LONDON SOUTH BANK UNIVERSITY

A low carbon cooling guide

Technical Report: Advice and guidance to support implementation of energy planning policy

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Executive summary

This guide helps designers, developers and planners on the adoption of low carbon cooling systems in new developments and buildings being refurbished. Sections 1 to 5 provide an introduction to environmental issues related to cooling buildings for planners, architects and developers. Sections 6 to 8 provide a more detailed method for assessing environmental performance of cooling systems for designers and planners assessing developments. This guide has been developed by London South Bank University with support from the Greater London Authority (GLA).

Climate change is increasing the need for cooling in buildings in the UK, and changing user expectations are driving developers and their clients to install these systems more widely. Introducing air conditioning with cooling into a design can increase electrical energy consumption by up to 50%, adding to global warming. There is a lack of clear guidance about the relative efficiency and carbon performance of different cooling systems and this guide helps address this.

London South Bank University[1] have also developed a model for forecasting future cooling energy demand in buildings across London, giving a range of possible future scenarios and carbon emissions to 2030. This work for the GLA shows that climate change might give rise to 350,000 tonnes CO_2 per year by 2030 based on the higher temperature rise scenario. However, the drive towards more efficient systems can strongly mitigate, and even offset, growth in CO_2 emissions provided the very best solutions are adopted. These forecasts therefore highlight the importance of specifying the most appropriate systems using the best available technologies. Where possible, mechanical cooling solutions should be avoided or reduced, but the uncertainty in how climate change will manifest itself may mean that it is better to design in high efficiency cooling solutions now, rather than risk individual (low efficiency) units being installed ad hoc in response to warming conditions. This is a particular issue in the residential market, and there is a need for good market data to be collected in order to address the uncertainties in this sector. The residential sector could be responsible for an extra 100,000 tonnes CO_2 per year by 2030. This shows why it is important to ensure that all new developments specify the best cooling technologies and systems available, and that there is greater use of new, innovative low carbon cooling solutions.

This guide presents a new cooling hierarchy and a new methodology for determining the environmental impact rating of cooling systems. The performance rating is called the Greenhouse Gas Impact Rating (GGIR), is simple to apply and understand by combining the indirect and direct Global Warming Potentials of a cooling system into a single number called the Greenhouse Gas Impact Factor(GGIF). The GGIR depends on which band the GGIF falls within. From the study of 4,000 systems the full GGIR range runs from 0 to 2100 $kgCO_2/y.kW$ in seven bands of 300 each. These bands are labelled A – G, with A being the best. A totally passive cooling system would have a GGIF of zero.

The GGIF is calculated via a thirteen step methodology that considers the key energy losses in a cooling system, and combines these with fuel CO_2 factors and refrigerant leakage rates to give a total global warming potential in kg CO_2 (equivalent) per year per kW of cooling demand. The methodology encourages passive measures and reduced running hours to be taken into account which can improve the rating. The guide contains typical values that can be used in each of the steps, but it is anticipated that, with use, further information will become available to improve the input numbers. The guide is therefore the first step in an evolutionary process that will encourage designers and developers to employ better cooling systems.

There is a wide variation in overall Greenhouse Gas Impact Factor (GGIF), even amongst typical modern designs. It is important that designers and planners understand which are the best and worst of these typical modern designs. In general, where passive or renewable systems can not be used, mechanical cooling for new developments should be rated at least A or B.

1. Introduction

Sections 1 to 5 provide an introduction to cooling issues for planners, architects and developers

1.1 Cooling is an increasing problem

It is estimated that cooling in buildings is responsible for around 15 TWh of energy demand in the UK[2], the vast majority of which is fuelled by electricity from the national grid. This is around 4% of the total electricity demand in the country, but all the evidence shows that this demand is rising as sales of electrically powered air-conditioning equipment is growing year-on-year. Electricity taken from the national grid has a high CO_2 content due to the mix of fossil fuels used at the power stations, and the poor efficiency of energy conversion (between 30 – 50%), see appendix B for further details on CO_2 emission factors. For this reason cooling can be responsible for higher CO_2 emissions per unit of energy delivered than heating. In general, cooling consumes around 15% of total electricity use in commercial & public sector buildings but the actual proportion in individual buildings will vary from zero to 40% depending on the design.

What is air conditioning?

Most buildings that require cooling use equipment called air conditioning to cool the building. This is typically refrigeration plant (chillers) that cool air which is distributed throughout the building by fans in air handling units that supply the air through ductwork. The heat extracted from the building is rejected to outside air by cooling towers or dry coolers (water to air heat exchangers). Fig 6.2 shows a simplified version of this.

The term **air conditioning** is often used to describe this overall approach. However, it is often misused. Where only the temperature is controlled, the correct term is **Heating & Cooling (or Comfort cooling)**. Full air conditioning actually changes the humidity of the air as well as temperature (see later). Buildings without any mechanically driven systems are referred to as naturally ventilated.

Heating is still responsible for higher overall CO_2 emissions in the UK, but successive changes in Building Regulations have significantly reduced the amount of heating required by new and refurbished buildings. This is leading to buildings that have an increased proportion of cooling, especially in the non-residential sector. Standards for cooling systems are prescribed within the Building Regulations[3], and new buildings incorporating cooling systems have to meet more stringent plant efficiency and control standards whilst also meeting tighter carbon targets than natural ventilated buildings. However, there is a lack of clear guidance about the relative efficiency and carbon performance of different cooling systems.

The impact of climate change is increasing the need for cooling in buildings in the UK, especially in the south of the country. Climate change is projected to increase average summer temperatures by up to 3.5ºC by the middle of the century, when two out of three summers will be as hot as the 2003 heatwave. This will also intensify the urban heat island effect, a phenomenon where urban areas become several degrees hotter than surrounding rural areas due to the built environment absorbing solar energy during the day and then releasing it as heat in the evening. Greater numbers of cloud-free days will increase the number of hours that an intense urban heat island (>4ºC) is experienced. Computer modelling suggest there may be a 18% increase in the number of hours an intense urban heat island is experienced by the end of the century[4].

Changing user expectations are driving developers and their clients to install cooling systems more widely. This is true in both the residential and non-residential sector. Although there are no specific statutory maximum temperatures in UK buildings, the Building Regulations set limits for overheating in naturally ventilated buildings, mainly to avoid air conditioning being added to them after construction. The regulations indicate that internal heat gains from people and lighting greater than 35 W/m^2 is a good measure of overheating. Alternatively, designers are asked to show evidence that internal temperature will not exceed 28°C for an agreed number of occupied hours per year. Avoiding overheating is therefore an increasingly important issue in building design and can often encourage the installation of expensive carbon emitting air conditioning.

1.2 The challenges for cooling buildings

Cooling systems are relatively complex with a huge range of cooling options, solutions and equipment combinations. The beginning of this guide provides a simple introduction to these issues for planners, architects and developers. The latter part of the guide provides a simple way of assessing the energy performance of cooling systems. This is mainly for engineers who are involved in designing cooling systems as part of the process of making planning submissions but also for planners who will need to assess these new developments. This guide also provides a wide range of references to more detailed guidance where this is available.

There are a number of difficult challenges faced by those trying to keep buildings cool. Occupant expectations are increasing, often to levels that are unrealistic. Occupants often believe that every building will be cooled, and cooled to the ideal temperature. Equally, developers and architects still tend toward deep plan buildings with high proportions of glass leading to high solar/internal heat gains, so increasing the need for cooling. This has also resulted in a trend towards over-engineered buildings, often turning what could be fairly good naturally ventilated solutions into high energy consuming air conditioned developments. These more complex buildings are more difficult to manage, often leading to poor operation and maintenance resulting in poor performance and excessive energy consumption[5]. The current Building Regulations[2] do require designers to avoid buildings that overheat to minimise the cooling required. In addition, the sale and rental values for air conditioned buildings still remain higher than those for their naturally ventilated counterparts, which can lead to air conditioning being introduced to buildings where it is not actually necessary. Designers also have to consider how they will deal with increasing average and peak outside air temperatures as a result of climate change, as this will lead to even greater cooling requirements. In major cities like London the urban heat island effect will only exacerbate these temperature increases still further[6].

The introduction of building energy performance certificates (EPC's and DEC's) to label buildings with their energy use might help mitigate the drive towards greater levels of cooling. These rating schemes directly highlight the increased energy use due to cooling and it is unlikely that an air conditioned building will ever reach a high rating. Also, the introduction of carbon trading in larger buildings (through the Carbon Reduction Commitment Energy Efficiency Scheme) will add to the cost of running air conditioned buildings and the code for sustainable homes sets increasingly tighter carbon targets for dwellings. However, designers will simply see these regulations as additional pressures. The additional energy demand of active cooling systems represents an energy demand that may make it difficult for buildings to achieve excellent energy performance ratings. In England and Wales the Energy Performance of Buildings Directive (EPBD) requires inspection of all air conditioning systems with rated outputs over 12kW at intervals not greater than 5 years[7]. This includes an assessment of the adequacy of the equipment and controls and the current size of the plant in relation to cooling load. This will raise questions in existing buildings about the original design of the air conditioning plant and how appropriate it is for the building, placing further pressure on designers.

1.3 Future cooling scenarios

Work has been carried out by London South Bank University to forecast London's cooling loads and resulting CO_2 emissions up to 2030[1,8]. The objectives were to:

- Assess current and future energy demand and CO_2 emissions from cooling systems in London
- Look at the potential impact of climate change on CO_2 emissions
- Assess the impact of expected system efficiency improvements and system mix

The forecasting model focused on 5 building types and then eight generic cooling system types were used for the analysis. The cooling and energy demands were estimated using the CIBSE TM41[9] methodology (i.e. a cooling degree-day approach). Six different scenarios were modelled to capture a range of possible futures. These include a base case and four variations assuming different climate change rates, changes in system efficiencies, and changes in the mix of systems installed.

Figure 1.1 provides a summary of the forecasts under the various scenarios showing the effect on future annual CO_2 emissions, installed capacity and energy demand respectively.

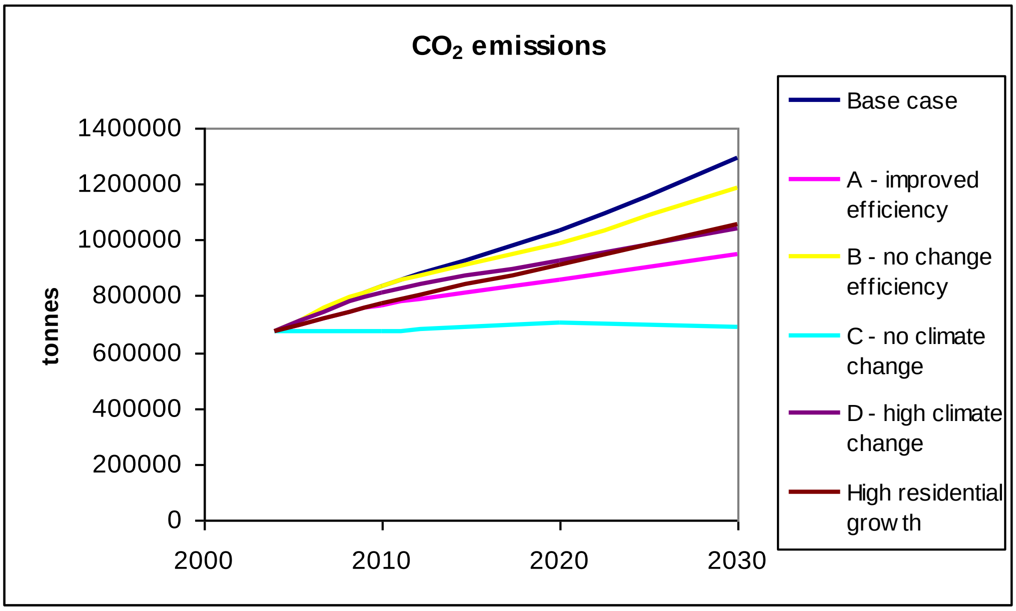


Fig 1.1 Summary of future CO_2 emissions from cooling for various scenarios

This work shows an estimate of 1.6 TWh of cooling energy demand in London, which is around 11% of UK total cooling electricity demand. This is considered highly plausible, and the omission of some building types (leisure centres, industrial and warehousing, hospitals and other specialist areas) may have a slight influence on this figure, but this serves as a good comparison of London cooled building stock. This set of scenarios is considered to be in the upper range of what would be expected, since floor area growth may not be as strong as assumed and the system efficiencies (CoSPs) are only at the lower end of what is already possible.

These scenarios suggest that under the higher temperature rise scenario the impacts of climate change might give rise to an additional 350,000 tonnes of CO_2 being produced per year by 2030 as a consequence of increased cooling. However, the drive towards more efficient systems can strongly mitigate, and even offset, growth in CO_2 emissions provided the very best solutions are adopted. These forecasts therefore highlight the importance of specifying the most appropriate systems and using the best available technologies. Where possible, cooling loads should be minimised and mechanical cooling solutions should be avoided or reduced. However, some designers may take the view that the uncertainty in how climate change will manifest itself may mean that it is better to include high efficiency cooling solutions now, rather than risk individual (low efficiency) units being installed ad hoc in response to warming conditions. This is a particular issue in the residential market, and there is a need for good market data to be collected in order to address the uncertainties in this sector. The residential sector could be responsible for an extra 100,000 tonnes CO_2 per year by 2030.

These results therefore indicate the need to develop good guidance on the best type of cooling systems for different applications. The ability to demonstrate the comparative environmental impact of different cooling systems is essential if the best systems are to be deployed. Such a comparison methodology needs to be relatively simple to use and understand. Any methodology should also be able to capture the complexities of cooling systems, and be transparent to non-specialists in the decision process.

1.4 The purpose of this guide

Most local authority planning requirements now include a strong consideration of energy efficiency and renewable with London taking a lead. The London Mayor has stated, through his Climate Change Mitigation and Energy Strategy, his commitment to reduce London's contribution to global climate change, tackle the problem of fuel poverty and promote London's economic development through the wider use of decentralised energy complimented by extensive energy efficiency activity. Considering projected climate scenarios, low carbon cooling technologies and strategies will play an increasingly important role in London meeting these targets. The revised London Plan[10] introduced New Policy 4A.6: Decentralised Energy: Heating, Cooling and Power, which places an emphasis on the use of low carbon cooling solutions, including community based schemes and trigeneration (also known as Combined Cooling Heat and Power, CCHP).

The policies in the London Plan, along with a Borough's own planning policies, are a primary consideration when assessing any planning application in London. The London Plan includes a requirement to include energy efficient design, efficient energy supply and renewable energy technology wherever feasible. The London Plan also includes a requirement for an energy assessment and requires a demonstration of the contribution of renewable energy technology. The Mayor's energy hierarchy has three clear stages, as set out in policies 4A.1 to 4A.7 of the London Plan, that are applied to each planning application, they use less energy, supply energy efficiently and use renewable energy.

Given the wide variety of cooling systems, and the various claims about how efficient or appropriate different systems are, there is now a clear need for improved guidance for the design community on available cooling techniques and technologies and how these can reduce carbon emissions related to cooling whilst meeting the expected increase in demand for cooling. This document aims to provide guidance on how to compare the relative carbon intensity of cooling technologies and strategies, and to demonstrate the advantages of low carbon solutions based on the following approach:

- Reducing the requirement for cooling
- Supplying cooling through passive means
- Using the most efficient mechanical systems

The aim is to provide a methodology that is useful to designers and developers that is also transparent and communicable to non-technical decision makers and planners. In this way, it is hoped to drive new designs towards the most efficient and least polluting systems available.

At the heart of this document, in Section 6, is a new methodology for defining the relative environmental impact of cooling systems using a Greenhouse Gas Impact Factor (GGIF), which leads to the concept of a Greenhouse Gas Impact Rating (GGIR). The methodology is a relatively simple step by step calculation that includes both energy and refrigerant environmental impacts, which provides a rating on an A to G scale. The methodology is supported by relevant data and assumptions along with a number of worked examples.

A comprehensive range of calculations have been undertaken to support and verify the methodology, and the results of these are presented to provide an initial ranking range for cooling systems.

The guide also provides an overview of cooling systems available for buildings along with a summary of cooling system components and strategies for reducing cooling demands. In conjunction with the development of this guide, another study was undertaken to assess the potential future cooling demand and associated CO_2 emissions in London under a range of future scenarios including; climate change, changes in system mix and improvements in system efficiency[1,8]. The results of this study serve to highlight the need for action if the CO_2 contribution from the increase in demand for cooling in London is not to grow. When set in the context of security of energy supply, social equity and it's contribution to climate change it is important that all relevant stakeholders are able to contribute to providing workable, affordable and low carbon cooling solutions.

1.5 A cooling hierarchy for new developments

This study has identified the need for a cooling hierarchy as shown below and in Figure 1.2. Whilst this is based on the philosophy set out in the London Mayor's Energy Hierarchy it has with a significant difference in the order in which issues are considered.

1. **Reduce cooling loads**
2. **Use renewable sources of cooling**
3. **Supply cooling as efficiently as possible**

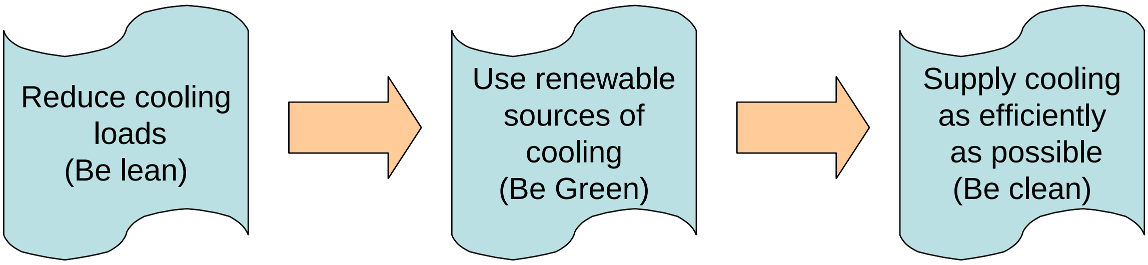


Fig 1.2 Cooling hierarchy for new developments

A notable difference to the energy planning hierarchies used commonly in local authorities is that the cooling hierarchy asks designers to consider renewable means of cooling before supplying cooling using energy consuming mechanical systems. This hierarchy also includes the obligation to connect to any district/community cooling systems where this already exists. The cooling hierarchy has influenced the development of the cooling methodology set out in section 6.

