper end of the range, the overall electric power input, P, would be:

$$P = 50/(0.75).(0.95).(0.98) = 71.6\text{kW} \tag{11.5}$$

Table 11.3 Typical pump/fan plant efficiencies

Item	*Efficiency ratio*
Fan or pump (small)	0.6–0.7
Fan or pump (large)	0.7–0.75
Motor efficiency	0.9–0.95
Variable speed (inverter) drive	0.96–0.98
Belt drive	0.95

It is possible to assess power loads for fans in relation to area or ventilation flow rate at an early stage. This covers the total power for all the supply and extract fans for a building. The Building Regulations Part L2A set a limit to the specific fan power (SFP), which therefore provides a reliable figure that can be used in load assessment, as it should not be exceeded in order to achieve compliance. Chapter 3 gives the definition of SFP and shows the limiting figures in terms of watts per litre per second.

Therefore, from an awareness of the building population and the design ventilation rate in litres per second per person, the maximum total fan power for the building can be estimated. For example, if an office building has a gross internal area of 15,000m^2 and an occupancy density of 10m^2 per person, the design population would be 1,500 people. If a maximum ventilation air flow rate of 14 litres per second per person is assumed, the total air flow rate would be 21,000 litres per second. For a central mechanical ventilation system with heating and cooling, the SFP is 1.8W per l/s. Therefore, the maximum total fan power for supply and extract is 37,800W or 37.8kW

This approach could be used as an installed load in assessments, and could be subject to diversification.

11.10.6 Humidification

Humidification can be provided to an air-conditioning system in a number of ways. One of these is to inject steam into an air stream from an electrode boiler. This is a purely resistive heating load, which can be a significant load, in relation to the other loads in a building. It is mainly a winter load. If an air-conditioned building does not have humidification included in the original design, it is important to be aware of any future possibility of humidification being provided, and how this requirement has been defined at the briefing stage. This is so that the required future spare capacity can be included in the load assessment, if appropriate.

11.10.7 Data processing loads

It is likely that the areas of buildings with the highest power load densities will be rooms used for data processing or similar facilities. This can cover a range of functions, such as computer rooms, communications centres, dealers' areas and tele-hosting facilities. This is a major growth area and the trend is likely to continue. It is associated with fast-changing technology, such as blade servers, and novel approaches to cooling to meet the high cooling density requirement in an energy efficient way. There is often considerable difference in opinion as to the most appropriate load density figures to use for these facilities, and it is essential to assess each case separately, and seek project-specific information from the client. Among many key issues to decide upon are the proportion of the area to which the load densities apply; and the most appropriate allowances to include for spare capacity and load growth. Table 11.4 shows typical load density values (probably on the high side) for technical equipment.

Clients' estimates of load density at the briefing stage are often considered to be on the high side. In some cases their figures are derived from the 'nameplate rating' of their existing or proposed equipment and therefore represent an overcautious

Table 11.4 Typical load densities for communications equipment areas

Communications equipment area	*Typical load density (W/m²)*
Dealer floor	400–500 (in the dealer area)
Main equipment room (MER)	600–1,200
Secondary equipment room (SER)	350–500
Data centre	500–2,000 (and occasionally up to 3,000 or even higher) A useful average figure is 1,500

approach. The stated ratings on nameplates will usually be the worst-case maximum load for the equipment. This is often considerably higher than the average power consumption during normal usage. It is always necessary to seek clear guidance at the commencement of the project, so that an agreed figure can be established as part of the design brief development process. For these functional spaces it will be necessary to determine the resilience (i.e. the redundancy or availability) criteria during design brief development, as this will have a fundamental impact on the power infrastructure design, the efficiencies and hence the resultant load (see Section 2.4.3).

Data processing loads vary widely depending upon the application and the technology. There is a relationship between the power density of the data processing equipment, and the type of cooling system that is most appropriate to satisfy the cooling load density. As the cooling load will, itself, give rise to a power load, it is essential that the power and cooling arrangements are considered together, so that a suitable overall power load can be estimated for both operating together.

Power densities of up to 1000W/m² are not uncommon and would usually be associated with conventional cooling systems. Some clients set a brief for power densities up to 3,000W/m². At load densities approaching these levels, it is likely that non-standard cooling systems will be required, necessitating care when estimating the corresponding power loads for cooling. Clients might also set a brief in relation to anticipated server cabinet loads, together with a notional layout. In such cases, careful consideration is required as the figures might be based on nameplate ratings, rather than the actual running load. Loads are often defined as ‘rack’ loads, which in data centres can typically range from about 5kW per rack up to 20kW per rack. However, it is difficult providing conventional cooling solutions for rack loads above 6kW. The key design decision will be to determine realistic operational loads for the equipment, and the diversity that can be applied. This will then represent the heat gain to the space and determine the cooling load; and thus the likely cooling solution, and hence the power required for cooling in the worst-case load scenario.

It is also necessary to take account of miscellaneous small items of equipment that are fed using ‘Power over IP’. This will represent a load on the relevant circuits supplying the cabinets, as opposed to small power circuits.

It should be recognised that, unlike most other loads, data processing loads are often continuous, running for 24 hours a day, every day of the year. This will be relevant to the diurnal and seasonal load pattern.

See also Section 11.13 on harmonics.

11.10.8 Loads supported by UPS systems

Assessment of loads associated with UPS systems is beyond the scope of this book, but it is necessary to have some awareness as they can be among the largest loads in a building. Data processing facilities, as described above, and other business-critical facilities, usually receive their power supply via an online UPS system. This will have an impact on the load as seen by the incoming power supply.

It might be assumed that the grid will always supply a perfect and continuous sinusoidal a.c. waveform. However, in reality, the power supply from the grid is not a perfect sinusoidal waveform, but is often distorted by spikes and harmonics. Furthermore, it can be subject to supply failures (brown-outs or black-outs) and transients. The degradation of waveform quality has been exacerbated in recent years by the increase in non-linear loads which create harmonics. The harmonic currents feed back into the supply and cause distortion of the voltage waveform.

An online UPS system performs two main functions: (a) continual conditioning of the power supply (to improve the quality of waveform); and (b) maintaining the power supply continuity during power failures by providing a short-term standby supply for the duration of the 'autonomy' period.

The increasing importance of maintaining continued operation of electrical equipment to business operations has led to a major expansion in the use of UPS systems for what have become known as 'business-critical systems'. There are various types of UPS system, all of which contain fairly complex items of equipment, including power electronic devices to rectify and invert a.c. mains. Most large UPS units take the existing a.c. mains and convert/re-generate a new a.c. supply for the critical load. To develop the design, it is normal to assess the specific operating mode in some detail with UPS equipment suppliers. Supporting a critical or sensitive system via an online UPS system will affect the load seen by the supply. If there is a test load, such as a load bank, the arrangement and timing for usage needs to be understood so that this can be taken into account. However, in most cases connection of test loads would not be concurrent with other worst-case loads.

Most systems will be designed to achieve a certain level of resilience, and will have a redundancy in modules so that the load can be maintained if one or more modules fail. Therefore, to assess the load related to a UPS system, it is necessary to know the key design parameters, including the resilience criteria, as outlined in Chapter 2. It is usually the case that there will be multiple parallel UPS modules in a UPS system – and possibly more than one system – to meet the criteria. In a simplistic sense, the factors that will influence the maximum demand load, and need to be taken into account, include:

- the design load, and the allowance for growth in the brief;
- the efficiencies of the UPS modules, for the part-load condition, i.e. the losses in the modules;
- the worst-case battery-charging condition concurrent with the design load;
- any test load that might be run concurrently with the main UPS load;
- the impact of harmonics on the supply side load, taking into account any front-end harmonic filtration.

UPS module efficiencies would be typically up to about 96%, but will vary with loads as described in Chapter 9. The selection of the numbers and ratings of modules will have an impact on the overall load, and hence the carbon impact. The maximum demand assessment for the system must, of course, take account of the worst-case simultaneous load for the system in relation to the range of operating scenarios. Such loads always merit detailed assessment and discussion with the manufacturers of the specialist equipment.

11.10.9 Parasitic loads

For certain types of electric power equipment, there will be an additional load related to ancillary equipment that is required to facilitate the operation of the main equipment. These can be considered as 'parasitic' loads and, if fed from the equipment under consideration, they will reduce the net power available to meet the intended primary load. One example would be a UPS system that requires ventilation and/or cooling equipment to ensure the room temperatures in which the UPS modules and batteries operate are maintained below prescribed maximum levels; and possibly other loads for control and monitoring facilities. Another example would be ancillary equipment for a CHP plant, or other generating equipment. Parasitic loads must be included, as appropriate, within assessments for worst-case concurrent loads.

11.10.10 Lifts and escalators

The vertical transportation equipment within buildings – lifts and escalators – can often represent a considerable proportion of the installed load. However, while due account will need to be taken of the loads for sizing the local power infrastructure that serves them, the value of load that should be carried forward to the total building maximum demand requires engineering judgement. For passenger lifts the motors do not work continuously, and do not work at constant load, so load assessment is not straightforward.