2. Overview of cooling in buildings

Buildings are subjected to a number of heat gains from internal and external sources. Internally heat comes from people, lighting, machines and small power loads (and, perhaps, poorly controlled heating systems!). External sources of heat are direct solar gains (heat from the suns rays entering the building), and when outdoor air temperatures are high, conduction of heat through walls etc, and convective gains from warm outside air entering the building. The magnitude of each of these heat sources varies from building to building, and will depend on the building form (shape, mass, shading etc), its function, and the way people operate within it.

Heat also comes in two forms – sensible and latent heat. Sensible heat is that which changes the temperature of the air and surroundings, whereas latent heat is carried in the form of water vapour in the air. Latent heat sources include perspiration from people, transpiration from plants, processes like laundries, or direct transfer from the outdoor environment. Many cooling systems are designed to reduce latent heat gains, which may be as high as 10 – 20% of the overall cooling load.

The productivity associated with a work place is often linked to the working environment, and in particular the comfort the occupants feel. Overheated buildings can be extremely unpleasant places to work, but there is a danger of demanding conditions in a building to be controlled within very narrow limits leading to higher energy consumption. Building temperatures and humidities should be controlled within reasonable limits to ensure good productivity, but not so tightly that temperatures are kept at a constant year round value as this is an expensive strategy. There are productivity consequences in allowing internal temperatures to rise to say 28°C. Equally, there are running cost and carbon emissions implications in air conditioning to 19°C or to within 50% ± 5% relative humidity.

2.1 How heat gains get into buildings

Solar gains

Solar gains can often be the largest source of heat gain, the majority of which comes through windows. Some solar gain is transmitted through the opaque fabric of the building where it is heated by the sun, but in well insulated buildings this component is small and normally has a significant time lag associated with conduction of heat into the building. Direct solar gain through glazing, however, is difficult to deal with. Windows are excellent architectural features allowing views out and daylight in – which in itself can provide good carbon savings by reducing electric lighting. External solar shading (e.g. architectural features, overhanging screens etc) and solar control glass which reflects light can be important strategies for reducing solar gains. Internal blinds can help, but these tend to absorb solar gains then re-radiate much of the heat to the internal space, and when closed they cause the lights to be put on, further increasing the thermal gains. If direct sunshine is allowed to fall on thermally massive structures (such as concrete floors), there can be a significant delay between the heat entering the building and the internal space experiencing a temperature rise.

Conduction and convection from outdoor air

When the outdoor temperature is higher than the indoor temperature there will be a transfer of heat through building fabric (conduction) and by air entering the building (convection). The conduction gains will be very small, but air infiltration, or mechanical ventilation, can give rise to significant loads. Air infiltration will also impart a latent gain to the space. With all-air cooling systems, air is used as the cooling medium throughout the building. More air is needed for this than the building ventilation requirements, and so this introduces a significant additional load on the system when the outdoor air temperature is warm and humid. This has to be mitigated by the use of heat recovery equipment that can gather heat that would otherwise be thrown away e.g. conditioned air extract from the building. Therefore, minimising air flow into the building, whether natural or forced air, is an important strategy in reducing cooling loads.

Internal gains

All activities and processes in a building give off heat. People normally metabolise at around 80-120 Watts depending on activity levels. All of the energy from electric lights ultimately turns to heat, and machines (for example computers) are continuously having to reject heat to the surroundings. Equipment such as fans and pumps and their motors all put heat into the cooling systems that they make work.

In winter these so called ‘casual’ gains can usefully offset heat losses to reduce the amount of heating energy required, but in summer they can serve to overheat the building to unacceptable levels.

Ventilation versus cooling?

Ventilation essentially means air movement.

Natural ventilation - air movement through open windows or encouraged by wind or warmer air rising up a stack/atrium.

Mechanical ventilation – forced air movement through ductwork using fans driven by electric motors. The term mechanical ventilation often means fans moving air that is heated only. Air conditioning incorporates fans moving air that is heated/cooled or even humidified/de-humidified.

Cooling – reduces the temperature of the air in the building often using electrically driven chillers to cool the air in the ventilation system. Cooling can be seen as extracting unwanted heat from a building.

Mixed-mode systems - combine natural and mechanical ventilation and cooling in buildings which might otherwise have been fully air-conditioned.

2.2 Types of cooling system

Passive cooling

Cooling strategies that avoid or minimise the need for mechanical cooling will keep energy consumption to a minimum. These passive cooling systems/strategies should always be considered before including mechanical cooling, as outlined in chapter 5,. Figure 2.1[11] shows a hierarchical approach to ventilation in buildings that encourages passive low energy consumption solutions before mechanical cooling is introduced.

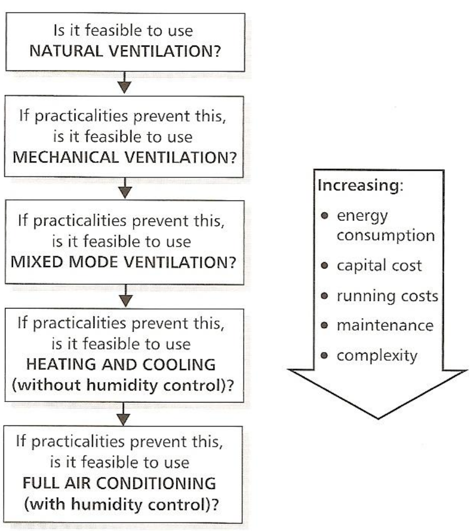


Figure 2.1 Ventilation hierarchy[11]

Heat always flows naturally from a high temperature to a low temperature. Where a building has high heat gains, if its internal temperature is higher than the surrounding external conditions it is possible to use natural heat transfer to reject heat to outside. This is the basis of passive cooling techniques that use natural and stack ventilation to offset the gains (discussed further in Section 3). The problem is that these mechanisms may not be enough to remove the heat fast enough, particularly in relation to the demands set by designers for cooling modern offices.

Refrigeration systems

Where passive systems are insufficient it is necessary to use mechanical systems to extract and reject the heat from the building. This cooling effect is generally provided by refrigeration plant (chillers) based on the ability of a working fluid (refrigerant) to absorb/reject heat. Chillers therefore move heat from the building to the outside air in much the same way as a domestic refrigerator moves heat from the fridge cabinet into the kitchen. Refrigeration machines can be based on a vapour compression cycle (electrically driven) or an absorption cycle (less efficient, heat driven), both absorb heat at low temperature (i.e. below the building operating temperature) and reject it at high temperature (above the outdoor temperature).

Broad system categories

All-air systems – Use air as the cooling medium throughout the building, often based around air handling units and air ductwork. Generally, the air is cooled by chilled water in the range 5-10°C.

Climatic systems – Use chilled water to cool the building structure to deliver cooling e.g. chilled beams and chilled ceilings. Generally, using higher temperature chilled water in the range 14-17°C.

Radiant systems – Use chilled water to provide cooling through large slabs of the building structure e.g. floor slabs. Generally, using even higher temperature chilled water in the range 16-22°C.

Fan coil units - are common delivery devices normally comprising a local heat exchanger and fan to further chill centrally supplied all-air system.

In all cases these mechanical systems have to reject the heat to a lower temperature (heat sink e.g. cooler outside air) – and in most cases this means raising the temperature of the working fluid (refrigerant) above the air outside. Alternatives can be to reject heat to low temperature sinks such as underground aquifers or surface water (rivers and lakes). More detail is given in Section 5, but in general chillers use less energy to pump this heat 'up hill' than the amount of heat they move. This makes refrigeration equipment potentially very efficient. Refrigeration efficiency or Coefficient of Performance (CoP) is heat moved divided by energy input and is often 3 to 4 and can be as high as 6 in modern chillers. i.e. 6 units of cooling are provided for each unit of energy used.

Refrigeration machines operate at higher efficiency when the evaporator (heat absorbing) and heat rejection (condenser) temperatures are closer together (less of a 'hill') – see Figure 5.3. The low temperature evaporator side (e.g. chilled water) is dictated by what cooling delivery equipment is placed in the building, whereas the higher temperature condenser side (cooling towers for heat rejection) depends on where the heat is rejected to (e.g. outside air). This is important as each 1°C reduction in temperature lift gives a 2% to 4% cut in energy consumption, and increases cooling capacity. Chilled water systems operating at 5-10°C therefore result in lower system efficiencies than say radiant slab systems operating at 16-20°C.

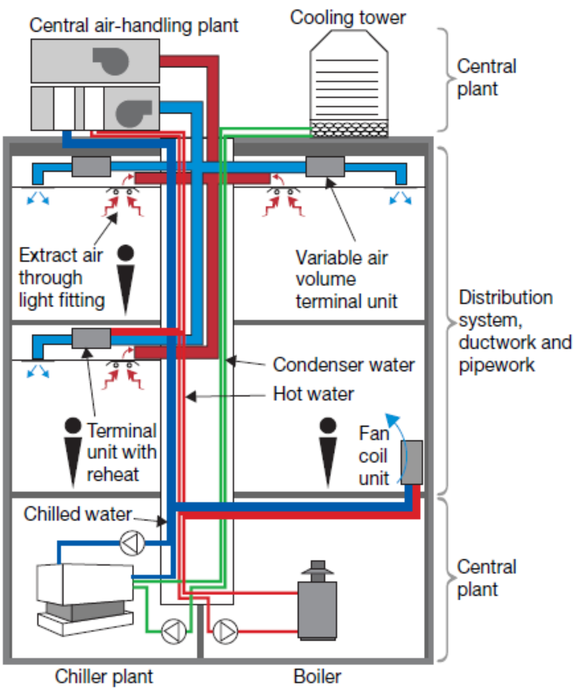


Figure 2.2 Typical all-air system[12]

Delivery equipment

Supply of Coolth is another term for delivering cooling, which can also be viewed as removing heat from a space.

Coolth can be delivered by introducing cool air into a space, or by changing the temperatures of the surfaces in the space. All-air systems have been the most dominant systems, and these either supply air from central plant or from distributed systems such as fan coil units, see Figure 2.2[12]. Each system has its own particular advantages and disadvantages, but the main problem with all-air systems is the significant quantity of air that has to be moved around the building using fans, which is highly energy consuming.

Chilled beams and slabs are a means by which the surfaces of a space can be cooled. This provides radiant cooling to the space. The advantage of these radiant systems is the surface temperatures cannot be too low, as this can lead to condensation of water vapour and the surfaces become wet. The higher operating temperatures mean the chiller does not have to work so hard to reject the heat. In addition, water is used as the distribution medium rather than air, which reduces the distribution costs, both in capital and energy running costs. The disadvantage is that these systems have a limited cooling capacity, and may not be able to deal with high peak loads.

Other delivery methods involve placing the refrigeration units within the work space and piping refrigerant around the building. These systems can be highly efficient, as in the case of variable refrigerant flow (VRF) systems, or highly inefficient in the case of split direct expansion (DX) units. These systems use air to provide the cooling to the space, but are unable to provide free cooling (see section 3) from external air that central systems are capable of.

Heat Rejection Equipment

Heat extracted from the building can be rejected to any suitable heat sink. Similar to the benefits discussed for overall passive solutions, any move toward passive heat rejection techniques will provide lower energy solutions. In most cases cooling systems reject heat to outside air, which in the heat of summer requires the chiller to do more work than in Winter. Heat is commonly rejected using a heat exchanger with a fan blowing the outside air across it. This can be part of the chiller with the refrigerant (typically R407c) being cooled (condensed) directly (an air-cooled chiller). Alternatively, it can be a water-cooled condenser with a separate water to air heat exchanger (e.g. dry cooler).

These air-cooled condensers generally have fans to blow air over the heat exchanger and therefore consume electricity in the fans. They can be improved by spraying water on the heat exchanger (evaporative condensers), which lowers the temperature of heat rejection, and improves the overall system efficiency (although water is evaporated, and lost). Cooling towers are even more efficient because they blow the air through the water itself. So, water cooled condensers can either be connected to a dry air cooler (similar to an air cooled condenser), an evaporative cooling tower, or alternatively to a direct water source. The latter may be from a local river, and can produce the best results as the temperature of heat rejection is below that of the outside air.

If a particularly low temperature water source is available then it may be possible to use this for direct cooling in the building. This is the realm of borehole and surface water cooling, but there are limitations to such systems, and this generally requires a licence to reject heat to the environment in this way.

A fast growing form of heat rejection is ground coupled cooling where heat is rejected to the ground around or below a building. This is generally done in conjunction with ground source heat pumps which take heat out of the ground in winter (using reverse cycle refrigeration systems), and putting it back in summer. There is a need to ensure the seasonal heat balance is properly calculated to maintain the overall system efficiencies.

Trigeneration (CCHP)

An alternative to electric chilling is absorption refrigeration that uses heat – either from fuel combustion or waste heat – to provide cooling. This can be used in tandem with combined heat and power (CHP) to give combined cooling heat and power (CCHP or trigeneration) systems[13]. Trigeneration appears to have excellent thermodynamic advantages, in that it uses heat from an electricity generating engine at a time that it would normally go to waste. This can vastly improve the overall fuel efficiency of a CHP installation that may struggle to find heat loads in the summer months. However, there are drawbacks. Absorption refrigeration is less efficient (with CoPs usually less than 1), and the plant and associated heat rejection equipment is larger and more expensive. There are arguments to show that, under the right conditions and set of assumptions, trigeneration can be more carbon intensive than using vapour compression electric chilling. This is currently a contentious area, but where economies of scale exist, with suitable heating and cooling loads, it may be sensible to encourage large district wide schemes involving absorption cooling systems. The analysis presented in this guide suggests that each system should be analysed on its own merits, and the underlying assumptions be fully justified.

See Sections 3 to 5 for further details on cooling systems.

2.3 Energy and carbon implications of cooling

Most refrigeration plant is electrically driven which, if taken from the national grid, has a high CO_2 content. However, the efficiency of electrically driven refrigeration plant is such that heat pumps can have a better carbon performance than condensing boilers in heating applications. The argument in a climate such as the UK is that cooling is an unnecessary luxury in most instances. It is sometimes suggested that it should only be used where there is a strong business need to maintain lower temperatures, or where internal temperatures become excessive for long periods of time. The problem is that climate change appears to be making the need for cooling more apparent, especially in cities such as London that have an additional 'heat island' effect.

3. Minimising cooling loads (BE LEAN)

There is considerable potential at the early stages of design stage to minimise or even avoid the need for mechanical cooling. Further detail can be found in the CIBSE Guide F – *Energy Efficiency In Buildings*[11] CIBSE Guide B4[14], Saving Energy in Refrigeration[15], Good Practice Guides 280[16], 291[12], 290[17], and the ASHRAE Handbook[18].

Introducing mechanical ventilation and/or air conditioning into a design can increase electrical energy consumption by up to 50%. However, there are instances where some form of forced ventilation system using a fan is unavoidable e.g. deep plan buildings, high internal gains, exacting environmental conditions etc. Even then, designers should seek to make effective use of outside air conditions with a view to minimising demand. If mechanical cooling has to be installed then good sizing[19], zoning and controls are key factors in making any mechanical ventilation strategy energy efficient. Where the system also controls humidity i.e. full air conditioning as opposed to simple heating and cooling, then this will increase energy consumption even further. Variable flow systems (e.g. Variable Air Volume - VAV) are preferable for energy efficiency to systems that run at full output no matter what the cooling demand (e.g. central all-air fan coil systems). Also control strategies that use free cooling at times when outside air conditions are suitable, as explained below,. It is essential that cooling systems and their constituent items of plant are correctly commissioned to ensure high efficiency and good operation[20].

Passive Measures

The building envelope should be considered as a climate modifier rather than solely a means of excluding external climatic conditions. There are a range of passive (non mechanical) measures that can help reduce the cooling demand of the building, without the need for energy input, such as natural ventilation. Passive measures are not always sufficient to provide all the cooling in their own right but can help to reduce the overall cooling load significantly. Examples of passive measures include[11]:

- Good site layout
- Good building orientation
- Compact built form (shape, size etc)
- Increased thermal mass (i.e. heavyweight structure)
- Increasing natural ventilation (e.g. stack effect)
- Reduced internal gains
- Enhanced spatial planning
- Relaxed internal design criteria
- Solar shading
- Window optimisation

Site layout, the potential size and shape of the building present both opportunities and constraints. The site conditions influence the built form and can be used to advantage to promote passive ventilation and daylight strategies whilst minimising solar gains.

Choosing the optimum orientation to maximise daylight and to minimise summer heat gain and winter heat loss can have a significant impact on energy efficiency, particularly if it avoids or minimises air conditioning. For example, north-facing windows suffer very little solar gain and benefits are often gained by having the major building axis pointing east/west. East or west-facing glazing is harder to shade from direct sunlight, as the sun angles are low at some times of year. South facades receive both direct and diffuse radiation and are relatively easy to control. The use of thermal mass can also help attenuate temperature swings and minimise cooling requirements.

Compact building forms have a relatively small exposed surface area for a given floor area, thus reducing the influence of the external environment. A compact design may also benefit by requiring less space for the distribution of horizontal and vertical services, particularly for air ductwork. However, if commercial pressures and/or a compact design lead to a deep plan, i.e. over 15m in depth then the core of the building may require continuous electric lighting and internal activities may prompt mechanical ventilation or air conditioning. The energy efficiency benefits from natural ventilation and daylight penetration are most easily obtained up to 6 metres inwards from the windows[11].

Naturally ventilated buildings generate the driving force for air movement by relying on a range of techniques which maximise the potential of the stack effect. Stack induced ventilation uses air passages at differing heights and wind effects, often by ventilating from at least two facades, see Figure 3.1. Using natural ventilation, avoiding mechanical energy using devices e.g. fans, will save energy in air movement but can also be used to minimise the need for cooling. Ducts, shafts, solar chimneys etc. can be used to create a column of air at higher temperature thus generating pressure differences that give rise to the stack effect. Passive stack effects can also be promoted through an atrium that will additionally act as a buffer to reduce fabric heat losses. Guidance and case studies on the control of natural ventilation are provided in CIBSE AM10[21].