Figure 11.9 shows two LV switchboards that illustrate the comparison between the typical cumulative load for a group of passenger lifts and for a group of escalators. In both cases the total connected load is 80kW. For the passenger lifts the average power will be small compared with the connected load, although there is no definitive guidance. For the purposes of notional assessment, a suitable diversity figure might be 0.25. So the total average load, Pav, would be:

$$\mathrm{Pav} = [(4).(15) + (2).(10)].(0.25) = 20\mathrm{kW} \tag{11.6}$$

As this demand only occurs at peak periods for lift passenger traffic, which do not usually coincide with peaks in other loads, this load is often omitted from the maximum demand figure for the building. Escalators have a different operational pattern. They tend to run continuously and, in many cases, the load will not vary significantly throughout the operational period of the day. For the escalator motors shown, a diversity of 0.9 might be applied, so the total load Pav would be:

$$\mathrm{Pav} = (4).(20).(0.9) = 72\mathrm{kW} \tag{11.7}$$

The load figure for escalators would usually coincide with the peaks for other loads, should it be included in the EMD for the building.

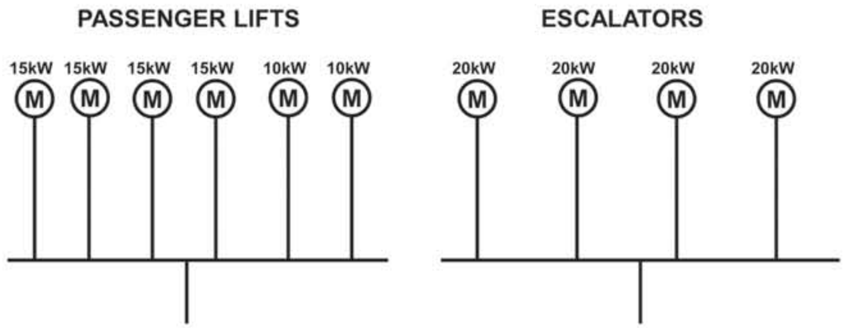

Figure 11.9 LV switchboards supplying lifts and escalators

11.11 Load assessment tabulation method

Because an initial load assessment is largely about allocating loads to parts of buildings, or to particular electrical systems, and then obtaining a diversified summated figure, the simplest way to undertake a load assessment is using a tabulation or spreadsheet technique. However, prior to creating a load table, it is worthwhile producing a table showing the significant time periods when each of the system loads occurs, as it is necessary to identify the time at which the worst-case concurrent load occurs. Figure 11.10 gives an example for an office building. This shows assumed periods when each system load might be at its normal level; periods at which loads might be at part of their normal level; and periods when the extent to which the load would be at its normal level is uncertain, and could only really be determined from a client's guidance on the intended functional operation. For the HVAC systems, the level of electrical load would, of course, be related to the thermal or ventilation demand; and hence to the external ambient conditions, to some extent. In the example shown, the peak load is likely to be early to mid-afternoon when the peak cooling load occurs;

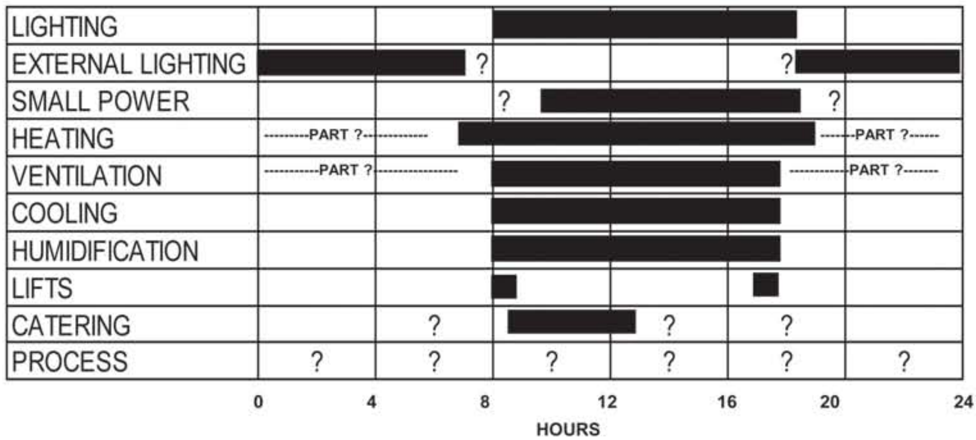

Figure 11.10 Typical significant time periods for electrical loads in a conventional office building

and would exclude external lighting, lifts and possibly most of the catering load. Separate diagrams should be created for each building type, and for summer and winter, to identify the concurrent loads that should be included when estimating the summer and winter peaks.

Table 11.5 demonstrates an example of theoretical initial load assessment tabulation for an office building. Where appropriate, load densities are used and multiplied by the area to give an undiversified load. A diversity factor is applied to give a diversified load in kW, and an average power factor is applied to give a maximum kVA figure for the system. Consideration can then be given to any adjustments required for the winter and summer peak demands. In this case it indicates that the EMD will occur in summer, the dominant influence being the cooling system chillers and pumps. A suitable table should be produced for each load centre and should be updated as the design progresses and more information becomes available.

11.12 Brief note on assumptions and simplifications

The simplified approach outlined here assumes balanced, linear loads. This is relevant when calculating design current from the total kVA load. Modern building loads often have significant harmonic content, which makes demand assessment more complicated. It is worthwhile noting the following points:

- It is useful to use the gross internal area when applying load densities in initial load assessments, as this will tend to provide a design margin. More detailed assessments at later design stages can allocate different load densities for treated areas, and for circulation and other areas.
- Always be clear as to whether you are dealing with kW or kVA values, single-phase or three-phase.
- kW loads can always be added numerically because they are in phase. Strictly, kVA loads can only be added numerically if the power factor is the same. Like the currents, they are phasors (rotating vectors) and can only be added vectorially. However, as most power factors in buildings are similar lagging values, designers tend to simply add them numerically. For the level of detail required in an initial assessment this is usually sufficient, but it is important to recognise the limitations.
- If power factor correction is installed, take account of this at the appropriate location in the system.
- a.c. parameters are always expressed as r.m.s. (root mean square) values.

11.13 Brief note on the impact of harmonics

The impact of harmonics is mentioned here in the briefest sense only, to provide some awareness as this can be an important factor in the load assessment for buildings.

The simplified approach to assessing power loads outlined here tends to assume linear parameters, i.e. a pure sinewave for the supply voltage and, therefore, a pure sinewave for the current. For modern electrical systems in buildings, this is far from being the case. The voltage supply waveform (and hence the current) sometimes contains imperfections; but of more relevance, many loads are non-linear and create harmonics, including:

Table 11.5 Example load assessment tabulation (early stage – very basic)

Ref	*Service*	*Area (m^2)*	*Load density (W/m^2)*	*Undiversififed load (W)*	*Diversity*	*Diversified load (kW)*	*Average PF*	*Maximum kVA*	*Winter Peak (kVA)*	*Summer Peak (kVA)*	*Notes*
1	Lighting	10,000	12	120,000	0.9	108	0.9	120	120	80	
2	Ext. lighting	–	–	5,000	1.0	5	0.9	6	6	–	
3	Small power	10,000	15	150,000	0.7	105	0.8	131	131	131	
4	Lifts	10,000	10	100,000	0.4	40	0.8	50	50	25	Sometimes ignored
5	Catering	–	–	40,000	0.6	24	1.0	24	24	24	
6	Heating (pumps)	–	–	40,000	1.0	40	0.8	50	50	–	Assume no summer heating
7	Cooling (chillers and pumps)	10,000	50	500,000	1.0	500	0.95	526	100	526	Assume some winter cooling
8	Vent. fans	10,000	3	30,000	1.0	30	0.9	33	33	33	
9	Humidification	–	–	80,000	0.7	56	1.0	56	56	–	
10	Computer centre (all incl.)	–	–	–	–	–	–	250	200	250	to include UPS, harmonics, etc.
								Sub totals	770	1069	
						Add spare/future capacity (15%)				160	
									E.M.D.	1229	KVA (summer peak)

(consider further diversity?)

- fluorescent lighting (with high frequency control gear);
- electronic equipment that incorporates switched-mode power supplies (e.g. PCs) to create the required d.c. supply;
- variable speed drives (variable frequency inverters) supplying motors for fans, pumps, etc.;
- UPS systems.

With the presence of harmonics, the current waveform will be distorted, and the r.m.s. value (equivalent heating effect) will be higher than for a linear load of the same power. As a consequence, all system components which carry harmonic currents (cables, busbars, switchgear, transformers) would have to be selected with suitable design ratings. Therefore, it is important to determine the true r.m.s. load, and size equipment to suit. This is also relevant to service capacity, and regulations for limiting harmonics at the point of common coupling.

11.14 Summary

In this chapter, the key factors related to load assessment for power systems in buildings have been considered. These include:

- Load assessment must be correctly related to the items of equipment in the power system; and an awareness of the loads at different locations will influence the power system design; so these are interrelated aspects of design development.
- Load assessment is not an exact science and requires engineering judgement based on careful consideration of the load pattern for all items.
- The design decisions based on load assessment will determine the key design parameters of a system.
- Overestimating or underestimating the load can have considerable detrimental impact.
- At the early design stage, the main method of load assessment is the application of load densities for building or system types.
- It is essential to have a clear understanding of the mechanical systems (HVAC) loads as these will have a dominant influence on the overall load in many types of buildings.
- It is necessary to understand the factors affecting diversity, and apply diversity where appropriate.
- The load pattern should be understood in relation to diurnal and seasonal variations
- Load assessment is required for each item of distribution equipment, as well as for the overall load.
- Load assessments should be undertaken in a clear, tabulated manner, and updated as the design develops.
- It should be recognised that many buildings have UPS systems that present complexities in load assessment; and the presence of harmonics arising from UPS systems and other non-linear equipment will have an impact on the load and equipment sizing.

Chapter 12

Space planning for services

12.1 Introduction

The active engineering systems will comprise a myriad of items of plant, central equipment, distribution elements and terminal components. Although the terminal components will be located within, or immediately adjacent to, the spaces being treated, the major items of plant and distribution elements need to be provided with dedicated spaces within the building. The nature of the mechanical and electrical equipment components used in active engineering systems in buildings requires that the spaces allocated are markedly different from spaces used for occupancy. Such equipment can be potentially hazardous, due to the energy systems used; and, due to the need to restrict access to competent operational personnel, will, in nearly all cases, require being located in discrete and dedicated enclosures or spaces. The division of spaces within the building can, therefore, in the simplest sense be considered to comprise primary spaces for the occupational needs of the building; spaces for access and circulation to the primary spaces; and secondary spaces for active engineering plant and equipment. The plant spaces can be subdivided into spaces for the building owner's M&E equipment; and spaces for the energy or services provider's equipment, for which the determining criteria will be their own standard space requirements and access regulations. Where the building is split into landlord and tenant areas, there might also be a requirement for subdividing plant spaces.

The assessment, selection and allocation of suitable spaces for the M&E services is one of the most important design activities for the building services engineer, and is usually known as 'space planning'. A not inconsiderable proportion of the building volume is usually dedicated to M&E equipment, and the 'lead designer' for these spaces is, in effect, the building services engineer, rather than the architect. The importance of making appropriate design decisions for space planning cannot be overestimated, not only to allow for the initial design and installation, but also for the future usage of the building. As discussed in Chapter 3, the space allocation will have a key determining influence on the operation and maintenance. As such, it will influence the longevity of equipment, energy performance and the overall effectiveness of the active systems; and is, therefore, a key consideration for an energy efficient building.

As with many aspects of interdisciplinary design, there is a requirement for a carefully balanced, astute approach that considers the many other design imperatives and demands on the allocation of spaces. The process of space planning has, traditionally, been a matter requiring extensive negotiation, primarily between the building services engineer and the architect; but also, often to a lesser extent, with the civil and structural engineer. It is most important that the case is made with clarity and the requirement is properly outlined and recorded. To do this, the building services engineer will normally be required to make the case through demonstrating that the options proposed have been the outcome of a logical assessment process. The starting point is to have a clear strategy from which the planning can commence; and for the proposed allocation to be demonstrable through drawn information and presented as a logical and auditable design exercise. The designer's duties for health and safety, under the CDM regulations, have been outlined in Chapter 2 and are relevant to all aspects of space planning for services.

Because this book is about design for energy efficiency, the focus here is on space planning for the main energy using systems – the HVAC and electrical systems. The space planning will also have to include an allocation for other services, such as sanitary systems; hot and cold water systems; fire engineering and other life-safety systems; and a variety of communication, control and alarm systems. The space planning for lift services, covering lift shafts and lift motor rooms (where required) forms a fundamental element of the space planning for the structural cores of the building, and is beyond the scope of this book. The drainage systems will relate to the locations of toilets and bathrooms and will also influence the design of cores. They are a special consideration in space planning, due to the need to seek vertical continuity. A brief introduction is provided to builder's work for services.

12.2 Space planning strategy

So that spaces for services can be successfully integrated into the building design in a holistic manner, it is essential to develop an appropriate strategy at the initial design stage. The key issues for space planning strategy can be considered to be:

- design objectives
- architectural form and structural design
- suitability of locations for all main plant
- internal and external access routes
- operational aspects, including health and safety
- fire strategy and means of escape
- economics
- planning considerations.

Each of these aspects is described in the following sections.

12.2.1 Design objectives

The design objective, from the building services perspective, is to allocate spaces for all equipment in suitable locations to facilitate ease of initial installation; subsequent routine operation and maintenance; and future upgrading or replacement. The requirement is to ensure that, throughout the process of design development, spaces are allocated for all relevant items of equipment. As outlined in Chapter 2, the system schematics should be maintained as the primary representation and statement of intent for the active system designs, and will be developed in line with the load assessments to provide notional equipment capacities. The series of engineering system schematics then forms an auditable or control checklist for the spaces that will be required.

The proportion of the building allocated to plant spaces can vary widely. For buildings with simple engineering systems – such as residential accommodation, warehouses and naturally ventilated offices – it might be in the region of 2–4% of the gross floor area. For buildings with a more intense services provision – such as fully air-conditioned commercial offices – it might be in the region of 4–10% of the gross floor area. For buildings where the functional activity requires services at a more complex or industrial level – such as research laboratories or data centres – the proportion could be 15–20% of the gross floor area, or more. It must be emphasised, however, that the space planning exercise is about much more than simply estimating a total proportion of gross floor area; although that is an important metric for cost effectiveness. It is, more specifically, about allocating *suitable* spaces in *suitable* locations for the types of systems involved. And, while total internal area is important, it should be seen more as a three-dimensional design issue, relating spatial coordination to ergonomics, to identify the most appropriate mix of spaces. In reality, because different building forms will provide differing amounts of roof space for services, the internal area required is not necessarily a representative measure of the total space requirement.

The notional capacities of equipment – which can be used, in conjunction with manufacturers' literature, to determine generic equipment sizes – provide the base information from which the space planning process commences. To achieve these objectives, spaces will be required both for major plant and for distribution components. The requirement tends to fall, therefore, into these distinct categories: (a) plant rooms; (b) vertical distribution (risers); and (c) horizontal distribution. An important feature is, of course, the continuity and connectivity of spaces to allow for the connections between main equipment, main distribution (both horizontal and vertical); and more localised distribution to terminal equipment. Horizontal distribution tends to fall into two distinct categories: (a) distribution for primary elements, which is best located outside of the occupied zone; and (b) distribution for final branches and circuits, which is usually located within the floor or ceiling zones of occupied spaces. Where practical, spaces should be designed to allow for zoning divisions, and with some degree of flexibility and expansion.

12.2.2 Architectural form and structural design

The building form will have a considerable influence on the planning of spaces for services. The shape itself will influence the arrangement of plant spaces and distribution routes. A tall, narrow building, will lend itself to a very different space planning strategy compared to a low, wide building. In a tall building, the space planning will be dominated by vertical distribution, with plant areas likely to be restricted to the basement, ground floor and roof area. As the other floor plates will have core space that limits the prime functional space at each level, it is preferable not to make any further reduction. There is a limitation in external access, which is, in practice, only directly available at ground and basement levels. The best access to outside air is at roof level. For a low, wide building, the space planning will be dominated by horizontal distribution. There will be more options for plant areas with external access, and large areas of roof space for access to outside air.

The architectural aspirations for the elevations will also influence the locations available for plant rooms, as will the visual appearance and planning criteria related to the roof area. Most plant rooms will require louvres in external walls, to a greater or lesser extent, depending on the specific plant requirements. Louvres would require careful visual integration into the elevation or facade treatment, and can be a limiting factor in achieving a satisfying architectural solution. It is often the case that an architect would propose that a continuous louvred 'band' be provided, for example for the whole of a floor level in a tower, or for one facade, rather than a more *ad hoc* arrangement of discrete louvres to match distributed plant requirements.

The development of the structural design will also have a primary influence. The building is likely to have one or more primary cores containing the primary vertical structure or 'spine(s)'. These are areas of the building where the main continuous vertical elements are co-located, such as the lift shafts, lift lobbies and staircases, together with the main risers and other shafts. The development of the cores is an essential early stage design activity involving the structural engineer, architect and building services engineer. The allocation of space for risers is a key determining factor, alongside allocation of lift shafts and lobbies; together with means of escape and other features – such as wet risers, dry risers and sprinkler services – arising from the fire strategy. The cores form an important part of the overall structural frame. Toilet areas and lobbies are usually located within the core areas. The structural frame will have columns and beams that could be of reinforced concrete or steelwork. The floor slabs will have a cross-sectional profile that might be flat, or might have a deeper shaped profile to provide structural strength. There might be reinforced

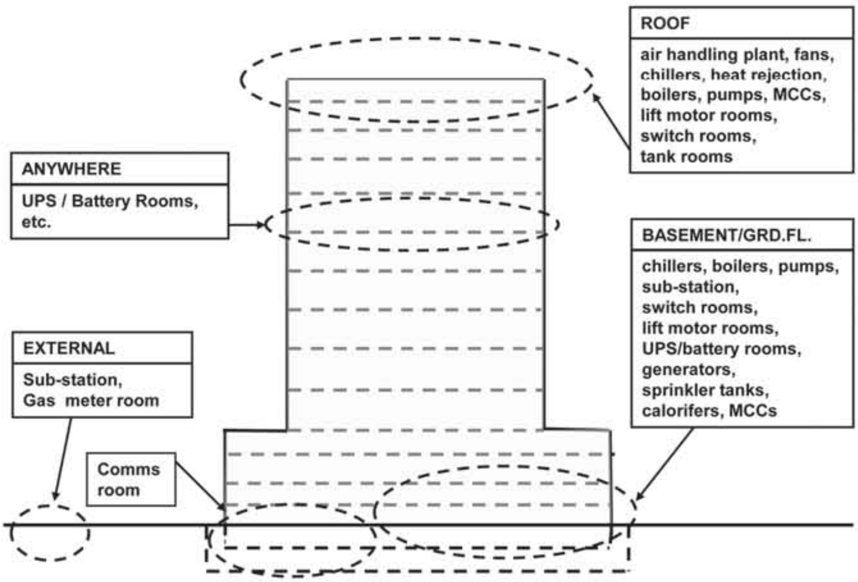

Figure 12.1 Typical locations for major items of plant

concrete downstand beams, or solid or perforated steel beams. All of these factors will influence the options available for plant spaces, risers and horizontal distribution zones. An essential design integration activity for the building services engineers is to understand the limitations in the structural design advised by the structural engineer. This relates to the need to achieve structural integrity, while seeking planned holes or slots within slabs and beams (if required) to allow vertical and horizontal distribution of engineering systems.