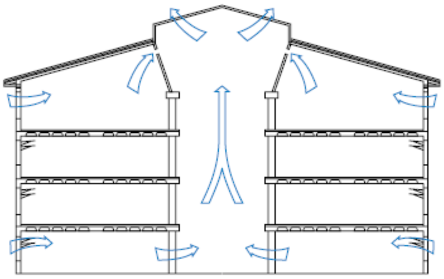


Figure 3.1 Stack effect through a central atrium

There are often limitations to the passive measures that can be introduced in city developments like tight building sites, high external noise levels, air quality issues etc. However, architects need to work closely with building services engineers at the very outset of development design to maximise the opportunity for passive measures to be exploited.

Shading

Daylight can be controlled either actively, e.g. with external adjustable manual or automatic blinds, or passively using architectural features such as orientation and overhangs to reduce solar gains when the building may be susceptible to overheating[22]. These shading devices are often referred to as brise soleil.

The appropriate type, size and positioning of any shading device will depend on climate, building use and the source of the light to be excluded (high or low angle direct sunlight; diffuse sky light; or perhaps reflected light from paving on the street outside). Deciduous trees or vines can be used to screen the solar heat and glare in summer and filter light in winter, and planting can sometimes solve the problem of reflected light from neighbouring structures, water or ground finishes. Designers should balance the benefits of having moveable external blinds against the relative robustness of fixed external shading. i.e. movable blinds will have higher capital and maintenance costs but should provide better shading.

Interior shades protect occupants against the immediate effects of direct sunlight and against glare. But when infra-red radiation penetrates the glazing most of it is trapped in the room and must be dissipated by ventilation or mechanical cooling. Mid-pane blinds are often a useful compromise and tend to require less maintenance and cleaning[22].

Reducing cooling loads

Minimising the need for cooling can reduce energy costs and, in some cases, the capital cost of plant. The need for cooling can be minimised by:

- reducing cooling loads

- raising cooling supply temperatures
- using ‘free’ cooling.

Cooling loads can be reduced in many ways, for example by:

- selecting office equipment with lower power use
- Selecting efficient lighting systems
- optimising set points (e.g. space temperature, air supply temperature, recirculation rate and humidity)
- improving control of temperatures, flows and humidities (but not necessarily closer control)
- reducing the occupancy density (people per unit floor area) which in turn will reduce the internal gains.

Raising supply temperatures

Raising the temperature at which cooling is delivered allows higher evaporating temperatures which increases refrigeration efficiency and, therefore, reduces energy consumption. It may also increase the cooling capacity of a given size of refrigeration plant. For example, the energy cost of delivering water at 6°C is some 10% more than at 10°C. Furthermore, the capital cost of the central plant is likely to be lower, although this may be offset by higher costs of fan coil units, distribution systems, terminal units and other emitters. Temperatures at which cooling is delivered can be raised by:

- installing larger, more efficient heat exchangers for cooling air, but with increased capital cost
- increasing chilled water or supply air volume flow rates, and increasing pipe and duct sizes to maintain the same pump or fan power
- increasing chilled water flows through heat exchangers and increasing pipe sizes to avoid increasing pumping energy e.g. using chilled ceilings
- separating cooling duties that require low temperatures (e.g. de-humidification or areas where cooling loads are exceptionally high) from more general cooling duties that can be achieved with higher temperatures
- raising set points (the required internal temperature) at times of lower cooling demand (e.g. compensating chilled water temperatures).

Free cooling

Free cooling can be achieved by drawing external air into the building when the external air is cooler than the space. This is usually achieved through controls that revert the system to a full-fresh-air condition when the external temperature is low, sometimes called enthalpy control[23]. The control system alters air dampers to take in more of the cooler fresh air and recirculates less of the warmer stale air, reducing the demand for mechanical cooling as a result.

Free cooling can also be achieved using external air to cool a secondary fluid, usually water or glycol, to cool air in the building. The secondary fluid can be cooled via cooling towers, air-cooled heat exchangers (dry air-cooling coils) or evaporative heat exchangers. Some options are discussed below. All these devices take the heat extracted from the building (in cooling) and reject the heat to outside air (see later).

Free cooling systems such as these can be particularly effective in situations where the cooling demands are high and unrelated to outside air temperature, for example in computer suites and telephone exchanges. The potential for this free cooling is demonstrated by the fact that, in London, the external wet bulb temperature is below 8°C for more than 40% of the year.

Systems that circulate water directly through a cooling tower to avoid running the chiller are often called 'strainer cycle' systems. A diverter valve causes cooled water to circulate directly from the cooling tower to the cooling coils in the chilled water system. A strainer is provided in the circuit so that the cooling tower water can be kept sufficiently clean to prevent blockage of the small waterways in the cooling coils. The pressure drop across the strainer will increase the pumping pressures, and this has to be balanced against the free cooling provided. The potential for contamination and fouling of the chilled water circuit can also be a significant problem. To avoid some of these drawbacks, indirect systems are available, incorporating a plate heat exchanger with a closed-circuit cooling tower. However, use of this system reduces the amount of potential free cooling due to the temperature difference across the heat exchanger.

Reducing operating hours

It is possible to significantly reduce the energy consumption of cooling systems by reducing the hours that the system operates. This might be achieved by:

- Setting a lower temperature limit below which the systems does not operate – say 24°C
- Introducing passive measures to reduce cooling loads
- Limiting the season or months the system operates
- Allowing the summer set point to float depending on external conditions (i.e. raising the required internal temperature as outside air gets warmer)

The annual hours in which a cooling system will run vary according location, design parameters, heat gains and type of system installed. Typically the range is as follows[11]:

	Standard Air Conditioned Office		Prestige Air Conditioned Office	
	Good Practice	Typical	Good Practice	Typical
Installed Capacity (W/m^2)	90	125	100	135
Annual Running Hours	1500	2500	2500	3000
Energy Use Indicator - EUI ($kWh/m^2.yr$)	14	31	21	41

Table 3.1 Typical cooling system running hours for offices[11]

Night cooling

Increased ventilation at night can help remove heat that is stored in the building structure during the daytime to avoid high summer temperatures. A range of passive and active night cooling strategies can be used to achieve this objective, the simplest generally relies on good window design to allow ventilation at night, other solutions include drawing cool night air through the building using fans. Further guidance on night cooling can be found in CIBSE AM13[24], GIL 85[25] , BSRIA BG1/2008[26] and BRE IP4/98[27].

Solutions include using the thermal capacity (thermal storage in the thermal mass) of the building itself by passing air through the building structure, e.g. hollow core slabs. In this way, the building envelope can be used to dissipate at night, heat that has been absorbed during the day. Thus, the fabric provides a reservoir for incidental heat gains. These can be used for space heating in cold weather, or dissipated to outside air using a night purge in warm weather. However, it is important to take account of the fan energy used to move the air through the structure. Low energy mechanical ventilation systems operating at around 1 W/litre/s should always be the design target. It is also essential that the controls ensure that the summer night purge is undertaken during the coolest part of the night.

Night ventilation in well insulated buildings with high thermal response factors can reduce the maximum daytime temperatures by 2-3°C, provided the thermal mass is exposed and a good control strategy is deployed, see BSRIA Technical Notes TN 11/95[28] and TN 5/96[29]. Software packages such as NiteCool provide low energy ventilation sketch design tools, giving a quick and easy method to investigate the feasibility of using natural ventilation to improve summer comfort levels.

Mixed mode ventilation

If a complete mechanical or natural ventilation strategy is not feasible, a mixed mode approach may be considered rather than full air conditioning[24]. These can be seen as partial air conditioning solutions, e.g. part of the building or for parts of the year. Mixed mode alternatives can stretch the performance of natural ventilation by using mechanical systems only when and where necessary. Mixed mode designs can be seen as a logical extension to buildings being fitted out after construction (shell-and-core), as mechanical cooling only needs to be added where the occupant confirms it is required. Over-design can be avoided, capital expenditure reduced and adaptation to meet changes in use can be allowed.

Thermal storage

Thermal storage techniques can smooth out the peaks and troughs in cooling demand, improving the loading and efficiency of chillers[30]. The economics are highly dependent on the electricity tariff. Opportunities include:

- chilled water storage during periods of low demand
- ice storage, where ice is formed on plates or tubes and subsequently defrosted to provide chilled water
- other phase change and eutectic materials that freeze at low temperatures depending on the particular substance (they can be frozen during periods of low load e.g. night-time, and then defrosted at peak periods to act as thermal storage)
- use of the building's thermal capacity (storage using the fabric of the building)

The main advantages/disadvantages of thermal storage systems are shown in Table 3.2.

Advantages	**Disadvantages**
Smaller chiller required, running for longer hours at or near its design duty, thus maximising its CoP and therefore improving overall system efficiency	Mixing losses in the storage vessel
Reduced operating cost e.g. ability to operate for longer periods on low cost tariffs and reduced maximum demand charges	Increased conduction losses from the system because of the lower temperatures and the larger surface area
Steadier load operation increases reliability and reduces maintenance cost (i.e. reduced plant cycling)	Increased plant room space required to allow for the storage vessel
Operation at lower condensing temperatures because of reduced night time temperatures, thus enhancing CoP	Ice systems operate at lower evaporating temperatures to enable ice production, thus reducing CoP (new phase-change materials that 'freeze' at higher temperatures may overcome this)

Table 3.2 Advantages and disadvantages of thermal storage systems[11]

The chiller and thermal store can be used for partial or full storage. Partial storage provides load levelling, with the chiller still operating during the day to meet the peak cooling load. Full storage eliminates the daytime operation of the chiller altogether, thus reducing electrical energy costs, but increasing the store size. These various operational modes are discussed in CIBSE TM18[30] and CIBSE Guide H[31].

Short term thermal storage, where cooling is smoothed out over say half an hour to a couple of hours, provides a number of benefits:

- it allows plant to be operated more efficiently by not exactly matching demand (e.g. compressors may be operated at full load and then switched off, rather than to running continuously at part load)
- it allows high electricity charges to be avoided (e.g. maximum demand)
- it may allow plant sizes and capital costs to be reduced.

Longer term thermal storage, over several hours, can take advantage of off-peak electricity prices. However, refrigeration efficiency can be reduced because the production of ice and the over cooling of a building require cooling to be delivered at lower temperatures.

Heat (energy) recovery

Heat/energy recovery systems can be used to recover coolth energy that would otherwise be rejected to waste, resulting in lower running costs and possibly reduced plant capacities. Figure 3.2[32] shows two example systems. These systems are most commonly applied in ventilation systems, using devices such as heat wheels, plate heat exchangers or run-around coils to recover energy from exhaust air, then use it to pre-heat or pre-cool supply air. They are a means of transferring coolth energy remaining in the exhaust air back in to the supply air and are typically located in ductwork near to, or inside, the main air handling plant[33].

Typical energy recovery systems include

- Run around coils
- Plate heat exchangers
- Thermal wheels
- Heat pipes

Energy recovery devices can sometimes be difficult to justify on a purely economic basis. There must be sufficient energy being rejected at times when it can be used to justify the added complications and running costs of installing heat recovery devices. Check that any additional electrical energy input required, e.g. fan power to overcome resistance of heat exchangers or coils, does not negate the energy saved, bearing in mind that it uses electricity rather than the fossil fuel energy. Note that extra fan power is needed whenever the system is in operation, although the degree of heat recovery varies throughout the year. Include the additional fan or pump running costs when calculating the viability of the scheme.

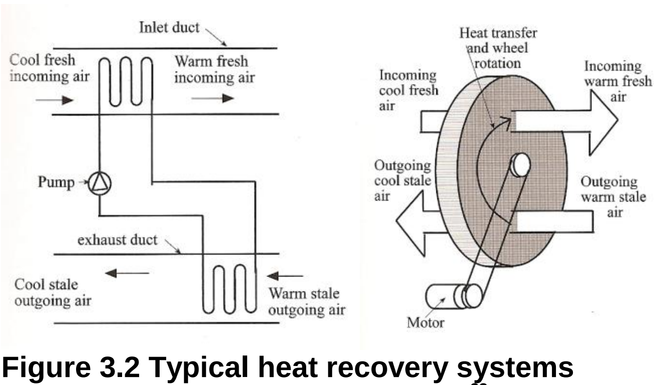


Figure 3.2 Typical heat recovery systems
- Run around coil (left), heat wheel (right)[32]

Energy/coolth recovery is cost-effective where there is a simultaneous demand for heating and cooling and it is feasible to use coolth recovered from one area to cool another. Some systems are particularly suited to such situations, e.g. single (unitary) heat pumps.

4. Renewable cooling solutions (BE GREEN)

If cooling cannot be avoided by the reduction methods shown in section 3 then it is important to select the cooling solutions that will result in the lowest carbon emissions. Before moving to mechanical systems it is important to consider renewable cooling solutions. For example, the London Plan requires 20% on-site renewables and this presents an opportunity to implement innovative renewable cooling systems in new developments[25,26].

Intelligent system design considers the addition of components to the system which reduce in the outside air temperature onto the heat rejection method and thus reduce the need for mechanical cooling. Examples of these are:

- Desiccant cooling
- Evaporative cooling
- Ground and water cooling
- Earth Pipes & Labyrinths
- Ground Water Cooling (Aquifers)
- Surface Water Cooling (Sea/River/Lake)
- Solar air conditioning
- TermoDeck
- Night cooling (see section 3)
- Free Cooling (see section 5)
- Seasonal Storage
- Peak Lopping Systems

Desiccant cooling

Desiccant dehumidification offers an alternative to using mechanical regeneration to dehumidify[25]. It is particularly applicable in full fresh air systems, or where low humidity is required and can utilise waste heat to regenerate (drive the moisture from) the desiccant. Desiccant cooling could present a renewable cooling option if driven by a renewable source of heat.

Evaporative cooling

Water evaporated in non-saturated air will produce a reduction in dry bulb temperature and an associated rise in moisture content. This evaporative cooling can provide an energy efficient alternative to mechanical cooling. It can be applied in three ways[25]:

- Direct evaporation – where evaporation takes place in the supply air stream
- Indirect evaporation – where the exhaust stream is cooled using evaporation and then used to cool the supply via a heat exchanger
- Direct/indirect combination – the two methods used in series to increase the cooling delivered.

Larger plant is required than conventional systems and there are legionella concerns although the risk is limited by the lower water temperatures involved.

Ground and water cooling

There are a range of opportunities for using the natural energy storage of the earth, the sea, rivers and lakes for cooling buildings, see GIL 85[25]. Opportunities include:

- Ground coupling using air – by passing air through the ground at depths of 2-5m to take advantage of the 12ºC, or lower, soil temperatures, see earth pipes and labyrinths.
- Ground water cooling (aquifers) – consist of two wells drilled into the ground. Water is pumped from one well to the other via a heat exchanger to provide cooling. Ground water has greater thermal capacity than air, allowing more energy to be stored. It is also possible to reverse the flow during winter to take advantage of the heat collected during summer.
- Ground coupled heat pumps – using the thermal mass of the ground as a heat sink to improve the CoP of a reversible heat pump.
- Surface water cooling (sea/river/lake) – by pumping water from these sources and extracting cooling via a heat exchanger it is possible to directly cool the space/supply air or to pre-cool the chilled water circuit. Great depth is required to reach cold water and fouling/corrosion problems must be avoided. Alternatively, the surface water could be used as a heat sink/source for a heat pump.

Ground Coupling Using Air (Earth Pipes & Labyrinths)

This method utilises the natural storage energy of the earth (low sub-soil temperatures) to cool air passed through underground pipes or a labyrinth structure, usually at depths of between 2m and 5m[25,26]. The soil temperature at such depths is approximately equal to the average yearly external temperature. In the UK this is typically in the region of 10-14ºC, providing useful cooling in the summer months. The performance of such systems is sensitive to a number of factors, the most important being the actual soil temperature. The other major parameters that need to be considered by the designer are the air velocities and volumes, underground pipe lengths, diameters, soil conductivity, and moisture level. This sensitivity means that control of the outlet air condition from the system is limited, with the amount of sensible cooling provided being dependent on the outside air condition. The cooled air from the underground pipes can be used directly to provide cooling. Alternatively, for buildings that demand strict internal conditions, ground coupled air cooling can be used as pre-conditioning for any conventional ventilation or air-conditioning system. During the heating season, ground temperatures can be above outside air temperatures and these systems can then be used for pre-heating ventilation air.

Ground Water Cooling (Aquifers)

Ground water cooling essentially consists of two well sets drilled into the ground, where water is pumped from one well set to the other via a heat exchanger, to provide useful cooling. In areas where there is no ground water movement, the cycle can be reversed during winter. The heat collected over summer can be used for heating, this making such systems ideal for inter-seasonal storage of heating and cooling energy. Groundwater has the benefit of greater thermal capacity per unit volume when compared with air. This allows a larger amount of energy to be stored. In applications where there is ground water movement, the system can be used as a heat sink/source for a heat pump. Alternatively, ground water can be used as a heat sink with conventional mechanical cooling. The lower condenser temperatures lead to higher coefficients of performance (CoPs), and hence improved energy efficiency. In the UK, the Environment Agency controls the extraction and use of ground water. Contact should be made at an early stage of any project where using this technology is considered.

Surface Water Cooling (Sea/River/Lake)

Use of the sea, rivers, and lakes for cooling buildings is achieved by pumping water from these sources (preferably at depth) by an open loop system and extracting cooling via a heat exchanger[25,26]. The surface water can be used to directly cool the space/supply air or to pre-cool the chilled water circuit. The effectiveness of direct cooling will depend on the temperature and variability of the surface water. The system can be used to cool the building directly. Alternatively, the surface water can be used as a heat sink/source for a heat pump or as a heat sink with conventional mechanical cooling. The lower condenser temperatures lead to higher CoPs and hence improved energy efficiency. In the UK, the Environment Agency controls the extraction and use of surface water. Contact should be made at an early stage of any project where using this technology is considered.

Solar air conditioning

It is possible to use high temperature solar water heating as a source of heat to drive for an absorption chiller[26]. However, very high efficiency (oil filled) collectors are required and the absorption chiller will have relatively low CoP. However, it does present a renewable form of cooling and may become more practical and cost effective as this technology develops in future.

It is also possible to use photovoltaics as a source of electricity for a vapour compression chiller. However, very large PV arrays would be necessary to drive a chiller of any substantial size and the costs of these would be prohibitive. However, it does present a renewable form of cooling and may become more practical and cost effective as this technology develops in future.