The structural engineer will require details of the typical weights and footprint area of equipment, together with information on any vibration that is likely to arise. The disposition of M&E plant and equipment will be a major consideration in the structural design, particularly the heaviest items, such as water tanks, fuel tanks, chillers, boilers and transformers. Where practical, these items should be located at basement or ground level, to avoid any additional structural impact (and cost) from locating them higher up the building.

12.2.3 Suitability of locations

For most buildings, only certain areas lend themselves as being appropriate as plant areas, due to either economics, ease of access or proximity to outside air. In most buildings, prime space is allocated for the primary occupancy functions of the building. Services spaces tend to be located in lower grade or 'back of house' areas, rather than displacing primary occupation. Figure 12.1 shows the typical locations available for major plant, and in many cases it will be a balance between basement/ground floor and roof areas, with only minimal intrusion into other areas. It should be emphasised that the location must provide the necessary height as well as floor area. Many individual plant items, and the preferred 'stacked' plant arrangements, will require significantly more than the normal floor-to-ceiling heights.

The suitability of different locations will depend on the type of equipment being considered. Figures 12.2 to 12.4 cover some of the key issues, most of which are simple, common sense design factors.

A number of possible locations could, in theory, be considered for air supply and exhaust equipment, as shown in Figure 12.2. For central systems with significant air volumes, the most practical location is likely to be in a clear roof space. However, the extent of roof space is limited on tall, slim buildings and can result in extensive distribution ductwork. A proportion of the plant could be located elsewhere, such as in the basement, but this is often inappropriate and impractical. This is due to the difficulty in obtaining access to the required quantity and quality of outside air. Where a basement solution is the only option, it can be made to work. It would require an air well, or a means of drawing in/discharging ventilation air from higher up in the building. Intrusion into prime space would, however, cause limitations in space planning for occupied areas and require louvres on the facade. It would also involve acoustic and access issues.

Heat rejection equipment for cooling systems requires a clear roof area that will provide suitable air movement for efficient operation and be acceptable in terms of appearance. The uppermost roof area is the ideal location. For wet cooling towers there are issues related to the 'plume' or cloud of condensation arising, and avoidance of any possibility of *Legionella*.

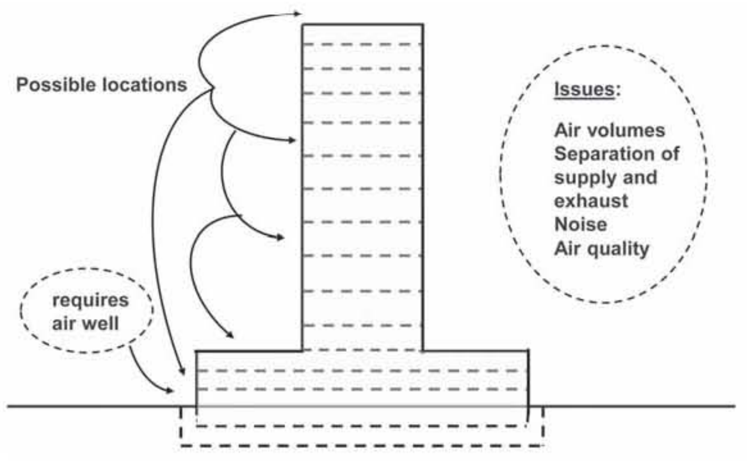

Figure 12.2
Potential locations for air supply and exhaust equipment

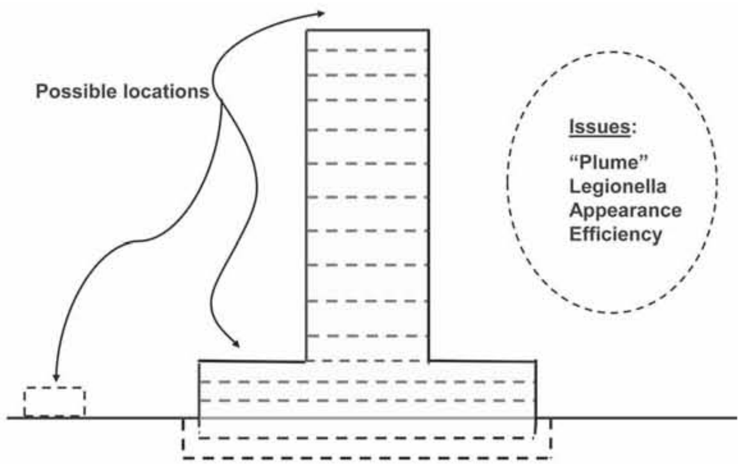

Figure 12.3
Potential locations for heat rejection equipment

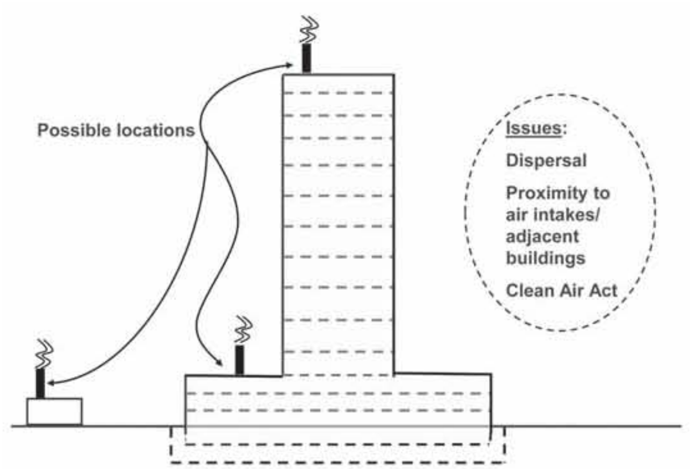

Figure 12.4
Potential locations for fume exhaust discharge equipment

There are good safety reasons to locate boilers and generators in basement areas, as this limits the extent of potentially hazardous fuel distribution (gas or oil) within the building. The disadvantage is the routing of flues to a suitable exhaust location. Similarly, there are good reasons to locate chillers at roof level, to achieve effective heat rejection and minimise the presence of refrigerants within the building. The disadvantage can be noise and vibration close to the prime top-storey areas.

Fume exhaust discharge equipment – for example, flues from boilers and generators, but also exhaust from laboratory gases – must be located so that dispersal satisfies the requirements of the relevant environmental regulations. The fumes must not impinge upon air intakes or adjacent buildings. As indicated in Figure 12.4, only the uppermost roof area is likely to be satisfactory, but this can cause problems with long flues from lower areas due to excessive pressure drop; and there would also be cost considerations and an increase in the space required in risers at each level.

12.2.4 Internal and external access routes

All plant areas require access for the initial installation to be undertaken, and for routine operation and maintenance throughout the life of the building. The access provision is for competent personnel and for replacement of equipment. The access for people will require doors from suitable circulation routes and should relate to the escape routes in accordance with the fire strategy. As operational personnel will be bringing tools and equipment, these access routes should, ideally, be within or from 'back of house' areas. The access for equipment will require sufficient spaces for moving all items of plant into their final locations during the construction stage. Such access might be through demountable panels or similar, and so might be of a temporary rather than permanent nature. The access requirements during the operational stage must be sufficient for the largest individual components that will be replaced, either as a routine replacement procedure, or as a consequence of failure. These considerations will often involve aspects such as road access, roof access, goods lifts and craneage; this may therefore require a strategy in itself.

12.2.5 Operational engineering

In addition to the necessary access and egress provision outlined in the previous section, the arrangement and disposition of equipment within the space must be such that the required operational activities can be undertaken safely and effectively. This will require clear access to all items where activities of a regular or routine nature take place. The access space should be sufficient for the tasks undertaken, and is a three-dimensional ergonomic design consideration covering the personnel and equipment activities. The nature of activities for plant replacement is sometimes set out in a plant replacement strategy document at the design stage.

For electrical equipment, there is a specific need to provide adequate space in switchrooms and similar areas, for the installation and replacement of individual items. There should also be sufficient accessibility for the required range of activities, including operation, maintenance and testing, along with inspection and repair. The arrangements should satisfy the requirements in relevant codes and regulations, such as those defined for operation or maintenance gangways in BS7671 (2008).

12.2.6 Fire strategy and life-safety systems

Most buildings will have a fire strategy that defines the features incorporated to resist the spread of fire and smoke, and allows for safe escape of occupants. This normally results in specific features relevant to the space planning, such as:

- fire compartmentation for spaces, comprising walls, floors, doors and cavity barriers in ceiling voids;
- certain building compartments will have a specified fire rating, typically one-hour, two-hour and sometimes four-hour rating;
- defined 'means of escape' routes

The planning of M&E services needs to take into account the fire strategy. For example, it may not be possible to locate certain types of plant rooms next to designated means of escape corridors. Special features are required where penetrating fire-rated components, in order to maintain integrity, such as fire/smoke dampers in ventilation ductwork and fire-rated packing for electrical trunking, cable trays and similar.

The fire strategy might require specific engineering systems to effect detection and alarms related to a fire condition; and fire protection for the occupants and structure in the form of smoke control systems (to keep the escape routes clear of smoke); smoke clearance systems; sprinkler systems and/or fire suppression systems. There might be standby generation and fuel storage associated with these systems. These life-safety systems will also require space allocation, which can be considerable. These systems are not part of the normal energy consuming systems and are not covered specifically in this chapter.