TermoDeck

TermoDeck is a fan-assisted heating, cooling and ventilating system. It uses the high thermal mass of structural, hollow core slabs to warm or cool fresh air before it's distributed into the room spaces of the building. Controlled by the building management system, supply of air passes through the hollow cores very slowly, giving plenty of time for passive heat exchange between the air and the concrete hollow core slabs. The exposed concrete releases heat to, or absorbs heat from, the air passing through it. So by the time the air enters the room it at the temperature required for occupant satisfaction. Thermal mass helps to both cool a building in the summer and keep it warm in winter. The manner in which TermoDeck uses the thermal mass of the building and the radiant effect of the ceiling soffit, combined with high insulation levels and energy recovery methods can achieve low energy buildings such as the Elizabeth Fry Building at the University of East Anglia.

5. Mechanical cooling systems (BE CLEAN)

Where cooling cannot be avoided and where renewable cooling cannot meet the building cooling loads then it is important to select the most efficient mechanical cooling solutions to minimise carbon emissions. Modern mechanical cooling systems can have overall efficiencies that are much greater than more traditional solutions. For example, chillers are now available with CoPs of 6 compared to standard chillers at 3 or 4. Introducing mechanical air conditioning into a design can increase electrical energy consumption of the building by up to 50%. However, there are instances where some form of mechanical system is unavoidable e.g. deep plan buildings, high internal gains, exacting environmental conditions etc. Even then, designers should seek to make effective use of ambient conditions with a view to minimising demand.

Cooling systems comprise a number of elements, and there is a great diversity of systems, sub-systems and possible configurations. Estimates drawn up in the production of this guide suggest there are around 18,000 combinations of components, rising to over 200,000 possibilities when different refrigerant options are included, although many of these possible systems may be highly impractical. This is clearly too many to analyse to give definitive guidance about which systems perform best. It is necessary to look at the key system components, and identify the most common system combinations. Figures 5.1 and 5.2 show these key components. Additional to these components is the source of fuel used to run the system, whether electricity, natural gas, etc. For the purposes of this guide some 4,000 combinations have been analysed.

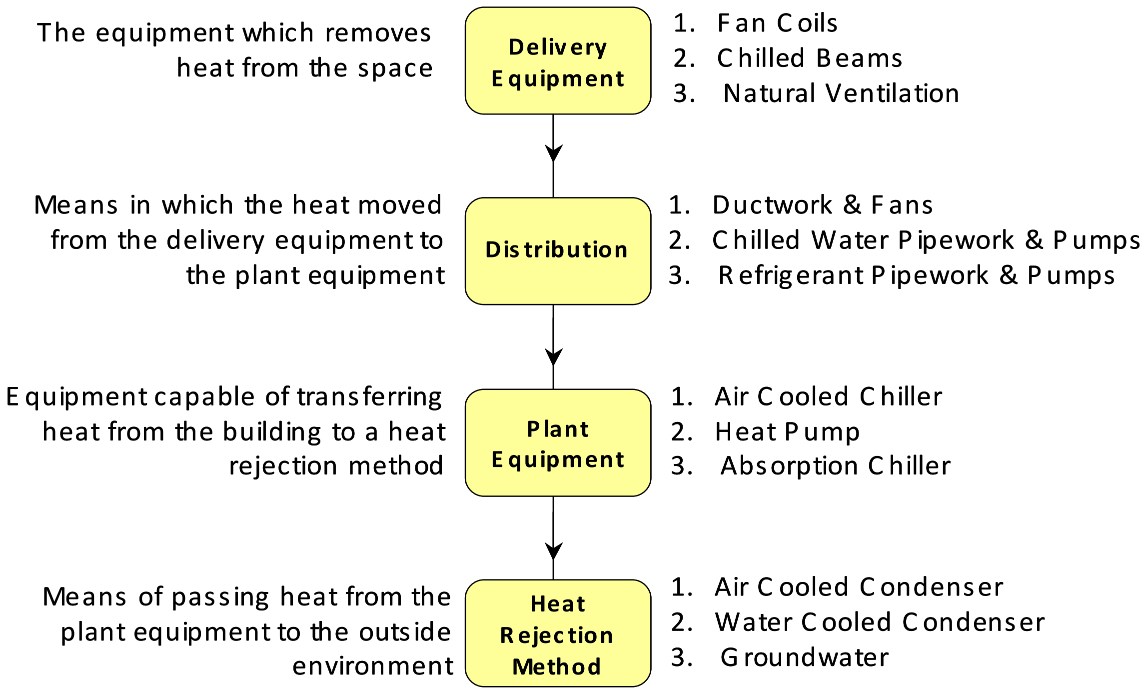


Figure 5.1 Key system components of a cooling system

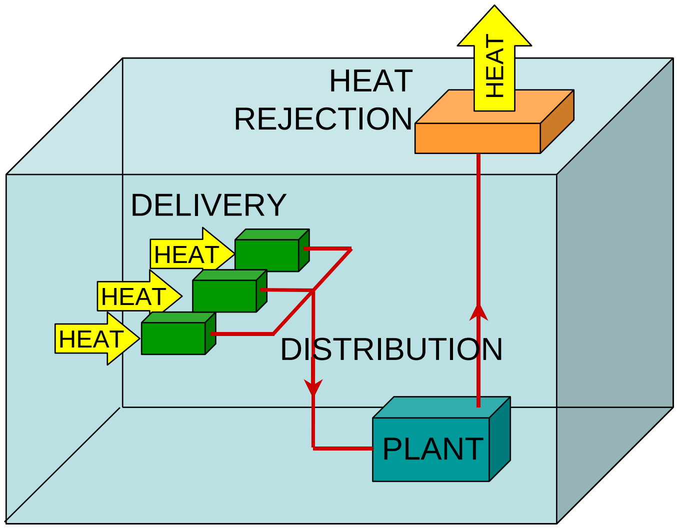


Figure 5.2 Components of a cooling system in a Building

5.1 Delivery equipment

Delivery Equipment is that which removes heat from the space. Figure 5.3[32,34] and Table 5.1 show the types of equipment available and the design values for the cooling fluid, often chilled water. It also details the loss in efficiency associated with the heat which is gained to the system by the operation of the pumps and fans. Operational heat gain refers to fans and pump gains i.e. delivery losses in the methodology. (Distribution losses refers to duct and pipe gains).

Delivery Equipment	Types	Chilled Water Delivery Temperature (°C)	Operational Heat Gain (%)
Passive	Natural Ventilation	n/a	n/a
Forced Air Systems	Night Cooling (Mixed Mode)	n/a	n/a
	Constant Volume Mechanical Ventilation	n/a	n/a
	Variable Air Volume (VAV)	5-11	13
	Displacement Ventilation	5-11	13
	Fan Coils (no dehumidification)	5.5-11	13
	Variable Refrigerant Flow/Volume (VRF/VRV)	5-10	13
Climatic Systems	Chilled Beams - Passive	14-17	n/a
	Chilled Beams - Active	14-17	13
	Chilled Ceilings - Radiant	14-17	13
	Chilled Ceilings - Convective	14-17	13
Radiant System	Radiant Slab Cooling	16-22	13
	Radiant Floor Cooling	16-22	13
	Radiant Floor Cooling (c/w Dehumidification)	16-19	13

Table 5.1 Typical delivery systems, showing typical operating temperatures and typical associated heat gains due to system operation[35-42].

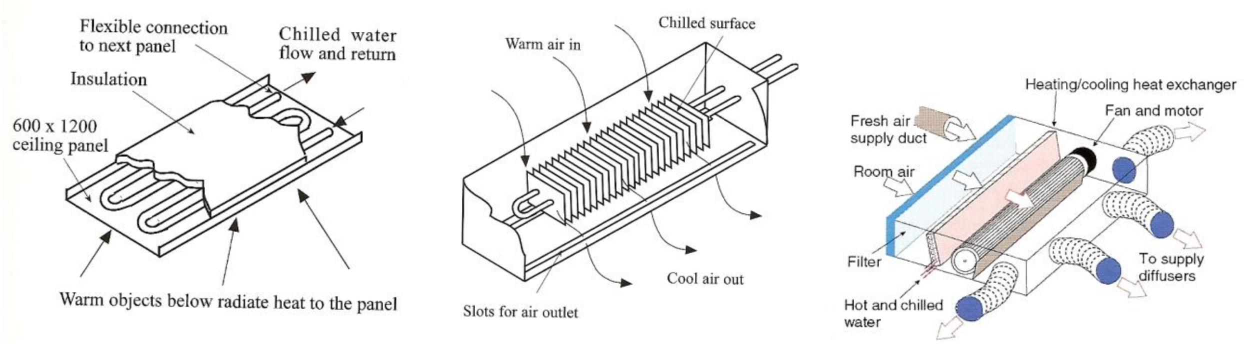


Figure 5.3 Typical delivery equipment (Left to right – Chilled ceiling, chilled beam, fan coil unit)[32,34]

5.2 Distribution equipment

Distribution equipment is the means by which the coolth is transported from the plant equipment to the delivery equipment. Table 5.2 gives the main types of distribution equipment, together with associated heat gains due to operation of the system. Operational heat gain refers to the distribution losses including duct and pipework gains, i.e. heat pick-up from the building.

The use of air as the cooling medium in a building has a number of drawbacks. The low specific heat of air (1.02 kJ/kg) and low density (1.2 kg/m^3) gives it a very poor heat carrying capacity. In addition, cooling systems have a much smaller temperature difference with the treated space than heating systems. This all leads to very high volumes of air movement around the building to deliver the required cooling effect, and as fan power is directly proportional to volume flow rate this leads to high fan power consumption. Duct sizes are also large, imposing a space requirement on the building design.

By contrast, cooling by liquid media – water or direct refrigerant – reduces the distribution energy. For example the specific heat and density of water (4.18 kJ/kg and 1000 kg/m^3) give it almost 3,000 times the heat carrying capacity per unit volume as that of air, leading to much smaller pipe sizes and significantly lower pumping costs. However, liquid distribution systems cannot take advantage of free cooling opportunities provided by air systems. When the outdoor air is low enough to remove the building gains, the central plant can be switched off. This can occur for significant periods of time in the UK, leading to reduced chiller running hours. Climatic (chilled beams) or radiant slab systems, and Variable Refrigerant Volume (VRF) systems may therefore have longer running hours, even though they have better overall efficiencies.

Distribution Equipment	Types	Operational Heat Gain (%)
Passive	Air	n/a
Active	Duct work & Fans	13
	Chilled Water pipe work & Pumps	13
	Refrigerant pipe work and Pumps	13

Table 5.2 Distribution equipment and associated heat gains[36]

5.3 Main 'Plant equipment'

Plant equipment is that which transfers the heat from the building to a heat rejection method. Table 5.3 below shows the different types of plant equipment and their associated refrigeration cycles.

Plant Equipment	Cycle
Heat Pump (Air)	Vapour Compression
Heat Pump (Thermal Piles)	
Heat Pump (Ground Source Vertical Closed Loop)	
Heat Pump (Ground Source Horizontal Closed Loop)	
Packaged Vapour Compression Chiller	
Vapour Compression Chiller	
Borehole	Heat Exchange
Single Effect Absorption Chiller	Vapour Absorption
Double Effect Absorption Chiller	
Triple Effect Absorption Chiller	

Table 5.3 Plant equipment

Other cycles include vapour sorption and adsorption, but these are less common in buildings and will not be considered in this guide.

Vapour compression systems

Vapour compression chillers of one kind or another dominate the cooling market. The basic equipment is shown in Figure 5.4[34]. The vapour compression cycle is shown in Figures 5.6 and 5.7. The simplest image is the domestic refrigerator where electricity drives a compressor and heat is moved from the refrigerator cabinet into the kitchen. Around three to four times as much heat is moved than electricity input. The process involves the repeated compression & expansion of a refrigerant (typically R407c) as it passes around the circuit. From the compressor discharge, hot high pressure vapour is condensed to a sub-cooled liquid, i.e. a liquid below its saturation temperature. This liquid is then expanded to low pressure in the expansion device; the heat necessary for this expansion is absorbed at low temperature from the cooled space via the system evaporator. The rate of flow of refrigerant is controlled to ensure that it returns to the compressor as a superheated vapour, free from liquid. In the compressor, pressure is added to the vapour and the cycle is repeated. The efficiency of this system is strongly dependent on the pressure difference between the condenser and the evaporator, which is in turn dictated by the temperatures at these components. Both higher evaporator temperatures and lower condenser temperatures lead to systems with better Coefficients of Performance (CoP) – see "What is CoP" box for more detail.

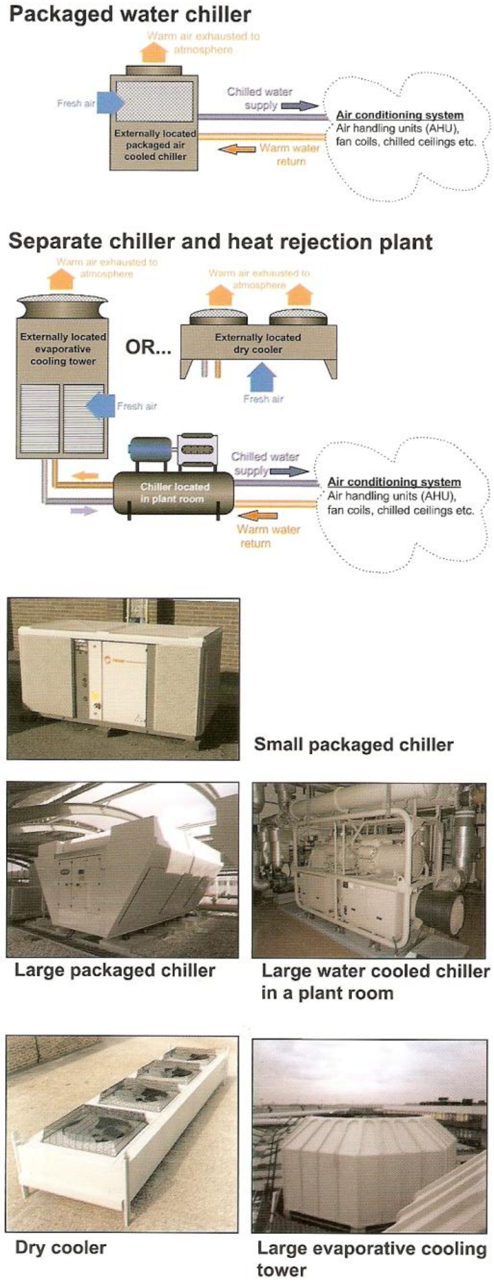


Figure 5.4 Refrigeration equipment[34]

Absorption systems

The vapour absorption chiller is driven by heat input rather than electricity but has a much lower efficiency[13]. Absorption chillers have a separate working fluid (a solution of either ammonia or Lithium Bromide) and refrigerant (water), see Figure 5.5[32] and 5.9. In the generator, as heat is supplied to the working fluid water is boiled off and passes into the refrigerant circuit. It is condensed in the condenser, expanded to a lower pressure in the expansion device and absorbs heat from the cooled space via the evaporator. At the same time, a strong solution of lithium bromide passes from the generator to the absorber, via a pressure-reducing device, where the returning water is reabsorbed into solution to form a weak lithium bromide solution. This weak solution is then pumped back to the generator for the cycle to continue.

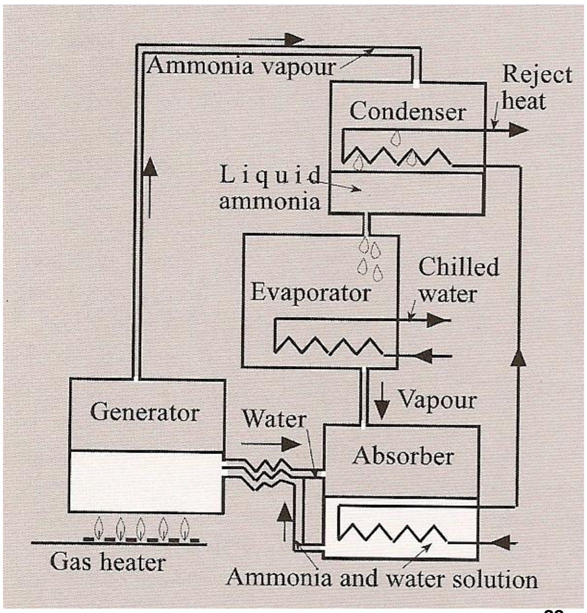


Figure 5.5 Absorption chiller operation[32]

Various heat recovery techniques are employed to improve the efficiency of the process. The most common type of system is single effect, with CoPs typically around 0.6, but double and triple effect are available which increase the CoP up to 1.2 by introducing higher grade heat sources.

Absorption systems reject more heat than other systems due to the low CoPs, which means dry air coolers or cooling towers are larger in comparison[13]. There is a limiting outside air temperature at which these systems can reject heat, although this is generally higher than UK summer temperatures. However, for dry-air coolers the cooling output can be dramatically reduced during the height of summer, making these impractical. The use of cooling towers or dry-coolers with spray assistance overcomes this since this adds an evaporative component to the cooling effect.

Borehole cooling

Borehole systems can also be used to provide cooling in a building. Groundwater located in aquifers 50-200m below ground is generally 12°C outside of cities and 14°C inside central London, but it can be as high as 14-16°C at depths of 300m. These systems are ideally matched for climatic and radiant slab systems (e.g. chilled beams and ceilings or radiant floor systems), with CoP ranges from 9 to 140. Water is extracted from these aquifers and pumped to a buffer tank & filters on the surface, where solid debris is removed to prevent pump damage. The water is then passed through a heat exchanger where it absorbs heat from the chilled water transporting heat from the space. The warm groundwater can then be used as grey water within the building, discharged to drain or pumped to another borehole below ground. Advice must be sought from the Environment Agency when investigating borehole cooling, and licences are necessary for water abstraction and rejection.

5.4 Heat rejection equipment

Heat rejection equipment passes heat from the plant equipment to the external environment.

Figure 5.6[14] and table 5.4 show the types of equipment available and the associated temperature differences across the heat exchangers. There is currently no reliable information available to identify associated heat gains or electrical loads. The delta T (ΔT) refers to the temperature difference between the air or water coolant coming onto the condenser and the refrigerant condensing temperature. For air cooled this is the outside air temperature – which has been taken as 27°C for the methodology. For water cooled this is based on the wet bulb temperature down to 23°C.

Heat Rejection Method	Types	Temperature difference (ΔT) across Heat Exchanger
Passive	Air	n/a
Active	Air-cooled Condenser	8-11
	Water-cooled Condenser	10-15
	Ground-cooled Condenser	5-11
	To drain (boreholes)	n/a

Table 5.4 Types of heat rejection equipment

The two basic types of condenser are:

- direct: air-cooled or evaporative
- indirect: condenser heat is rejected via a water system by using cooling towers or dry air coolers.

Evaporative condensers are the basis for the most efficient refrigeration systems since the condensing temperature can closely approach the external wet bulb temperature. A cooling tower system achieves a similar performance, although the condensing temperature may be somewhat higher because of the additional heat transfer stage.

Direct air-cooled condensers are less efficient, producing condensing temperatures several degrees above external dry bulb temperature. Water-cooled condensers in conjunction with dry air coolers are the most inefficient option, producing even higher condensing temperatures, often with associated high water pumping and fan costs.

Water treatment is also a key issue for cooling towers and evaporative condensers. Effective treatment is essential to avoid legionella, corrosion and fouling. Poor water treatment can greatly increase energy and water costs. Legionella can be controlled if the tower is designed and operated in accordance with CIBSE Technical Memoranda TM13[43].

The larger the condensing system, the better the plant performance, but with correspondingly higher capital costs.

Air-cooled condensers

Air-cooled condensers are the simplest form of condenser heat rejection plant, in which air is blown over finned tubes containing the condensing refrigerant. They are generally found on stand-alone plant such as packaged air conditioners, split systems or some packaged air handling plant. Air-cooled condensers are less efficient than water cooled systems as they operate at higher condensing temperatures and do not have the benefit/opportunity of ustilising evaporative water cooling. However, they gain by not having pumping and other auxiliary energy consuming plant associated with condenser water systems.

Evaporative condensers

An evaporative condenser is an extension of an air-cooled condenser. As well as air being blown over the tubes, the tubes themselves are continuously wetted by a re-circulating water system. They are able to achieve a similar performance to water-cooled condensers and open circuit cooling towers, but eliminate the condenser water pumps. The other potential benefit of using evaporative condensers is that they can make use of the thermosyphon effect to provide free cooling during periods of low demand and low outside air temperatures.

The thermosyphon effect involves the natural circulation of refrigerant without being pumped by the compressor[44]. Thermosyphoning which requires specially designed chillers can only take place during cold or cool weather when the condensing temperature is lower than the evaporating temperature.

Wet cooling towers

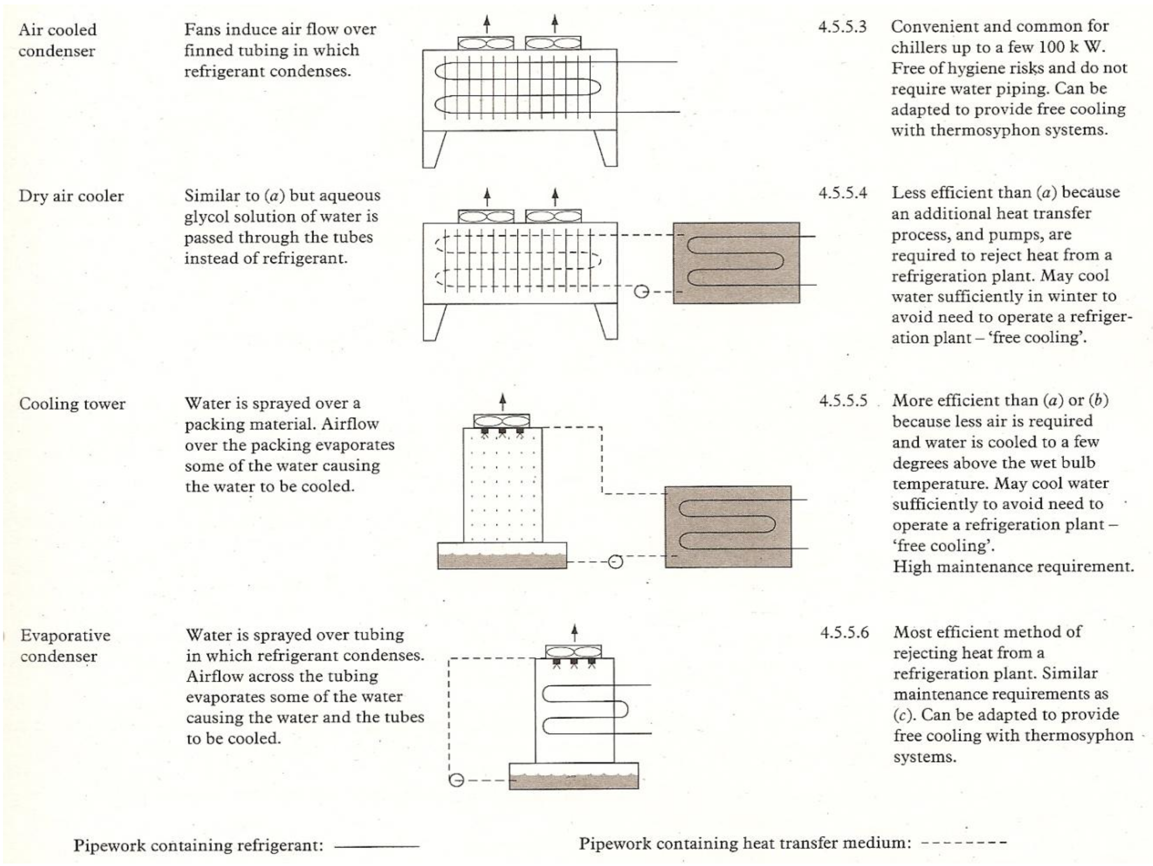
There are two types of wet cooling tower:

- Open circuit: water from the condenser is pumped to the cooling tower and is cooled by the evaporation of some of the condenser water. This requires all the water passing through the condenser circuit to be treated and results in increased water consumption due to the loss of water blown away during the process – often called drift losses.
- Closed circuit: condenser water is circulated in a closed loop and a separate water circuit is pumped through the cooling tower, cooling the condenser water by transferring heat through a heat exchanger. This minimises water treatment costs but it also reduces energy efficiency due to the temperature difference across the heat exchanger, although this effect can be minimised by specifying a high-efficiency heat exchanger.

Wet cooling towers minimise condensing temperatures and thus enhance chiller CoP since they reduce the water temperature to near the external wet bulb temperature. However, the auxiliary power to drive a wet cooling tower is greater than other types of heat rejection system.

Dry coolers

Dry coolers reject heat from the condenser water without making use of evaporative cooling. Since there are two heat exchangers between the refrigerant and the final point of heat rejection, such systems are the least energy efficient.



Air cooled condenser	Fans induce air flow over finned tubing in which refrigerant condenses.	4.5.5.3	Convenient and common for chillers up to a few 100 k W. Free of hygiene risks and do not require water piping. Can be adapted to provide free cooling with thermosyphon systems.
Dry air cooler	Similar to (*a*) but aqueous glycol solution of water is passed through the tubes instead of refrigerant.	4.5.5.4	Less efficient than (*a*) because an additional heat transfer process, and pumps, are required to reject heat from a refrigeration plant. May cool water sufficiently in winter to avoid need to operate a refriger-ation plant – 'free cooling'.
Cooling tower	Water is sprayed over a packing material. Airflow over the packing evaporates some of the water causing the water to be cooled.	4.5.5.5	More efficient than (*a*) or (*b*) because less air is required and water is cooled to a few degrees above the wet bulb temperature. May cool water sufficiently to avoid need to operate a refrigeration plant – 'free cooling'. High maintenance requirement.
Evaporative condenser	Water is sprayed over tubing in which refrigerant condenses. Airflow across the tubing evaporates some of the water causing the water and the tubes to be cooled.	4.5.5.6	Most efficient method of rejecting heat from a refrigeration plant. Similar maintenance requirements as (*c*). Can be adapted to provide free cooling with thermosyphon systems.

Pipework containing refrigerant: ———— Pipework containing heat transfer medium: - - - - - - - -

Figure 5.6 Types of heat rejection equipment (from CIBSE Guide B4[14])

What is Coefficient of Performance? - an introduction to cooling cycles

Refrigeration systems (especially vapour compression systems) can move greater amounts of heat than the amount of energy needed to operate them. Normally the term efficiency is used to describe the output divided by input, but in this case this yields a value greater than 1. For this reason the term CoP is generally used for refrigeration systems. The Coefficient of Performance (CoP) for vapour compression cycles is the ratio of the energy removed at the evaporator to that supplied at the compressor. Figures 5.7 and 5.8 show the vapour compression cycle in a schematic and on a pressure enthalpy graph, which is used to calculate its performance. Figure 5.9 shows how the CoP is calculated.

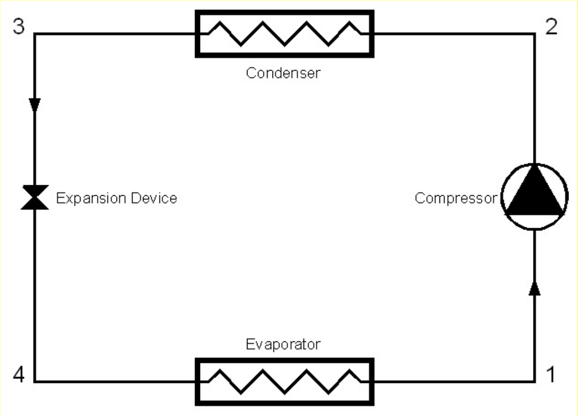


Figure 5.7 Vapour Compression Schematic

Phase	What's happening?
1 - 2	COMPRESSION of refrigerant gas to a higher pressure.
2 - 3	CONDENSATION of high pressure gas to a high pressure liquid in the condenser.
3 - 4	EXPANSION of high pressure gas to a lower pressure.
4 - 1	ABSORPTION of heat from cooled space to produce hot gas.

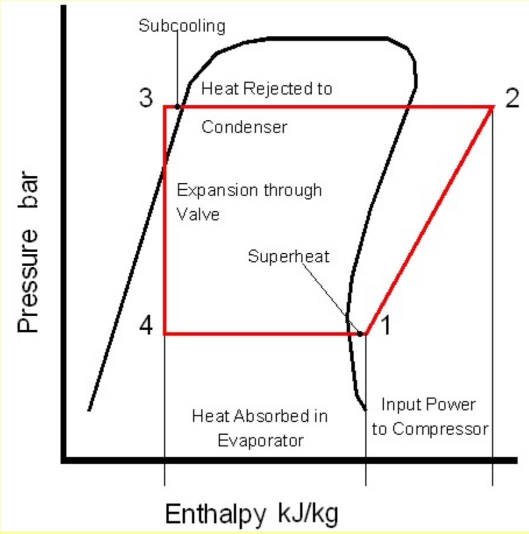


Figure 5.8 Vapour compression cycle

Vapour compression systems are electrically driven. A motor drives a compressor to compress the refrigerant (typically R407c).

Ways in which the CoP can be improved are:

- Increase in compressor isentropic efficiency to reduce input power requirements.
- Bring the evaporator temperature closer to the condenser temperature.
- Increase the degree of superheat, although excessive increases can damage the compressor.

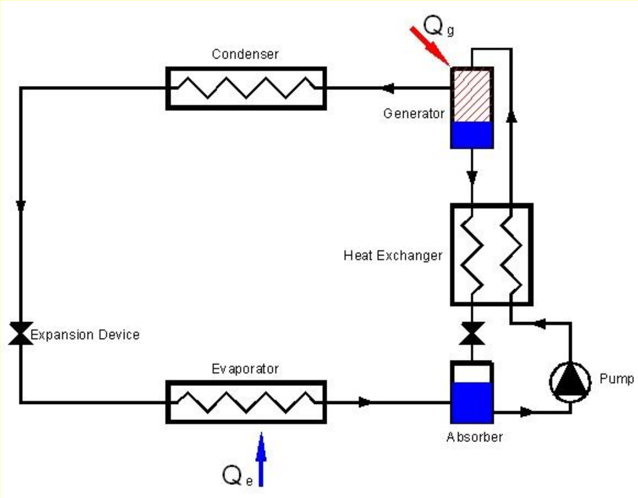


Figure 5.9 Vapour absorption schematic

Absorption systems are driven by heat and are less efficient than vapour compression systems. They use a separate working fluid (a solution of either ammonia or Lithium Bromide) and refrigerant (water).

For absorption cycles the definition of CoP is the ratio of the refrigerating effect to the energy supplied to the generator which is subtly different to that for vapour compression chillers.

6. An environmental impact methodology

6.1 Introduction to the methodology

Sections 6 to 8 provide a more detailed method (with examples) for assessing cooling systems for designers and planners assessing

This section sets out a methodology for obtaining a Greenhouse Gas Impact Factor (GGIF) for cooling systems in buildings, leading to a Greenhouse Gas Impact Rating (GGIR). The GGIF is a single number that can provide a comparison between different cooling system options and configurations, while the GGIR is an A to G ranking based on different bands of GGIF. The aim is to provide a reasonably straight forward methodology so that developers and consultants can demonstrate the relative impact of a proposed design solution, and present this to planners and decision makers.

In order to tackle this complex task a thirteen step methodology has been developed in which a number of key factors can be entered at each stage. It is recognized that this will be carried out very early in the design process, and detailed information about a possible design solution may not be known. Ranges of some of the simplifying assumptions are presented here in order to assist with the process.

The GGIF has units of kg CO_2 per annum per kW of design cooling load (kg CO_2 $y^{-1}kW^{-1}_{des}$) and is comprised of two parts – indirect and direct Global Warming Potential (GWP), with GWP measured in kg CO_2 equivalent. The indirect GWP is the CO_2 released from the energy used to operate the system, while the direct GWP is due to refrigerant leakage from the system in terms of CO_2 equivalent. The total GGIF is the sum of these two. The overall process is shown diagrammatically in Figure 6.1. Note that this methodology does *not* include embodied CO_2 of systems.

The basic methodology is presented below, followed by indicative solutions for a range of system types developed from a comprehensive analysis of over 4,000 system types. The user will be able to use the methodology with their own numbers and system knowledge, or alternatively use the examples in the guide and the information in appendix D to generate the GGIF. Where the user draws on their own working knowledge, it is important that the assumptions are justifiable and based on good evidence.

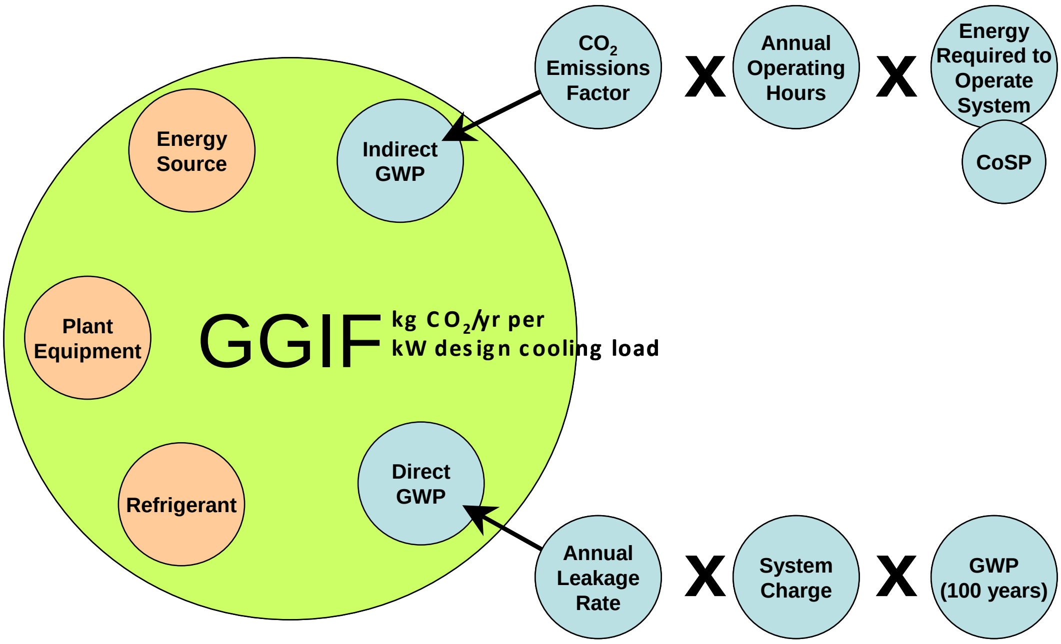


Figure 6.1 Key components that make up the Greenhouse Gas Impact Factor (GGIF)

The key factors governing the environmental impact of cooling systems are

- The building cooling load
- The passive measures to reduce the load on the mechanical system
- The type of system and component configuration
- Coefficients of System Performance (CoSP) – dependent on all the losses and energy used by the system
- Full and part load operation
- Hours of operation
- Carbon content of energy source
- Refrigerant charge and leakage rates

6.2 GGIF METHODOLOGY STEPS 1 – 7 Calculating Coefficient of System Performance (CoSP)

The first seven steps of the methodology calculate the system efficiency, called the Coefficient of System Performance (CoSP), which is defined as:

CoSP = Building Cooling Load (kW) ÷ Total system input power (kW)

The CoSP can change depending on operating conditions. In particular there will be a peak condition CoSP and a seasonal average CoSP, the latter is difficult to determine without detailed knowledge of the building and system design. This methodology therefore proposes to adopt fixed conditions for an instantaneous CoSP in order to provide a standard comparison between systems.