12.2.7 Economics

An essential aspect of building design is the need to provide sensible and economic usage of the space. The primary purpose of the building is to house the occupancy function for which it is intended. Any space that is not allocated for the primary function detracts from the economic viability, so a balance needs to be struck. It is usual to relate the usable and non-usable spaces in terms of 'net-to-gross' ratios, particularly for office buildings. The net area is, in simple terms, the gross area minus the non-usable space; although more formal definitions are in use in the industry. For commercial buildings it is likely that clients and developers would aim for net-to-gross ratios in the order of 75% or above, to be economically viable. However, this will depend on the type of building and wider aspects of the function, financial assessment and business case.

12.2.8 Planning issues and acoustics

The wider planning issues relevant to building services engineering have been described in Chapter 2. For the most part, these relate to the impact of plant and plant rooms, either from a visual aspect, or from aspects such as the acoustic impact during daytime and night-time operation; or fumes and pollution. The planning of spaces for plant must address the specific issues advised by the planning authorities, and this can be a primary consideration that can have a fundamental impact on the options available.

12.2.9 Selecting plant room and riser locations

A key factor in the iterative development of spaces for equipment is to ensure that the schematic diagrams for all of the engineering systems are the primary means of development for proposals, with the development of plant spaces following the schematic proposals. This will ensure that suitable spaces are allocated for all components of the building services systems, and are continually correlated with the systems proposals as they undergo iterative development.

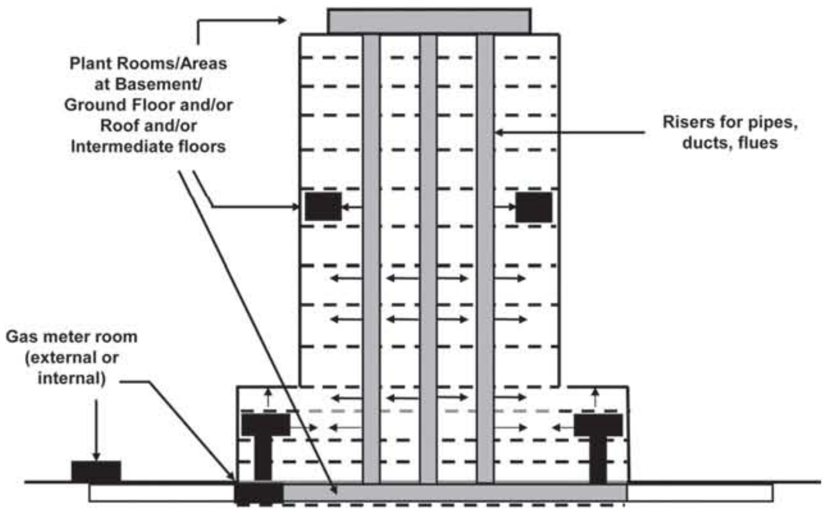

Figure 12.5 Mechanical systems: typical generic spatial requirements

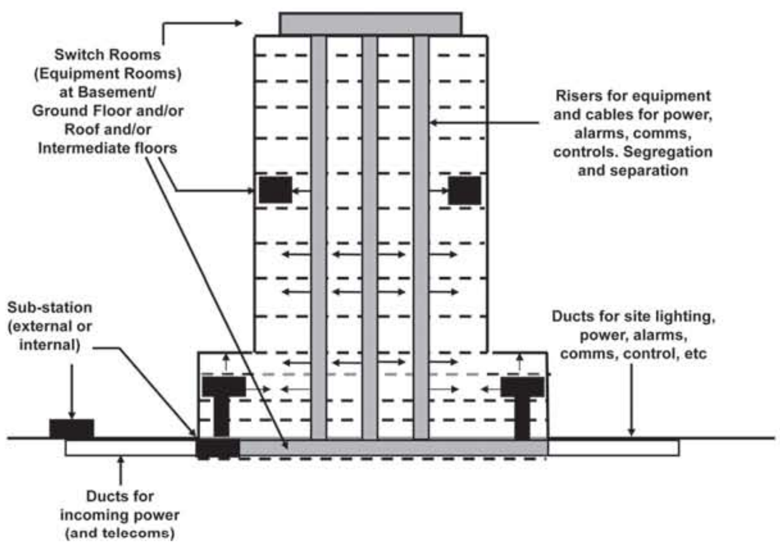

Figure 12.6 Electrical systems: typical generic spatial requirements

In a generic sense, the typical space requirements for mechanical and electrical systems are quite similar, as shown in Figures 12.5 and 12.6. In both cases there are likely to be plant areas at ground and/or basement levels, and at roof level; together with other plant areas whose disposition would depend on the building form and function. In each case there would be a number of risers connecting the plant areas. The major difference is one of scale, with mechanical plant areas and risers usually considerably larger than those for electrical services, particularly due to the requirements of air-handling units and ductwork distribution. However, the growth in the range of electrical systems has resulted in a general increase in the space required for electrical risers in modern buildings, and more space for on-floor electrical cupboards for local distribution.

12.3 Space criteria for mechanical and electrical equipment

It is necessary to understand the physical considerations that apply to each item of plant, so that appropriate space can be allocated for each item individually, and for all items as an interrelated and coordinated arrangement. Figure 12.7 shows the main physical considerations that would apply to a generic item of plant. It is essential to develop a design as a three-dimensional exercise. It should be recognised that the height required for equipment, particularly air-handling plant rooms, often presents considerable challenges. The mass is of major interest to the structural engineer (or civil engineer for sub-structure areas) as allowance will be required within the structural design. Suitable access is required for initial installation and for future operation and maintenance. At some stage the plant will need to be replaced, either in full or in part, for which suitable space is required. Depending on the item of equipment, it might be necessary to provide restricted access for reasons of health and safety. It might also be necessary also for security reasons; particularly where the item might be of a business-critical nature. But this can also be important in multi-tenanted buildings.

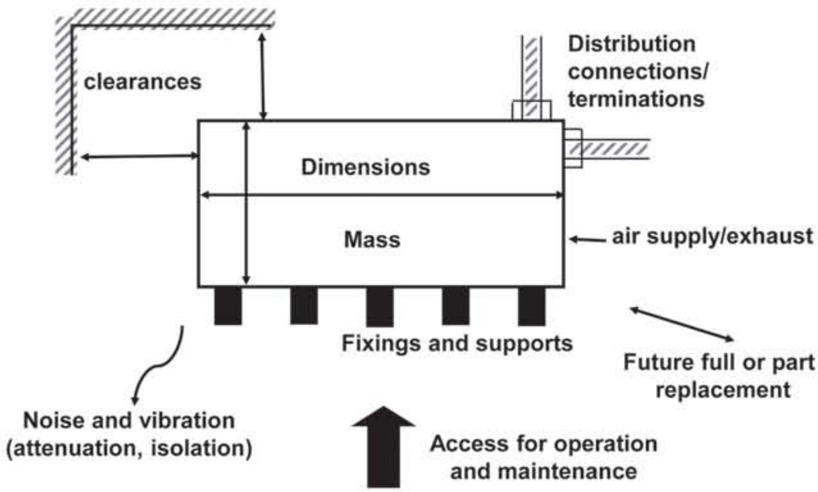

Figure 12.7 Generic physical considerations for location of equipment

All items of equipment and their distribution connections will require some form of supports or fixings, and these are shown generically in Figure 12.8. If an item of equipment causes significant noise and vibration, it will require some form of anti-vibration mountings and flexible connections to the rigid distribution elements.

There are many issues related to architectural appearance and planning that will restrict the potential locations for plant areas. Some of the key issues are shown in Figure 12.9. While the roof level is an important location for plant, there are likely to be restrictions in terms of appearance – often requiring some form of louvred aesthetic screen – and overall height. Noise breakout to adjacent premises, and noise and vibration impact on the upper floor, are also major issues. Similar considerations apply to mid-level plant areas.

There are also many restrictions in relation to the structural design. Some of the key aspects are shown in Figure 12.10. The mass of equipment has to be accounted for, together with any movement and vibration during operation. Similarly any proposal for distribution components to penetrate the structural slab will require approval, particularly if it is in close proximity to a vertical structure – which is usually the case with risers. Risers are special cases and require particular attention and negotiation with the structural engineer. The sizes required for openings in the slab, and the specific structural solution, will require careful coordination to achieve an acceptable solution. An essential feature will be horizontal openings at the riser for on-floor distribution. Any openings required in downstand beams will require approval, as will any penetrations of fire compartments.

Certain items of renewables equipment will, by their nature, require special considerations in space planning. Wind turbines require clear space so that the wind pattern

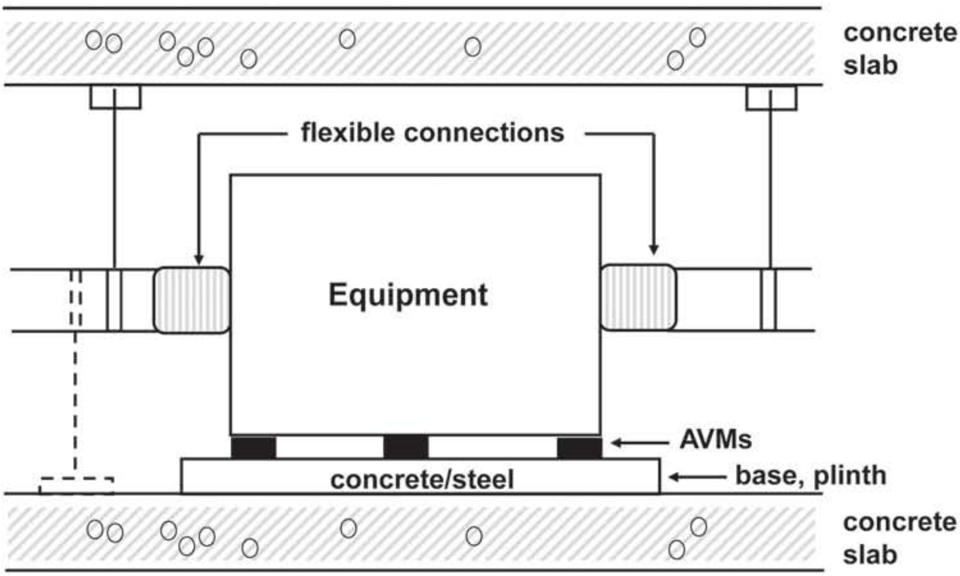

Figure 12.8 Generic supports, fixings and isolation

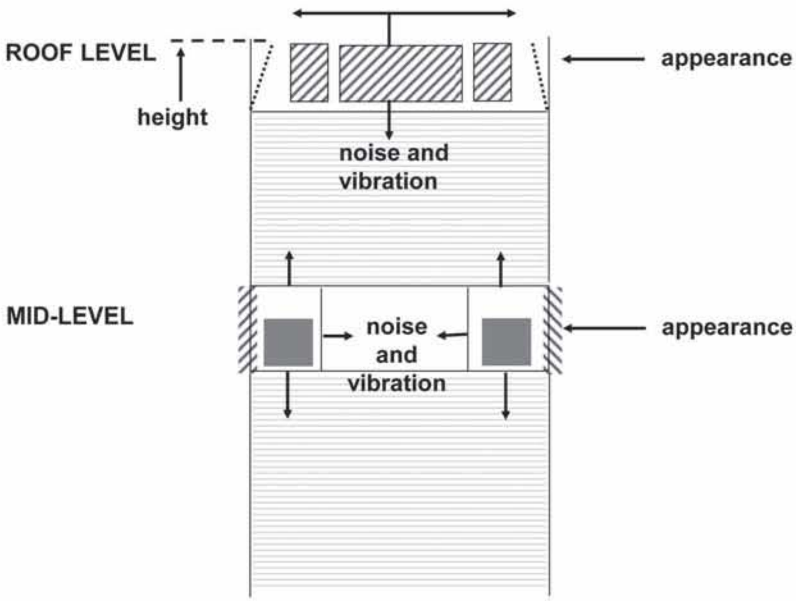

Figure 12.9 Main restrictions: architectural/planning

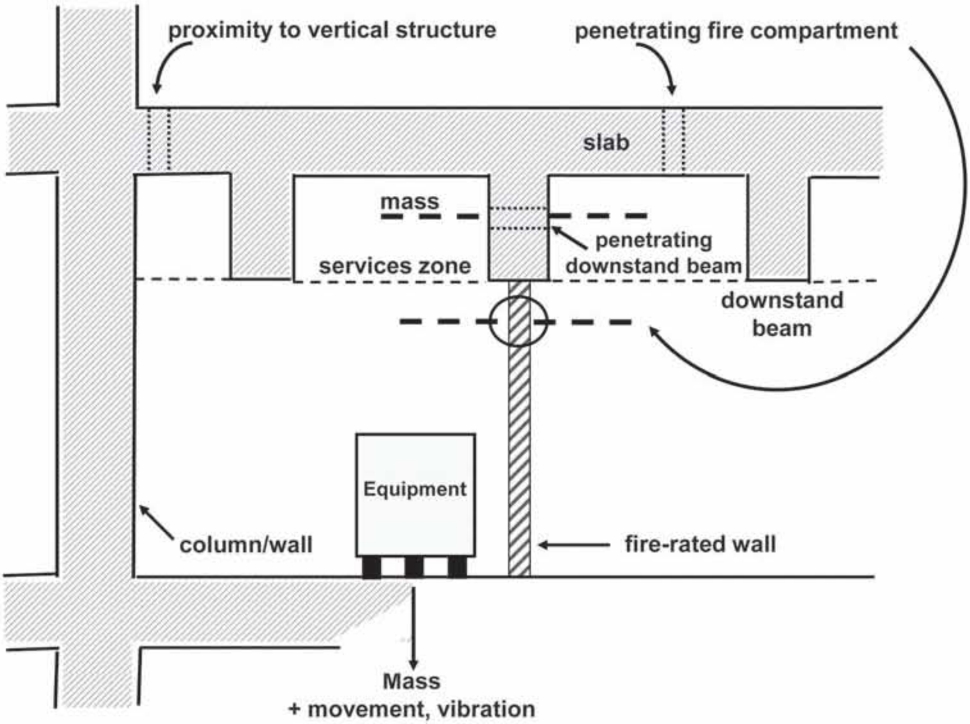

Figure 12.10 Main restrictions: structural

provides effective energy yield, and also allows sufficient clearance for health and safety and the maintenance activities. Photovoltaic panels require a location that provides good energy yield and avoids shading. The integration of wind generation and/or photovoltaics into a roof plant area therefore adds considerable challenges to the planning. Ground source heat pumps require detailed design integration with the civil engineering proposals for below-ground areas for the pipework systems, alongside space allocation for equipment.

In some cases, to provide a coordinated solution for equipment and distribution, the equipment is raised on a support platform to provide a distribution zone underneath. Figure 12.11 illustrates an example where pipework and valves are located in a zone below raised equipment and arranged such that no services rest on the roof finishes.

The photographs in the sections that follow show examples of equipment in plant areas during the installation stage, so they are not necessarily in a completed state.

12.4 Space planning for plant rooms

A useful checklist of generic factors to consider when assessing space requirements for all types of plant rooms is to:

- prepare block plans for every item of plant
- refer to manufacturers' technical literature
- seek an economic layout
- compare initial services space allocation with other projects and 'rules of thumb'
- consider space for access, operation and maintenance, and plant replacement (either in full or in part)
- consider health and safety implications
- consider zoning of systems
- make use of reference information
- means of escape provision and adherence to the building fire strategy; for plant rooms and roof areas, provide an alternative means of escape
- space for future plant.

In addition to these generic factors, other specific factors will be relevant depending on the type of plant room, as outlined below.

12.4.1 Heating plant rooms

Specific considerations include:

- location of natural air inlets, or mechanical ventilation
- location of flues and planning approval
- select a room separate from refrigeration and air-handling plant
- floor drainage
- noise and vibration control.

Figure 12.12 shows the coordinated layout in a heating room with boilers on the left and pump sets in the centre. Ductwork is located at high level with sufficient clear space below. The layout has been arranged with due regard to the locations of the circular structural columns, and clear access routes have been provided between items of plant.

Figure 12.13 shows an arrangement of twin pump sets. Each pump set is located on an inertia base, which itself is mounted on a concrete plinth, to provide isolation from vibrations. Clear access space has been provided between each pump set.

12.4.2 Chiller plant rooms

Specific considerations include:

- select a room separate from heating and air-handling plant
- floor drainage
- noise and vibration control.

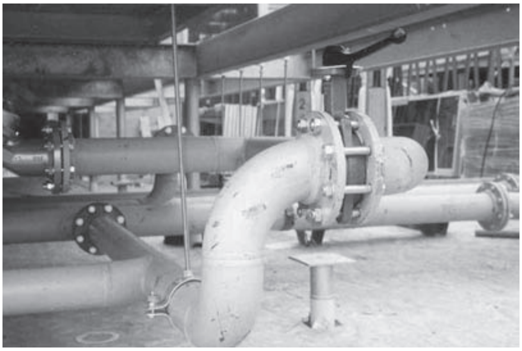

Figure 12.11 External services located below plant

Source: courtesy of Hoare Lea

Figure 12.12 Typical heating plant room

Source: courtesy of Hoare Lea

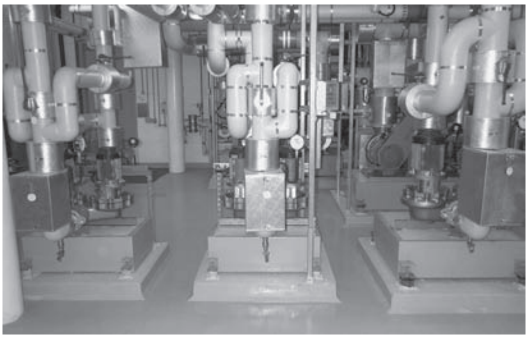

Figure 12.13 Pump sets

Source: courtesy of Hoare Lea

12.4.3 Air-handling plant rooms

Specific considerations include:

- location of outdoor air and exhaust louvres
- proximity of ductwork risers
- floor drainage
- clear height of plant room (if internal)
- noise and vibration control, including the size of attenuation equipment.

Figures 12.14 and 12.15 show air-handling units in roof level plant areas during the installation stage. The units are mounted on raised structural platforms, providing access for operation and maintenance.

12.4.4 Electrical substations

Specific considerations include:

- ownership, metering and access
- plant replacement strategy for transformers
- proximity to other services and electromagnetic compatibility (EMC) issues.