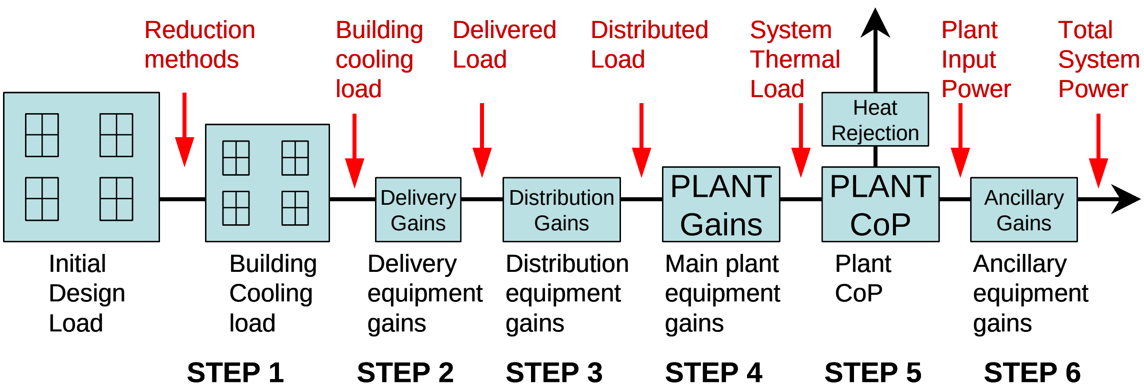
The CoSP must take into account of thermal losses in the system (which are in fact additional heat gains into the cooling system) from the following

- delivery and distribution (fan, pump, duct or pipe thermal gains)
- the central plant Coefficient of Performance (CoP)
- central plant thermal losses (e.g. heat rejection fan gains)
- distribution equipment energy consumption (fan and pump power)

Note there is a distinction between the first and last of the above – the first deals with additional thermal loads that the chiller plant has to reject, while the last is the energy consumed by ancillary equipment. This is discussed further in appendix C and has particular implications where different fuel sources are used for the chiller and ancillaries (for example in an absorption chiller system).

Figure 6.2 and Table 6.1 show the first seven steps of the methodology.

Figure 6.2 Steps 1 – 7 of the cooling GGIF methodology (Calculating Coefficient of System Performance (CoSP))



STEP 1	**Building cooling load** - is a result of reducing the initial design cooling load by introducing passive measures incorporated to reduce the load. e.g. improved solar shading, reducing internal gains etc. There is no firm guidance on how to quantify load reductions, but the step has been included in order to capture the benefits of these where possible.
STEP 2	**Delivered Load** - accounts for the thermal efficiency of the delivery system, for example the heat imparted to the air stream from a fans. Note that the fractional gains should be added to 1 before multiplying by the building load. For example for a 100 kW building Cooling Load and 13% delivery system gains e.g. Delivered Load = 100 x 1.13 = 113 kW. **See Table D1 in appendix D for typical values**
STEP 3	**Distributed Load** - is calculated the same way as Step 2, and this accounts for duct or pipework gains in the distribution system. Again Table D1 contains typical values.
STEP 4	**Input Load** - is the total thermal load on the chilling plant and accounts for heat gains from fans and pumps within the central plant. It is calculated in the same way as steps 2 and 3. Table D1 gives a typical value for chilling plant and an additional value where CHP and Trigeneration are employed. **See Table D1 in appendix D for typical values**
STEP 5	**Primary power** - accounts for the efficiency of the refrigeration plant by dividing by the CoP. This is a highly variable component that is dependent upon the type of plant (vapour compression or absorption), temperature of the delivered cooling, type of heat rejection (air, water or ground), prevailing external conditions, and refrigerant used by the system. The CoP should be calculated according to the specific system configuration, and Table D2 shows the key parameters for this calculation. One method of calculating this is to use freely available software, for example Coolpack, available from the Technical University of Denmark[45]. **See Table D2 in appendix D for typical values**
STEP 6	**Total system power** - in order to account for the total power consumed by the system is it necessary to add the electrical power consumed by the ancillary equipment – i.e. the fans and pumps of the distribution system and central plant fans and pumps. This is the electricity consumed by ancillaries as opposed to the thermal gains shown in steps 2 and 3. Note that distribution energy may be a significant component of a cooling system – up to 50% for all air systems. There will also need to be an adjustment at this stage where the chiller energy source is different from the fans and pumps, notably for absorption and trigeneration systems. In this case the ancillary power will have to be multiplied by the ratio of the CO_2 factors for the different energy sources: $$Ancillary\ Power = Fan\ and\ pump\ power \times \left(\frac{CO_2\ factor\ for\ electricity}{CO_2\ factor\ for\ chiller\ energy\ source} \right)$$ This issue of CO_2 factors brings with it specific complications discussed in appendix B.
STEP 7	**Coefficient of System Performance (CoSP)** - is calculated by dividing the Building Cooling Load from Step 1 by the Total System Power. Note that this number is not used further in the next stages of the methodology (see Section 6.3), but is a useful indicator in its own right, as it shows the relative efficiency of different systems. A range of CoSPs that do not include the ancillary power, and therefore only thermal CoSP (or CoSPth), have been calculated and presented in appendix D. These values can be used in conjunction with the Building Cooling Load to back calculate Plant Input Power of the central plant (the output of Step 5). The ancillary power can be added to this, as in Step 6, to give the Total System Power, which is the input to Step 8 in section 6.3. **See appendix D for typical values**

Table 6.1 Steps 1-7 of the GGIF methodology
(Calculating Coefficient of System Performance (CoSP))

6.3 GGIF METHODOLOGY STEPS 8 – 13 Calculating Global Warming Potential (GWP)

Figure 6.3 and Table 6.2 show the second half of the methodology (steps 8-13) to calculate the indirect and direct Global Warming Potentials (GWP) of the system, and the final Greenhouse Gas Impact Factor (GGIF). The output from Step 6, Total System Power, is the input to Step 8.

Figure 6.3 Steps 8 – 13 of the cooling GGIF methodology (Calculating Global Warming Potential (GWP))

STEP 8	**Annual Cooling Energy** – calculated by multiplying the Total System Power by the Annual Running Hours. These would normally lie in the range of 1500 to 3000 hours, with a mid range value of 2250 (see Table 3.1). This mid-rage value should be used in standard calculations, unless reduced running hours can be demonstrated from control or operational constraints. Note that this step does not produce an accurate forecast of annual energy, but a standardized figure for system comparison.
STEP 9	**Indirect GWP -** multiplying the Annual Cooling Energy by the appropriate CO_2 factor gives the annual CO_2 emissions from running the plant. Note that where chiller and ancillary equipment have different energy sources, the CO_2 factor for the chiller should be used, as Step 6 provided the necessary adjustment to account for the difference.
STEP 10	**Potential direct GWP** – is developed by establishing the refrigerant charge of the system and multiplying this by the 100 year Global Warming Potential (CO_2 equivalent) for that refrigerant. This gives the total direct potential impact if all of the refrigerant enters the atmosphere. The refrigerant charge can be obtained from manufacturer's literature, or estimated from Figure D9 in appendix D. Table D3 gives the GWP for a number of common refrigerants. It is important to avoid refrigerant leakage to maintain plant efficiency and to prevent impact on the environment[46,47].
STEP 11	**Direct GWP** – is calculated by multiplying the potential direct GWP by the annual leakage rate of refrigerant from the system. Recent figures for leakage rates are given in Table D4.
STEP 12	**Total GWP -** is the sum of the Indirect GWP and Direct GWP from Steps 9 and 11.
STEP 13	**Greenhouse Gas Impact Factor -** is the Total GWP divided by the original Design Cooling Load (the input to Step 1). The GGIF will therefore be lower if the following are observed: • Cooling is avoided through passive measures and good design • Distribution losses are minimised • Central plant CoP is maximised • Ancillary loads are minimised • Operating hours are demonstrably reduced • Refrigerant leakage impacts are minimized

Table 6.2 Steps 8-13 of the GGIF methodology (Calculating Global Warming Potential (GWP))

6.4 Greenhouse Gas Impact Rating (GGIR)

Using the Greenhouse Gas Impact Factors (GGIFs) from a complete range of systems, an A to G rating system has been established called the Greenhouse Gas Impact Rating (GGIR). This has been done for a wide range of systems and for a range of fuel sources and plant. Table 6.3 shows a summary of the system components examined, and the different fuel sources are shown in Table 6.4.

Component	Example
Delivery Equipment	Passive Systems
	Forced Air Systems
	Climatic Systems e.g. chilled beams
	Radiant Slab Systems
Distribution	Duct work & Fans
	Chilled Water Pipe work & Pumps
	Refrigerant Pipe work Pumps
Plant Equipment	Vapour Compression Cycles
	Absorption Cycles
	Open-loop Boreholes
Heat Rejection Method	Air-cooled Condenser
	Water-cooled Condenser
	Ground-cooled Condenser
	To drain (boreholes)

Table 6.3 Summary of system components in the study

Fuel Source	Cycle	Plant Equipment
Grid Electricity	Vapour Compression	Heat Pump (Air)
		Heat Pump (Thermal Piles)
		Heat Pump (Ground Source Vertical Closed Loop)
		Heat Pump (Ground Source Horizontal Closed Loop)
		Packaged Chiller
		Chiller
	Heat Exchange	Borehole
Natural Gas	Vapour Absorption	Single Effect Absorption Chiller
LPG	Vapour Absorption	Single Effect Absorption Chiller
Biomass	Vapour Absorption	Single Effect Absorption Chiller
Energy from Waste	Vapour Absorption	Single Effect Absorption Chiller
Solar Electric	Vapour Compression	Heat Pump (Air)
		Heat Pump (Thermal Piles)
		Heat Pump (Ground Source Vertical Closed Loop)
		Heat Pump (Ground Source Horizontal Closed Loop)
		Packaged Chiller
		Chiller
	Heat Exchange	Borehole
Solar Thermal	Vapour Absorption	Single Effect Absorption Chiller
Natural Gas Trigeneration	Vapour Absorption	Single Effect Absorption Chiller
Biomass Trigeneration	Vapour Absorption	Single Effect Absorption Chiller

Table 6.4 Fuel source and plant options considered for the GGIR study

Figure 6.4 shows the range of GGIFs for different energy sources. Note that the Indirect GWPs have been calculated based on thermal CoSP (CoSPth) only, and do not include ancillary power. The addition of this component would change the results, in particular by increasing the GGIF for all systems that use active distribution methods. Passive cooling systems are placed at zero, and with this additional factor there would be a marked increase between this and active systems.

The Trigeneration results are based on an electricity displaced CO_2 factor of 0.568 kg/kWh, although it is recognized that there may be different views on this. Nevertheless, the results suggest that the best electric vapour compression systems can compete in carbon terms with the best absorption systems. Note that the solar electric and solar thermal systems have been included for completeness. The positive GGIFs with these systems is largely due to the solar fraction that has been assumed – i.e. there is still a fossil fuel component with these.

The full GGIF range in Figure 6.4 has been divided into seven bands labelled A to G. This forms the basis of a ranking for cooling systems as it captures all the main system configurations, and shows the possible ranges of GGIF. Including ancillary power is likely to expand the full range, but this should not necessarily alter the bands and labels, but simply push most active systems into a lower band. The use of this banding will therefore encourage designs to achieve the best possible solution, while trying to minimize active cooling systems.

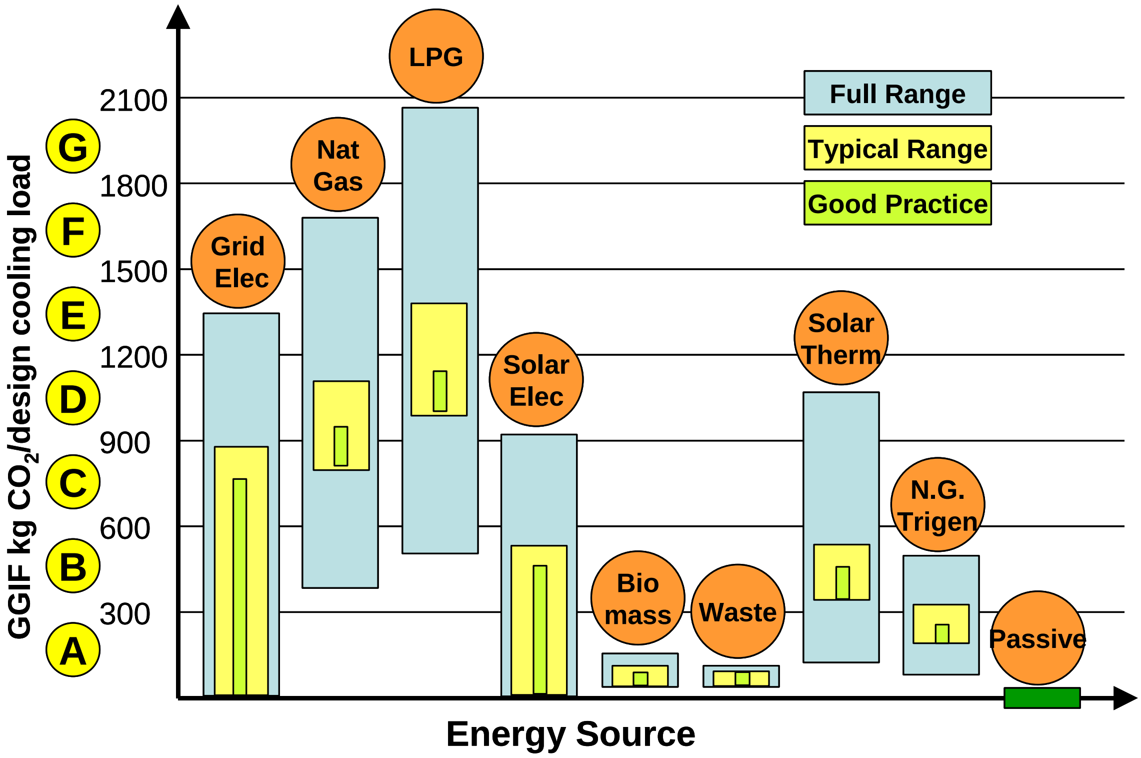


Figure 6.4 Greenhouse Gas Impact Factor ranges for different energy sources

7. Worked examples

This section provides a set of worked examples for a range of systems and parameters to show how the GGIR can be used to assess cooling systems.

Example 1 – Fan coils with air cooled vapour compression

Component	Type
Delivery system	Fan coils
Distribution system	Chilled Water
Chiller type	Vapour compression
Chiller fuel source	Electricity
Refrigerant	R404a
Heat rejection	Air-cooled

Methodology			Inputs	Operation
Steps 1-7 System Efficiency		**Units**	**Outputs**	
Step 1	Initial Design Load	kW	**100**	
	Reduction Method	kW	**0**	
	Building Cooling Load	kW	**100**	Initial design load - reduction method
Step 2	Delivery Equipment Gains	%	**13%**	
	Delivered Load	kW	**113**	Building Cooling Load x (1+Gains fraction) = 100 x 1.13
Step 3	Distribution Gains	%	**13%**	
	Distributed Load	kW	**127.7**	Delivered load x (1+Gains fraction) = 113 x 1.13
Step 4	Plant EquipmentGains		**10%**	
	System Thermal Load		**140.5**	Distributed Load x (1+Gains fraction)
Step 5	Plant CoP (A/W/G)	-	**3.30**	
	Plant Input	kW	**42.6**	System Thermal Load ÷ CoP
Step 6	Ancillary power	kW	**30**	Ancillary Power x (Electricity CO2 Factor/Chiller fuel CO2 Factor)
	Total System Power	kW	**72.6**	Ancillary Power + Plant Input Power
Step 7	CoSP	-	**1.4**	Design Load/Total System Power
Steps 8-13 GGIF				
Step 8	Annual Cooling Hours	hrs	**2250**	
	Annual Cooling Energy	kWh	**163268**	Total System Power x Annual Cooling Hours = 192.4 x 2250
Step 9	CO_2 Emission Factor	kgCO2/kWh	**0.422**	
	Indirect GWP	kgC02	**68899**	Annual Cooling Energy/Chiller CO2 factor = 462288 x 0.194
Step 10	Refrigerant Charge	kg	**30**	0.179 x chiller capacity in kW + 5.169 (Figure 7.7)
	GWP (100yrs)		**1647**	
	Potential Direct GWP	CO2e	**49920**	Refrigerant charge x GWP
Step 11	Annual Leakage Rate	%	**20%**	
	Direct GWP (100yrs)		**9984**	Potential Direct GWP x Annual Leakage Rate
Step 12	Total GWP (100yrs)		**78883**	Indirect GWP + Direct GWP
Step 13	GGIF	$kgCO_2/kW$	**789**	Total GWP/Design Load
		GGIR	**C**	

Table 7.1 Example 1 (Vapour compression, air cooled, fan coils)

Example 2 - **Fan coils with water cooled vapour compression** - uses the same characteristics as example 1, but using water cooled heat rejection, which improves the plant CoP. This improves the GGIF, but not the rating (GGIR)

Example 3 – Improved CoP & heat rejection - is the same as above, but employing improved heat rejection heat exchanger with a further improvement in plant CoP, and a subsequent improvement in GGIR

Example 4 – Absorption chiller - changes the central plant to a natural gas fired absorption chiller, with a change in plant CoP, and CO_2 factor. The significantly lower CoP gives this a worse GGIR than the vapour compression systems.

Example 5 – Trigeneration - replaces the absorption fuel with CHP heat (trigeneration). This brings the GGIR back to a C rating.

		Example	2	3	4	5
Methodology			Inputs	Inputs	Inputs	Inputs
Steps 1-7 System Efficiency		Units	Outputs	Outputs	Outputs	Outputs
Step 1	Initial Design Load	kW	100	100	100	100
	Reduction Method	kW	0	0	0	0
	Building Cooling Load	kW	100	100	100	100
Step 2	Delivery Equipment Gains	%	13%	13%	13%	13%
	Delivered Load	kW	113	113	113	113
Step 3	Distribution Gains	%	13%	13%	13%	13%
	Distributed Load	kW	127.7	127.7	127.7	127.7
Step 4	Plant EquipmentGains		10%	10%	10%	10%
	System Thermal Load		140.5	140.5	140.5	140.5
Step 5	Plant CoP (A/W/G)	-	4.10	6.30	0.72	0.72
	Plant Input	kW	34.3	22.3	195.1	195.1
Step 6	Ancillary power	kW	30	30	65	190
	Total System Power	kW	64.3	52.3	260.3	384.9
Step 7	CoSP	-	1.6	1.9	0.4	0.3
Steps 8-13 GGIF						
Step 8	Annual Cooling Hours	hrs	2250	2250	2250	2250
	Annual Cooling Energy	kWh	144581	117664	585764	865996
Step 9	CO_2 Emission Factor	kgCO2/kWh	0.422	0.422	0.194	0.067
	Indirect GWP	kgC02	61013	49654	113638	57762
Step 10	Refrigerant Charge	kg	30	30	30	30
	GWP (100yrs)		1647	1647	0	0
	Potential Direct GWP	CO2e	49920	49920	0	0
Step 11	Annual Leakage Rate	%	20%	20%	20%	20%
	Direct GWP (100yrs)		9984	9984	0	0
Step 12	Total GWP (100yrs)		70997	59638	123622	67746
Step 13	GGIF	kgCO2/kW	710	596	1236	677
		GGIR	C	B	E	C

Table 7.2 Examples 2 to 5

Example 6 – Reduced cooling load - takes the best vapour compression example above (example 3) and applies a cooling load reduction of 50%. This lowers the GGIF, but the GGIR remains a B.