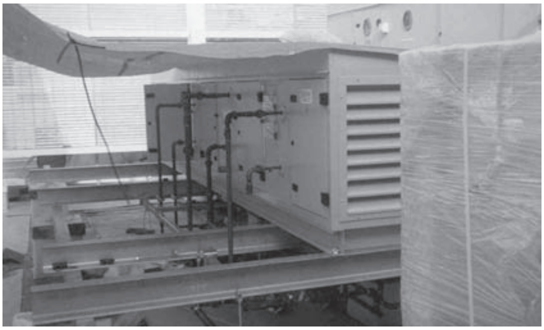

Figure 12.14
Air-handling unit within screened plant area

Source: courtesy of Hoare Lea

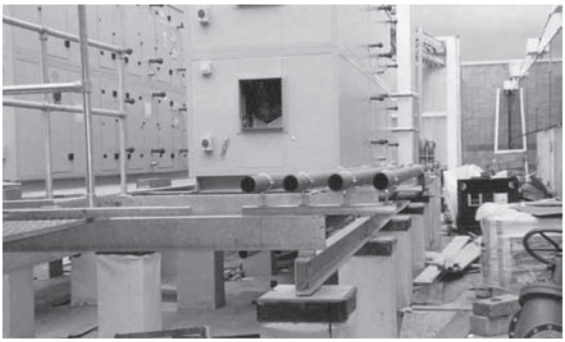

Figure 12.15
Air-handling units

Source: courtesy of Hoare Lea

12.4.5 Generator plant rooms

Plant room considerations for generating plant are complex and beyond the scope of this book. However, it is worth noting here some specific considerations as, in some buildings, these rooms can be a significant size. Acoustics issues are a major consideration for:

- plant installation and removal: skid-mounted sets or engine and alternator
- ventilation equipment and air movement; louvres and attenuation
- height to allow for silencers and lifting beam for maintenance
- separate plant space for fuel storage and pumping
- ducts for cabling and pipework.

12.4.6 LV switch rooms

Specific considerations for LV switchrooms are:

- switchboard access: front only *or* front and rear?
- switchgear maintenance and circuit breaker withdrawal
- switchboard extensibility: one end only *or* both ends?
- space for power factor correction and/or harmonic filtering equipment
- cable bending radii: initial installation and future (as this affects height)
- ducts for cabling
- wall-mounted equipment: distribution boards, control panels, etc.

12.4.7 UPS rooms

It is worth noting the key considerations as these rooms can be of significant size in some buildings:

- equipment installation and removal for switchgear, UPS modules, control panels, etc.
- operation and maintenance without disrupting business-critical systems
- separate room for battery racks
- ventilation equipment and air movement; louvres and attenuation
- ducts for cabling, etc.
- extensibility and expansion without disruption to business-critical systems.

12.5 Space planning for risers

There are two main considerations when planning spaces for risers: achieving vertical continuity (and retaining shape) throughout their height; and the suitability of horizontal spaces interconnecting with risers to facilitate distribution within plant areas and the ceiling and floor voids of occupied spaces. Vertical continuity is required so that the sizes and shapes of distribution components can remain the same throughout their length, and can be installed easily, without the need for any off-sets or changes of direction. Straight lengths of distribution components provide an economic solution, reduce time for installation, and help to minimise distribution energy losses.

The starting point for planning risers is to identify all of the risers required from the early stage schematic diagrams of the engineering systems, and make a preliminary assessment of their sizes. It might be necessary to make reasonable assumptions, as the full details will not be known until later in the design process. It is sensible to allow spare space in risers for future extensions or additions, perhaps allocating 10–15% of extra space. Where appropriate, reference should be made to any criteria for future expansion within the brief. In larger buildings, it is likely that there would be a number of mechanical risers, electrical risers, drainage risers and communications risers. These would, ideally, be separate. In smaller buildings, there might be a need to compromise by combining appropriate services in common risers (such as electrical and communications services), provided that certain separation criteria could be assured.

The iterative design exercises to explore riser options might result in corresponding developments of the system schematics, so that a satisfactory overall solution can be found for vertical distribution components and the spaces in which they are located.

12.5.1 Mechanical risers

The risers for the HVAC systems will, for most air-conditioned or mechanically ventilated buildings, with central air-handling plant, be the largest risers. This is primarily due to the need to contain supply and extract ductwork, which is usually much larger in cross-sectional areas than pipework or cabling services. Similarly, the ductwork connections on each floor will normally be larger than pipework or cabling services, with limited scope for change in direction. The risers for ductwork will, therefore, normally require the most space and require the most attention during the initial space planning exercises. It should be noted that mechanical services risers at each floor level usually only contain ductwork and pipework, together with branch connections to serve the relevant floor. Unlike electrical risers, they do not contain wall-mounted items of equipment requiring access. The thickness of insulation for ductwork and pipework must be considered in assessing the total space required.

The key considerations that apply to the allocation of mechanical risers are: the area, zone or tenancy to be served; the practical lengths of ductwork or pipework branches from riser mains; and the practicality of providing service connections from the riser to the ceiling and floor voids.

12.5.2 Electrical risers

Some of the same considerations apply to the allocation of electrical risers as for mechanical services. In the case of electrical risers, the design decision on the number of risers will need to consider the area, zone or tenancy to be served; the practical lengths of final circuit cabling from distribution boards; the practicality of equipment layout within the riser; and the practicality of providing services connections from the riser into the ceiling and floor voids. It might also be necessary to provide a degree of separation between different types of electrical service; and independence – for example to separate HV services from LV services, and to provide independent routes to business-critical or life-safety equipment.

An important difference between electrical and mechanical services risers is that, while mechanical risers tend to house distribution elements only – such as ductwork and pipework – electrical risers also house a variety of items of equipment. Key factors to consider in the design of electrical risers are:

- initial and future rising services: trays, ladders, busbars, and trunking
- initial and future equipment: distribution boards, control panels, contactors, etc.
- access for operation, maintenance and other activities in accordance with relevant codes
- separation and segregation of services; for example, separating power from control, monitoring and communications (due to EMC issues), as outlined below.

Figure 12.16 shows a typical layout of equipment in an electrical riser in an office building. This would normally house the distribution boards for lighting and small power, but could also include local equipment related to fire alarm, public address, security, building management systems/controls, metering, outstations and other systems. It might also contain harmonic filters. Risers are also likely to include 'through services', for example, LV cables passing through the floor level to feed chillers or other equipment at roof level.

Figure 12.17 shows an example of an electrical riser on the ground floor during the installation stage. At the stage shown, this only houses the LV cables that form the incoming supply rising to the LV switchroom at roof level.

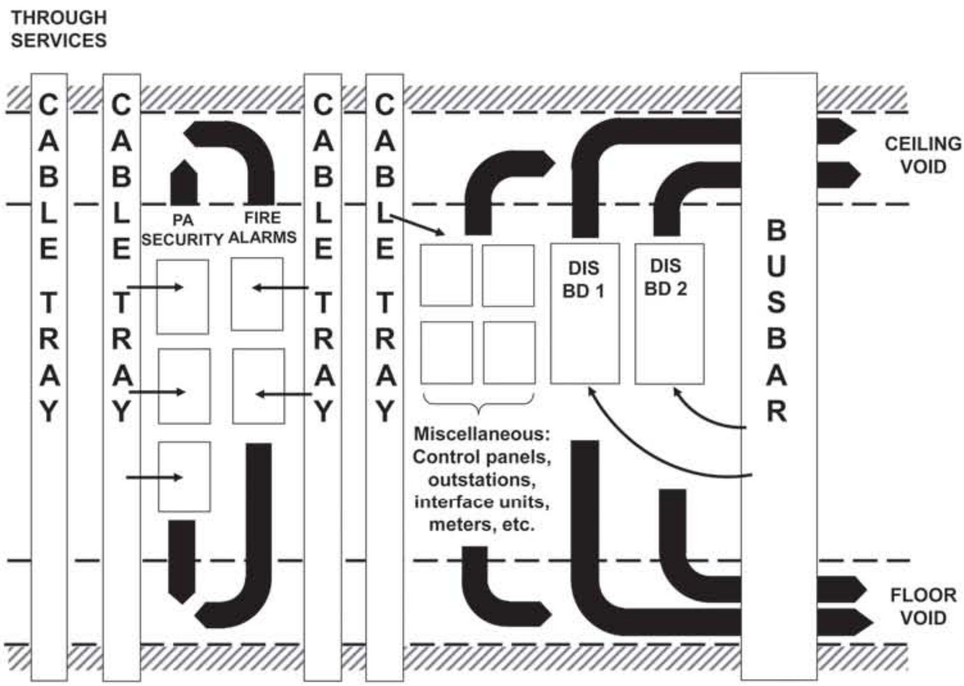

Figure 12.16 Electrical risers: typical equipment layout

Figure 12.18 shows an example of an electrical riser in an office building. At the installation stage shown, this contains distribution boards and tap-offs from a rising main busbar, with space for additional equipment.

Separate spaces should be provided for communications rooms and risers.

Note on electromagnetic compatibility (EMC)

It is necessary for electrical systems within buildings to be designed such that they achieve EMC. To do this, the following conditions must be satisfied:

- an item of equipment should not be adversely affected by its electromagnetic environment
- an item of equipment should not adversely affect the operation of other equipment.

Typical sources of electromagnetic interference (EMI) and radio frequency interference (RFI) are:

- power equipment, such as generators, transformers, cables and busbars
- lightning and transients
- transmission equipment, such as radar and radio.

Equipment that operates at low levels of power and voltage (such as electronic devices) is the most susceptible to interference, which could cause malfunction.

The best way to avoid interference is to locate the susceptible equipment so that it is separated by a suitable distance from the major power components. If separation is not possible, some form of metallic shielding is likely to be necessary, as illustrated in Figure 12.19. To reduce the likelihood of EMC problems, the cable installation arrangement should be close to symmetrical; and power cables should be separated from digital cables (CIBSE 2004b). EMC issues are complex and are beyond the scope of this book, but are mentioned briefly here as useful information in relation to the planning of spaces for electrical equipment.