Example 7 – reduced cooling load & trigeneration - does the same as example 6 but for the previous trigeneration solution (example 5) which reduces the GGIF, and improves the GGIR to B.

Examples 8 and 9 – Chilled beams - repeat examples 6 and 9 respectively, but use chilled beams as the delivery system, which improves both plant CoPs and reduces ancillary power loads. This improves the GGIRs to A in both cases.

		Example	6	7	8	9
Methodology			Inputs	Inputs	Inputs	Inputs
Steps 1-7 System Efficiency		Units	Outputs	Outputs	Outputs	Outputs
Step 1	Initial Design Load	kW	100	100	100	100
	Reduction Method	kW	50	50	50	50
	Building Cooling Load	kW	50	50	50	50
Step 2	Delivery Equipment Gains	%	13%	13%	13%	13%
	Delivered Load	kW	56.5	56.5	56.5	56.5
Step 3	Distribution Gains	%	13%	13%	13%	13%
	Distributed Load	kW	63.8	63.8	63.8	63.8
Step 4	Plant EquipmentGains		10%	10%	10%	10%
	System Thermal Load		70.2	70.2	70.2	70.2
Step 5	Plant CoP (A/W/G)	-	6.30	0.72	10.00	0.75
	Plant Input	kW	11.1	97.5	7.0	93.6
Step 6	Ancillary power	kW	15	94	3	19
	Total System Power	kW	26.1	192.0	10.0	112.6
Step 7	CoSP	-	1.9	0.3	5.0	0.4
Steps 8-13 GGIF						
Step 8	Annual Cooling Hours	hrs	2250	2250	2250	2250
	Annual Cooling Energy	kWh	58832	432042	22552	253395
Step 9	CO_2 Emission Factor	kgCO2/kWh	0.422	0.067	0.422	0.067
	Indirect GWP	kgC02	24827	28947	9517	16901
Step 10	Refrigerant Charge	kg	18	18	18	18
	GWP (100yrs)		1647	1647	0	0
	Potential Direct GWP	CO2e	29215	29215	0	0
Step 11	Annual Leakage Rate	%	20%	20%	20%	20%
	Direct GWP (100yrs)		5843	5843	0	0
Step 12	Total GWP (100yrs)		34811	38931	19501	26885
Step 13	GGIF	kgCO2/kW	348	389	195	269
		GGIR	B	B	A	A

Table 7.3 Examples 6 to 9

Table 8.4 shows a summary of GGIR for some typical systems. Those with rating of A or B can be seen as energy efficient solutions.

	VAPOUR COMPRESSION AIR-COOLED		VAPOUR COMPRESSION WATER-COOLED		ABSORPTION	
ALL-AIR	Component	Type	Component	Type	Component	Type
	Delivery system	Fan coils	Delivery system	Fan coils	Delivery system	Fan coils
	Distribution system	Chilled Water	Distribution system	Chilled Water	Distribution system	Chilled Water
	Chiller type	Vapour compression	Chiller type	Vapour compression	Chiller type	Vapour absorption
	Chiller fuel source	Electricity	Chiller fuel source	Electricity	Chiller fuel source	Natural Gas
	Refrigerant	R407c	Refrigerant	R407c	Refrigerant	LiBr
	Heat rejection	Air-cooled (19 K)	Heat rejection	Water cooled (9 K)	Heat rejection	Water cooled (9 K)
	GGIF	**601**	**GGIF**	**448**	**GGIF**	**946**
	GGIR	**C**	**GGIR**	**B**	**GGIR**	**D**
RADIANT	Component	Type	Component	Type	Component	Type
	Delivery system	Radiant panels	Delivery system	Radiant panels	Delivery system	Radiant panels
	Distribution system	Chilled Water	Distribution system	Chilled Water	Distribution system	Chilled Water
	Chiller type	Vapour compression	Chiller type	Vapour compression	Chiller type	Vapour absorption
	Chiller fuel source	Electricity	Chiller fuel source	Electricity	Chiller fuel source	Natural Gas
	Refrigerant	R407c	Refrigerant	R407c	Refrigerant	LiBr
	Heat rejection	Air-cooled (19 K)	Heat rejection	Water cooled (9 K)	Heat rejection	Water cooled (9 K)
	GGIF	**431**	**GGIF**	**299**	**GGIF**	**897**
	GGIR	**B**	**GGIR**	**A**	**GGIR**	**C**
CLIMATIC	Component	Type	Component	Type	Component	Type
	Delivery system	Central air system	Delivery system	Central air system	Delivery system	Central air system
	Distribution system	Chilled Water	Distribution system	Chilled Water	Distribution system	Chilled Water
	Chiller type	Vapour compression	Chiller type	Vapour compression	Chiller type	Vapour absorption
	Chiller fuel source	Electricity	Chiller fuel source	Electricity	Chiller fuel source	Natural Gas
	Refrigerant	R407c	Refrigerant	R407c	Refrigerant	LiBr
	Heat rejection	Air-cooled (19 K)	Heat rejection	Air-cooled (19 K)	Heat rejection	Water cooled (9 K)
	GGIF	**790**	**GGIF**	**638**	**GGIF**	**1136**
	GGIR	**C**	**GGIR**	**C**	**GGIR**	**D**

Table 7.4 Summary of GGIR for typical systems

8. Best and worst modern designs

There are a wide variation in overall Greenhouse Gas Impact Factor (GGIF), even amongst typical modern designs. It is important that designers and planners understand which are the best and worst of these typical modern designs. Although not exhaustive, Figure 8.1 shows the likely performance of some typical systems currently being included in new developments. Table 8.1 shows the performance ranked by the typical rating with a recommendation to include or not. These indicate some of the best system performance that might come from good modern designs. They also show the worst modern systems that might be submitted for planning permission. In some marginal scenarios these worst cases might be considered as the minimum acceptable by planners, although in most cases they would be regarded as systems to avoid. In general, where passive or renewable systems can not be used, mechanical cooling for new developments should be rated at least A or B.

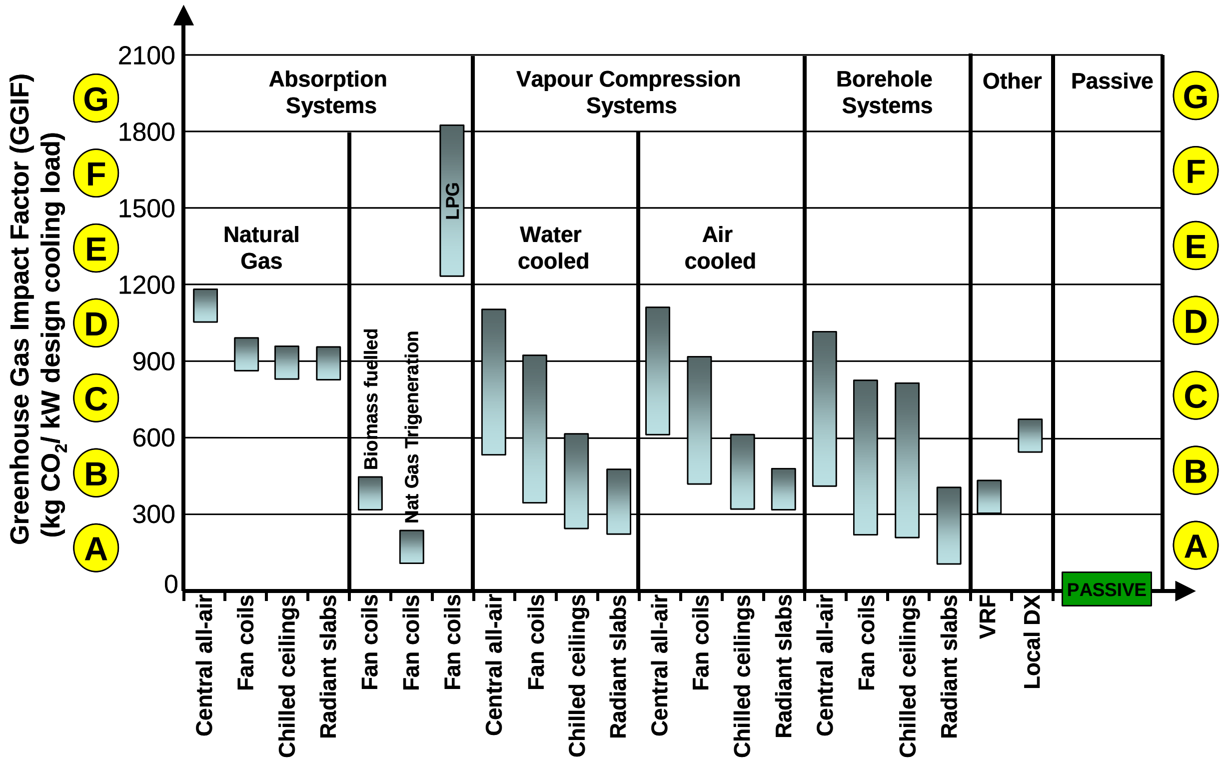


Figure 8.1 Performance ranges of typical modern designs

Some systems, particularly older designs, high carbon fuel systems and existing systems, will be very much worse than the ranges shown and should definitely be avoided/replaced. These systems are not shown for clarity but have been taken into account in reaching the A to G scale up to 2,100 kg CO_2/kW. LPG fired absorption chillers supplying a central all-air system have been included in Figure 8.1 to indicate that G rated systems are entirely possible but should be avoided at all costs. Other typical systems are shown in the worked examples in section 7.

In general, where passive or renewable systems cannot be used, mechanical cooling for new developments in London should be rated at least A or B.

Fuel	System	Chiller	Typical rating range	Recommendation
Natural gas trigeneration	Fan coils	Absorption	A	OK
Electricity	Radiant slabs	Vapour compression (Water cooled)	A – B	OK
Electricity	Radiant slabs	Borehole	A – B	OK
Electricity	Chilled ceilings	Vapour compression (Water cooled)	A – C	A - B Only
Electricity	Fan coils	Borehole	A – C	A - B Only
Electricity	Chilled ceilings	Borehole	A – C	A - B Only
Biomass	Fan coils	Absorption	B	OK
Electricity	Radiant slabs	Vapour compression (Air cooled)	B	OK
Electricity	VRF	-	B	OK
Electricity	Chilled ceilings	Vapour compression (Air cooled)	B – C	B Only
Electricity	Local Direct Expansion	-	B – C	B Only
Electricity	Central all-air	Vapour compression (Water cooled)	B - D	B Only
Electricity	Fan coils	Vapour compression (Water cooled)	B – D	B Only
Electricity	Fan coils	Vapour compression (Air cooled)	B – D	B Only
Electricity	Central all-air	Borehole	B – D	B Only
Natural gas	Fan coils	Absorption	C - D	Avoid
Natural gas	Radiant slabs	Absorption	C - D	Avoid
Natural gas	Chilled ceilings	Absorption	C – D	Avoid
Electricity	Central all-air	Vapour compression (Air cooled)	C – D	Avoid
Natural gas	Central all-air	Absorption	D	Avoid

Table 8.1 Performance ranges of typical modern designs

Observations

- Ground-cooled condensers perform better than air-cooled which generally perform better than water-cooled for vapour compression cycles. This is due to the difference in temperature across the condenser.

- For ground-cooled condensers the difference in temperature across the condenser can be as low as 5°C whereas for air-cooled this can be as high as 19°C and the water-cooled condenser range sits inside that of air-cooled. Therefore the compressor within the vapour compression cycle does not need to work as hard to reject heat to the outside environment when the temperature difference is low.

- Radiant slab systems perform better than climatic systems (chilled beams), which perform better than forced air. This is because the delivery temperatures are much higher. For a given ambient air temperature, low delivery temperatures require larger pressure increases in order to create the required refrigeration effect and therefore the compressor has to work harder to compensate for this, reducing the CoP.

- Little difference can be seen between vapour absorption cycles for radiant slab and climatic (chilled beam) systems.

- CoSPth of radiant slab and chilled beam systems always lie within a narrow band while that of forced air systems can fluctuate dramatically due to the larger delivery temperature range.

- Deeper boreholes have poorer CoSPths than shallow because of the increased pumping power needed to provide lift to the surface.

- Forced air systems require delivery temperatures lower than ground water. It would be impractical to have a borehole system as a secondary refrigeration system would be required to achieve this.

- Radiant slab systems give the best CoSPth with borehole systems

9. References

1. A.R. Day, P.G. Jones, G.G. Maidment - Forecasting future cooling demand in London, Energy In Buildings (2008)
2. Market Transformation Programme, Air-conditioning products, (December 2007)
3. Conservation of Fuel & Power, Building Regulations Part L (England & Wales) (HMSO) (2006)
4. The London climate change adaptation strategy, Greater London Authority (August 2008)
5. Bordass W., Flying Blind: Things you wanted to know about energy in commercial buildings but were afraid to ask The Association for the Conservation of Energy and the Oxfordshire Energy Advice Centre (October 2001)
6. London's Warming: The impacts of climate change on London (London Climate Change Partnership) (October 2002) www.london.gov.uk/gla
7. TM44: Inspection of Air Conditioning Systems (CIBSE) (2007)
8. Forecasting future cooling demand in London - Technical Report: Supporting London Plan Policy (London South Bank University) (June 2008)
9. Technical Memorandum 41, Degree-day: theory and application, (CIBSE) (2006)
10. The London Plan, Spatial Development Strategy for Greater London, Consolidated with Alterations since 2004 (Greater London Authority) (February 2008)
11. Energy Efficiency in Buildings – CIBSE Guide F (London: Chartered Institution of Building Services Engineers) (2004)
12. A designers guide to the options for ventilation and cooling GPG 291 (Carbon Trust) (2001) www.carbontrust.co.uk
13. An Introduction to Absorption Cooling GPG 256 (Carbon Trust) www.carbontrust.co.uk (1999)
14. Refrigeration and heat rejection CIBSE Guide B4 (London: Chartered Institution of Building Services Engineers) (2003)
15. Forbes Person, S., 2008, Saving Energy in Refrigeration, Air-Conditioning and Heat-Pump Technology, International Institute of Refrigeration, ISBN 978-2-913149-66-3
16. Energy Efficient Refrigeration Technology - The Fundamentals GPG 280 (Carbon Trust) (2000) www.carbontrust.co.uk
17. Ventilation and cooling option appraisal - a client's guide GPG290 (Carbon Trust) (2001) www.carbontrust.co.uk
18. Refrigeration systems and applications ASHRAE Handbook (Atlanta, GA: American Society of Heating, Refrigeration and Air Conditioning Engineers) (1998)
19. Brittain J R J, Oversized cooling and pumping plant GN 13/97 (Bracknell: Building Services Research and Information Association) (1997)
20. Refrigeration systems CIBSE Commissioning Code R (London: Chartered Institution of Buildings Services Engineers) (1991)
21. Natural Ventilation in non-domestic buildings, CIBSE Applications Manual AM10 (London: Chartered Institution of Building Services Engineers) (2005)
22. Technical Memorandum TM37, Design for Improved solar shading control, (CIBSE) (April 2006)
23. De Saulles T Free cooling systems BG8 (Bracknell: Building Services Research and Information Association) (2004)
24. Mixed mode buildings, CIBSE Applications Manual AM13 (London: Chartered Institution of Building Services Engineers) (2000)
25. New ways of cooling – information for building designers GIL 85 (Carbon Trust) www.carbontrust.co.uk (2001)
26. Pennycook K. Illustrated Guide to Renewable Technologies BG1/2008 (BSRIA) (April 2008)
27. Kolokotroni M Night ventilation for cooling office buildings BRE Information Paper IP4/98 (London: Construction Research Communications) (1998)
28. Martin A J Control of natural ventilation TN 11/95 (Bracknell: Building Services Research and Information Association) (1995)
29. Martin A Night cooling control strategies TN 5/96 (Bracknell: Building Services Research and Information Association) (1996)
30. Ice storage systems CIBSE Technical Memoranda TM18 (London: Chartered Institution of Building Services Engineers) (1994)
31. Building Control Systems - CIBSE Guide H (London: Chartered Institution of Building Services Engineers) (2000)
32. Nicholls R, Heating, ventilation and air conditioning (Interface publishing) (1999)
33. Heat Recovery Systems HRS 1/2009 (Bracknell: Building Services Research and Information Association) (2009)
34. De Saulles T. Illustrated Guide to Mechanical Building Services AG15/2002 (BSRIA) (2002)