Figure 12.17 Incoming electrical riser

Source: courtesy of Hoare Lea

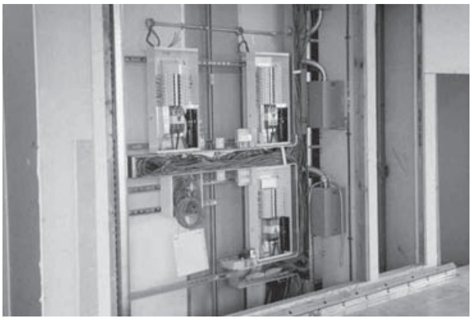

Figure 12.18 Electrical riser on office floor level

Source: courtesy of Hoare Lea

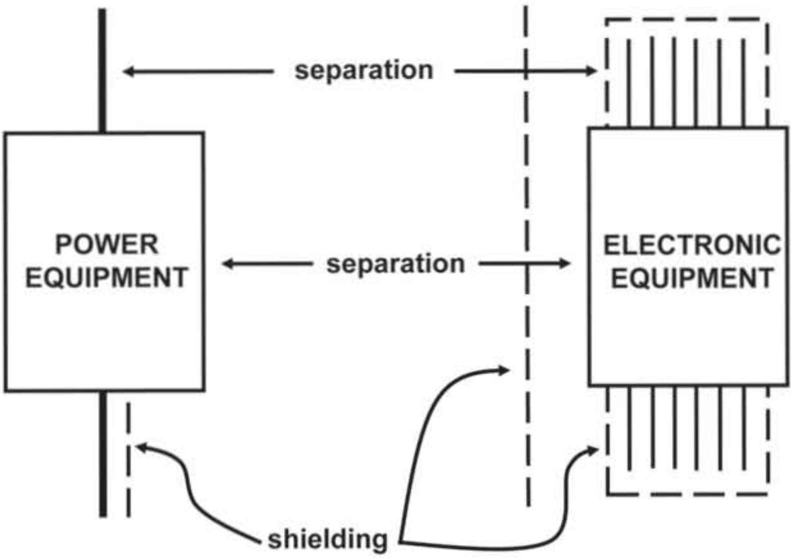

Figure 12.19 Separation and shielding for EMC

12.6 Planning horizontal distribution

The horizontal distribution elements that need to be housed tend to be of two types: (a) primary infrastructure, connecting main items of equipment to risers, or to other plant; and (b) secondary distribution from risers that form the circuits or branches that feed terminal equipment.

In some cases the horizontal space will house a mix of both of these types of distribution components.

At basement level, or other parts of the building with plant rooms, it is often the case that the slab-to-slab heights will be well above those on occupied floors, to provide the required heights in plant rooms. In such cases, primary distribution can often be located at high level in plant areas and adjacent circulation routes.

Figure 12.20 Services tunnel

Source: courtesy of John Pietrzyba

In buildings or site developments with extensive plan areas, it is sometimes the case that the most appropriate design solution for the primary infrastructure horizontal distribution is to create a services tunnel. Figure 12.20 shows a tunnel with the pipework located on one side and cabling on the other side. This allows space for future services, and access for operation and maintenance, with minimum disruption to the rest of the building. A service tunnel of this type would be a significant feature in the civil engineering design and requires consideration from the concept stage.

For the second type of distribution in occupied areas, there is usually a need to allocate spaces within ceiling voids and floor voids for horizontal distribution to terminal equipment. The specific arrangements at high and low level will depend, to a considerable extent, on the architectural proposals for the finishes and the nature of the space. In some cases, a design solution could be to not have a ceiling void, and the architect might consider that the exposed services and structure are appropriate for the type of space. Such a solution might be sought for environmental reasons, to benefit from the exposed thermal mass of the slab; but would usually require careful consideration from an acoustics perspective. Many modern buildings, however, are likely to require floor voids and ceiling voids, with raised floors and suspended ceilings, respectively. The design iteration to agree heights of ceiling voids and floor voids is an important part of the design process. There is an imperative to maintain sufficient clear floor-to-ceiling heights within the occupied zone, while minimising any additional height that will add to the cost of the building. From a building services perspective, the objectives are the same as for other plant areas. Key considerations are the level of access provided by demountable ceiling panels or floor tiles; and the three-dimensional arrangement of components within the void to minimise cross-overs that will add to the height requirement.

In most modern buildings, the floor void is a major services zone and requires similar considerations to ceiling zones in terms of design, particularly in relation to the clear depth available. For most office buildings, the raised floor void will contain power and data cabling as a minimum. Depending on the selected HVAC solution, the floor void could also contain pipework and ductwork. In certain types of buildings with intensive services requirements, such as data centres, the floor void will be the primary zone for services, and assessment of the depth will require detailed design attention.

The photographs below show examples of ceiling voids and floor voids with partially completed services installations at the construction stage.

Figures 12.21 and 12.22 give an indication of the depths required for ceiling voids, and the arrangement of services components to coordinate with structure and ceiling grid and coordinated services arrangements.

Figure 12.23 shows the floor void for a modern office building at construction stage. This illustrates the depth of the services zone within the floor void, and the ductwork, pipework and cable trays that had been installed at that stage.

Figure 12.21
Coordinated services in ceiling void prior to installation of chilled ceiling panels

Source: courtesy of Hoare Lea

Figure 12.22 Services in ceiling void

Source: courtesy of Hoare Lea

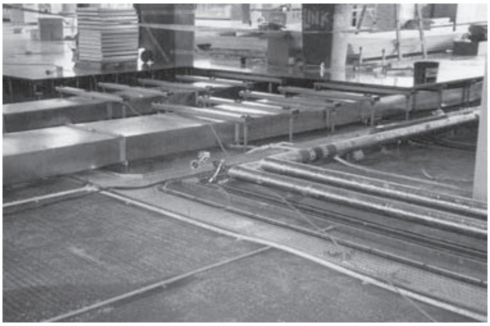

Figure 12.23 Services in floor void

Source: courtesy of Hoare Lea

12.7 Implications of adaptation to climate change on space planning

The need to design for adaptation for climate change is likely to have an impact on the space allocation for equipment. In particular, if cooling loads increase due to higher ambient temperatures, the required capacities of cooling equipment (and associated air-handling equipment) are likely to increase, and hence the space required. The higher ambient temperatures may also require different arrangements and physical sizes for heat rejection equipment; could affect air-handling unit sizes and associated ductwork and pipework; and power supplies for cooling and air-handling equipment. It is possible that the most appropriate provision would be to include a degree of flexibility and modularisation in the design to allow incremental changes to be incorporated. Overall, design for adaptation is likely to increase space requirements. This should be considered during the design brief development, in order to seek the client's view on the extent to which this should be addressed. Another possible implication of climate change is an increase in flood risk for some locations. This would raise issues about the wisdom of locating certain items of equipment – particularly electrical equipment – in basement areas. At present there is little guidance on how these issues should be addressed, but this is likely to be an aspect of design that receives increased attention in the future.

12.8 Builder's work

In addition to the principal plant spaces (plant room and risers) there will also be a need for a wide range of minor building work to facilitate the installation of the engineering systems. This must also be planned as an integral part of the building design and is generally known as 'Builder's Work in Connection' (i.e. in connection with the mechanical, electrical and plumbing services). This includes:

- bases, plinths, frames and supporting structures for equipment
- ducts and trenches for distribution components, such as pipes or cables
- pre-formed holes in concrete and other masonry construction for distribution components, such as pipes or cables
- pre-formed holes in steelwork for distribution components, such as ducts, pipes or cables
- components that are cast into the concrete structure for fixings and supports
- fire cladding and packing to maintain fire integrity where distribution components penetrate fire compartments.

All significant builder's work requirements should be advised to the architect and structural/civil engineer at an early stage so that they can be incorporated within the architectural and structural designs as they are developed.

Figure 12.4 shows the builder's work that has been provided for a roof plant area to allow the installation of large air-handling units. A series of supports have been provided for the equipment. Located around the edge of the area allocated for the equipment is the framework for the architectural louvred screens.

It should be understood that some of the same considerations for builder's work also apply to the external areas around buildings. The aspects of external integration that usually require most attention are the routes for major services distribution, such as drainage, power distribution, district heating pipework (if relevant), and gas and water pipework. All ducts and other external services need to be integrated and coordinated with the other external elements, such as roads, paths, paving, hard surfaces (such as car parks), planting and other landscape features.

Figure 12.24 Builder's work bases for large air-handling units

Source: courtesy of Hoare Lea

12.9 Summary

Space planning is an essential part of the building services design process to allocate dedicated spaces for active engineering systems components. When planning space allocations, a strategy should be established at the outset to cover aspects such as the design objectives, building form, suitability of locations, operation, maintenance, fire strategy and economics. Suitable locations should be identified that are appropriate for the types of equipment in plant rooms, and for risers for vertical distribution, and zones for horizontal distribution. There are generic space criteria for equipment that will determine the size of space required. The main considerations for space planning of plant rooms have been described in general form, together with the special consideration for different types of plant room. The planning and sizing of risers is a key aspect of the overall space planning process. Risers have generic requirements together with special considerations that apply to mechanical and electrical risers. The requirements for planning horizontal distribution have been outlined in brief, and form an important aspect of the planning of spaces and height allocations. The need to design for adaptation to climate change is likely to influence space planning in the future.

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Index