35. Butler, R.J. Oughton D.J.G. VAV Systems: Review of Current Guidance and Research. s.l. : BRE Publications, 1999
36. Jones, W.P. Air Conditioning Applications and Design: Second Edition. s.l. : Arnold, 1997
37. *Code of Practice COP 17/99 Displacement Ventilation and Static Cooling Devices.* s.l. : Department of Environment, Transport and the Regions, 1999
38. Ability Projects Ltd. Products - Trojan. *Ability Projects Ltd.* [Online] Ability Projects. [Cited: 17 December 2007.] www.abilityprojects.co.uk/pdf/trojan.pdf.
39. D. Butler, M. Swainson. *IP11/04 Perimeter Chilled Beams.* s.l. : BRE Centre for Environmental Engineering, 2004
40. Energie. Climatic Ceilings Technical Note: Design Calculations. s.l. : European Commission Directorate-General for Energy and Transport, 2001
41. Love, Zhen Tian & James A. A Field Study of Occupant Thermal Comfort and Thermal Environmental with Radiant Slab Cooling. s.l. : Science Direct, 2007
42. Energie. *Floor Heating and Cooling Systems: Applications of Low Temperature Heating and High Temperature Cooling.* s.l. : European Commission Directorate-General for Energy and Transport, 2001
43. Minimising the risk of Legionnaires' disease Technical Memorandum TM13 (CIBSE) (2002)
44. Blackhurst DR. Recent developments in thermosyphon cooling for air conditioning. In: Proceedings of the Institute of Refrigeration, 1998-1999, p. 4-1 to 4-12
45. Coolpack: a collection of simulation models for refrigeration systems, Technical University of Denmark, http://www.et.web.mek.dtu.dk/Coolpack/UK/index.html
46. Cutting the cost of refrigerant leakage. An introductory guide for users of small to medium sized refrigeration systems GPG 178 (Carbon Trust 0800 585794) www.carbontrust.co.uk (1997)
47. Minimising refrigerant emissions from air conditioning systems in buildings IP1/94 (London: Construction Research Communications) (1994)
48. Non-Domestic Heating, Cooling & Ventilation Compliance Guide, (Department for Communities and Local Government) (2006)
49. Market Transformation Report Approved briefing note BNXS01: Carbon Dioxide Emission Factors for UK Energy Use (2008)http://www.mtprog.com/ApprovedBriefingNotes/PDF/MTP_BNXS01_2008May20.pdf
50. Guidelines for DEFRA's GHG conversion factors for company reporting (2007) http://www.defra.gov.uk/environment/business/envrp/pdf/conversion-factors.pdf
51. BERR energy statistics http://www.berr.gov.uk/energy/statistics/source/electricity/page18527.html
52. Fuel Mix web site http://www.fuelmix.co.uk/index.htm
53. Myson M, Rudock JP, Tjelflaat PO, *Demand controlled ventilation for office cubicles—can it be profitable?,* Energy and Buildings, Vol 35, No 7, August 2003, Pages 657-662
54. *Carrier.* [Online] [Cited: 26 January 2008.] www.uk.carrier.com/product%20families.htm.
55. Air Cooled Chillers. *McQuay.* [Online] [Cited: 26 January 2008.] www.mcquay.com/mcquay/productinformation/aircooledchillers/aircooledchillers.pdf
56. Calm, James M. *Comparative Efficiencies and Implications for Greenhouse Gas Emissions of Chiller Refrigerants.* s.l. : International Journal of Refrigeration & Science Direct, 2006
57. A.R. Douglass, P.M.D. Forester, D.A. Hauglustaine, I.S.A. Isaksen, L.J.M. Kuijpers, A. McCulloch, T.J. Wallington. Chapter 8: Halocarbon Scenarios, Ozone Depletion Potentials, and Global Warming Potentials. [book auth.] G.J.M. Velders J.S. Daniel. *Scientific Assessment of Ozone Depletion.* 2007.
58. Haydock et al, BNCR 36 Direct emissions of refrigerant gases Energy Technology Support Unit (ETSU), 2003

APPENDIX A – Glossary of terms

CCHP	Combined Cooling, Heat and Power	
CDD	Cooling Degree-days	
Cf_H	CO_2 factor for heat	kg/kWh
CHP	Combined Heat and Power	
CoP	Coefficient of Performance	
CoSP	Coefficient of System Performance	
CoSPth	Coefficient of System Performance (thermal factors only)	
DX	Direct expansion (cooling system)	
GGIF	Greenhouse Gas Impact Factor	kg CO_2/kWh
GGIR	Greenhouse Gas Impact Rating	A – G label
GWh	Gigawatt Hours	10^9 Wh
GWP	Global Warming Potential	kg CO_2 equivalent
LPG	Liquified Petroleum Gas	
PH	Pressure-enthalpy	
Trigeneration	Alternative term for CCHP	
TWh	Terawatt Hours	10^{12} Wh
VAV	Variable Air Volume	
VRF	Variable Refrigerant Flow	
VRV	Variable Refrigerant Volume	

All-Air Systems	Use air as the cooling medium throughout the building, often based around air handling units and air ductwork. Generally, the air is cooled by chilled water in the range 5-10°C
Climatic systems	Use chilled water to cool the building structure to deliver cooling e.g. chilled beams and chilled ceilings. Generally, using chilled water in the range 14-17°C
Radiant slab systems	Use chilled water to provide cooling through large slabs of the building structure e.g. floor slabs. Generally, using chilled water in the range 16-22°C
Fan coil units	A common delivery devices normally comprising a local heat exchanger and fan to further chill centrally supplied all-air system.
Delivery Equipment	The equipment which removes heat from the space.
Distribution Equipment	Means by which the heat moved from the delivery equipment to the plant equipment.
Plant Equipment	Equipment capable of transferring heat from the building to a heat rejection method.
Heat Rejection Method	Means of passing heat from the plant equipment to the outside environment.
Design Power	Cooling requirement of the building.
Reduction Method	Use of methods which reduce the cooling load of the building, without energy input such as passive measures and intelligent system design.
Building Cooling Power	Cooling load required by the building once reduction methods have been introduced.
Cooling Degree Days	A measure of weather, derived from daily temperature, that can be used to estimate cooling energy consumption
Delivery Equipment Efficiency	The ability of the equipment to remove heat from the space and overcome any heat gains due to the components.
Delivered Power	The cooling load required by the delivery equipment to overcome any heat gains and still control the required.
Distribution Losses	The loss in cooling capacity caused by heat gains due to pipe and duct runs from the plant to the delivery equipment.
Distributed Power	The cooling load required by the plant to overcome any heat gains caused by distribution and the delivery equipment and still controls the temperature in the space.
Plant CoP	The Coefficient of Performance of the plant equipment. Ratio of energy required to drive the plant compared to its ability to remove heat from the system.
Plant Equipment Efficiency	The ability of the system to remove heat from the space and overcome any heat gains, due to the equipment within the plant and heat rejection

	method.
Primary Power	The power required by the plant in order to overcome any heat gains along the cooling system and still control the required temperature in the space.
Thermal Coefficient of System Performance ($CoSP_{th}$)	The ratio of cooling power required to overcome the heat gains due to ancillaries within the cooling system and the input power to the compressor.
Electrical Coefficient of System Performance ($CoSP_e$)	The ratio of cooling power and the power needed to supply this, including ancillaries.
Coefficient of Performance (CoP)	Ratio of heat absorbed in the evaporator and the input power to the compressor.
	Ratio of the refrigerating effect to the energy supplied to the generator.
Annual Cooling Hours	Running hours throughout the year required to operate the cooling system.
Annual Cooling Energy	Total annual energy in kWh to operate the cooling system.
CO_2 Emission Factor	Kilograms of CO_2 emitted by the energy source to operate the cooling system.
Indirect GWP	Annual CO_2 emitted by the fuel source of the cooling system.
Refrigerant	A fluid that absorbs heat by evaporating in one part of a refrigerating system and releases the heat by condensing in another part.
Refrigerant Charge	The amount of refrigerant in the cooling system (kg), required to operate at its highest efficiency.
GWP (100 years)	The global warming potential of the refrigerant after 100 years within the atmosphere.
Potential GWP	The potential environmental impact of the refrigerant in the system.
Annual Leakage Rate	The annual percentage rate in which refrigerant will leak from the system.
Direct GWP	Greenhouse gases emitted by the refrigerant which has leaked through the year.
Indirect GWP	Carbon Dioxide emitted by the fuel source used to power the cooling system.
Total GWP	The direct and indirect global warming potential of the cooling system.
Environmental Impact	The kg of CO_2 equivalent per kW of installed cooling system capacity.
ΔT	Difference in temperature
Compressor Efficiency	Efficiency of the compressor in the refrigeration system.
Superheat	Degree of superheat is the actual vapour temperature, less the saturation temperature
Sub-cooling	Degree of sub-cooling is the saturation temperature less the actual liquid temperature
Evaporator ΔT (Vapour Compression)	The difference in temperature across the evaporator within the refrigeration plant.
Evaporator ΔT (Absorption)	Difference in temperature across the evaporator within the vapour absorption cycle.
Generator Temperature	Temperature supplied to the vapour absorption cycle by an outside heat source, referred to as the generator.
ΔT across Heat Exchanger - Ground Condenser	Difference in temperature across the ground-cooled condenser within the vapour compression cycle.
ΔT across Heat Exchanger - Water Condenser	Difference in temperature across the water-cooled condenser within the vapour compression cycle.
ΔT across Heat Exchanger - Air Condenser	Difference in temperature across the air-cooled condenser within the vapour compression cycle.
Delivery Temperature	Temperature of the chilled water required by the delivery equipment.
Efficiency - Electrical Losses	Loss in electrical power required to power all ancillaries in a cooling system.
Efficiency – Heat Gains	Loss in cooling capacity caused by the heat gained from the ancillaries in the cooling system.
Cooling System	The equipment necessary to transfer heat from the space to the outside environment. i.e. heat rejection method, plant equipment, distribution losses, delivery equipment.
Refrigeration System	Use of an evaporator, compressor, condenser and expansion valve, to

	circulate refrigerant and transfer heat from the evaporator to the condenser.
Trigeneration	The use of heat from a Combined Heat & Power plant (CHP or cogeneration) to supply cooling via an absorption chiller – sometimes called Combined Cooling Heating & Power (CCHP)
GGIF	Greenhouse Gas Impact Factor (kilograms of greenhouse gases emissions (relative to CO_2) per annum per design power).
GGIR	Greenhouse Gas Impact Rating – an A to G rating based on the GGIF

APPENDIX B – CO_2 factors

CO_2 factors for different fuels are given in Part L2A of the Building Regulations (2006), a summary of which are shown in Table B1. The most commonly used will be grid supplied electricity (0.422 kg/kWh) for vapour compression and ancillary power, and natural gas (0.194 kg/kWh) for absorption.

The complexity arises when considering heat for absorption chillers supplied from Combined Heat and Power (CHP) in a so-called trigeneration or CCHP system. The carbon savings from CHP are normally determined by assuming the electricity saves on the carbon *displaced* from the grid (at 0.568 kg/kWh according to Table B1). (This is the prescribed method in the Non-Domestic Heating, Cooling and Ventilation Compliance Guide[48]). However, the absorption chiller avoids electricity *supplied* to a vapour compression machine (0.422 kg/kWh). Any comparison between two systems that uses different CO_2 factors is clearly ambiguous and should be avoided. However, there is no firm guidance on this whole issue. An alternative is to use the published electricity grid average CO_2 factor of around 0.53 from DEFRA[49-52].

Fuel	**CO_2 factor (kg/kWh)**
Natural Gas	0.194
LPG	0.235
Biogas	0.025
Oil	0.265
Coal	0.291
Biomass	0.025
Grid supplied electricity	0.422
Grid displaced electricity	0.568
Waste heat	0.018

Table B1 CO_2 factors from Part L2A Building Regulations 2006[3]

For trigeneration the CO_2 factor for the waste heat is dependent upon the heat to power ratio of the CHP machine, and the assumed electricity CO_2 factor, as shown in Figure B1. From this it can be seen that the lower the amount of assumed displaced electricity CO_2, the higher the carbon content of waste heat. There are some compelling arguments to suggest that the displaced electricity should be assumed to come from high efficiency gas fired central plant with CO_2 factors less than 0.4 kg/kWh. This can make trigeneration unattractive in carbon terms.

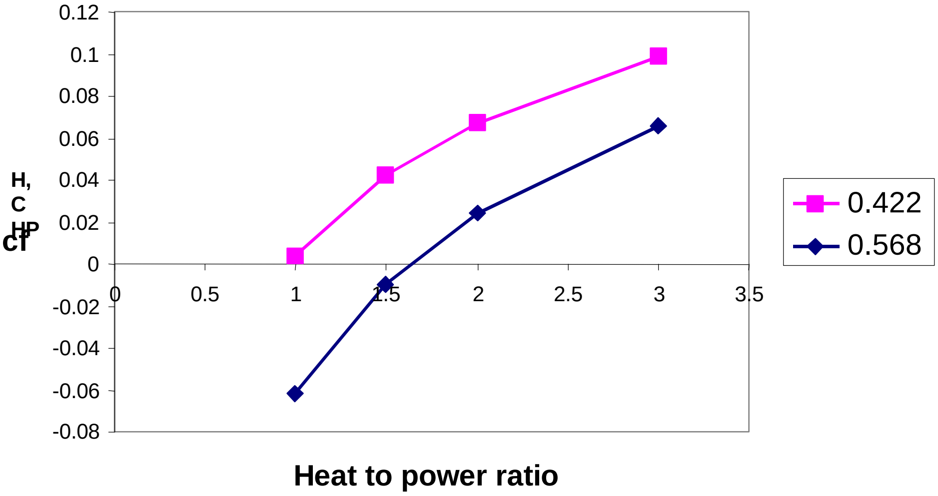


Figure B1 CO_2 factor for the heat from a CHP plant as a function of heat to power ratio for two different electricity CO_2 factors

APPENDIX C – Approaches to ancillary power

The ancillary power in the cooling system is all the energy consuming components required to transport the cooling media around the building, i.e. the fans and pumps. This includes air and chilled water distribution and heat rejection at the central plant. There is often a high energy penalty for using air as the main cooling medium due to its low specific heat capacity and low density. The power absorbed by a fan is a function of the volume flow rate, the pressure rise across the fan, and its efficiency:

$$Fan\ power\ (kW) = \frac{Volume\ flowrate\ (m^3/s) \times Fan\ total\ pressure\ (Pa)}{Fan\ efficiency}$$

High volume flow rates necessary to cool a building by air therefore lead to significant consumption of energy.

Water, on the other hand, has a much higher density (around 830 times greater than air) and higher specific heat (over 4 times better than air). Pump power is calculated in the same way as the fan power above, and because of the much smaller volumes being pumped (albeit at higher pressures) energy used to distribute water is much less than air. In an all air distribution system, chilled water pumping can be as little as 1 – 3% of the ancillary power loads.

There are three ways in which ancillary loads can be calculated for inclusion in the GGIF methodology

1. detailed calculation of air and water flows and pressure drops
2. using quoted specific fan power (SFP)
3. using ancillary power loads as a proportion of the building cooling load

1. Detailed calculations

Air flow rates are calculated as a function of the heat gains to be removed from the space (the building cooling load) and the temperature difference between the required room air temperature and the supply air temperature according to the formula:

$$Heat\ gains\ (kW) = V \times \rho \times c_p \times (t_R - t_S)$$

Where V is the volume flow rate of air in m^3/s, ρ is the density of air in kg/m^3, c_p is the specific heat of air in kJ/kg.K, t_R is the room air temperature and t_S is the supply air temperature both in °C. The room to supply air temperature difference is typically 8 K for many systems, but can be as low as 3 K for low level air systems. This choice of temperature difference has a significant bearing on the air flow rates, although supply air temperatures are often dictated by a number of constraining factors.

Ducts are sized depending on the resulting design air flow rates, and the pressure drops determined throughout the whole distribution system, including pressure drops in the central plant, fittings and terminal devices. (Note that this is a long and detailed procedure that normally only occurs at the detailed design stage). This determines the fan total pressure, which in turn can be used to calculate the fan power. Note that the pumping and heat rejection loads will also need to be calculated.

Example - For a 100 kW cooling load using an 8 K room to supply air temperature difference and taking the density and specific heat of air to be 1.2 kg/m^3 and 1.02 kJ/kg.K respectively gives:

$100 \div (1.2 \times 1.02 \times 8) = 10.2\ m^3/s$

If the system has a total calculated pressure loss of 1.5 kPa, and an overall fan efficiency of 85%, this gives a total fan power of:

$10.2 \times 1.5 \div 0.85 = 18\ kW$

2. Specific Fan Power

The calculation of fan total pressure and fan selection normally takes place at detailed design, in which case it is useful to use typical fan power values for different type of system for the determination of ancillary loads.

Specific fan power (SFP) is defined in terms of power per l/s of air delivered, and as a rough guide this ranges from 0.5 W/(l/s) to 2.5 W/(l/s), see Table C1[48], although some systems are quoted as having SFPs of up to 5 W/(l/s)[53]. The appropriate SFP value can be multiplied by the known air flow rate to estimate fan power.

System type	**SFP W/(l/s)**
Central mechanical ventilation including heating, cooling and heat recovery	2.5
Central mechanical ventilation with heating and cooling	2.0
All other central systems	1.8
Local ventilation units within the local area serving one room or area	0.5
Local ventilation units remote for the local area serving one room or area (includes terminal VAV systems)	1.2
Other local units, e.g. fan coils	0.8

Table C1 Specific fan powers for different air distribution types in new buildings (adapted from NDHCVC Guide[48])

Example - Taking the previous example of 100 kW cooling load and flow rate of 10.3 m^3/s for a central ventilation system with heating and cooling (SFP = 2.0) gives

$10.3 \times 2 = 20.6$ kW

Note the slight difference with the previous example, due to the approximations involved in an SFP approach. The pumping and heat rejection loads will again have to be calculated separately, probably based on manufacturer's literature.

3. Proportion of the building cooling load

It is possible to make some general assumptions about typical air flow rates and pressure drops. Table C2 below presents some typical electrical ancillary loads expressed as a percentage of the building cooling load. These values have been calculated using assumptions that line up with the SFPs of the previous Table C1. They include an arbitrary additional 20% contribution from central plant heat rejection fans and pumps, and 1 – 3 % contribution from pumping loads.

System type	% of building cooling load
Central mechanical ventilation including heating, cooling and heat recovery	30
Central mechanical ventilation with heating and cooling	25
All other central systems	22
Local ventilation units within the local area serving one room or area	6
Local ventilation units remote for the local area serving one room or area (includes terminal VAV systems)	15
Other local units, e.g. fan coils	10
Displacement ventilation with chilled ceilings	8

Table C2 Ancillary power loads expressed as a percentage of the building cooling load

Example - For a 100 kW building cooling load conditioned with a central plant with heat recovery the ancillary power loads will be

$100 \times 30/100 = 30$ kW

This method gives a total ancillary load, but contains more assumptions than the previous two methods.

APPENDIX D
– Information supporting methodology STEPS 1-13

The following provides supporting information for Steps 1 – 7 of the cooling GGIF methodology, calculating Coefficient of System Performance (CoSP).

Table D1 gives typical values for system heat gains and Table D2 provides key parameters for calculating chiller CoP both of which contribute to steps 1-7 of the method.

Step	Component	Equipment	Typical values (%)
2	Delivery Equipment Gains	Ducts & pipes	13
3	Distribution Equipment Gains	Fans & pumps	13
4	Plant Equipment Gains	Central chiller plant	10
		CHP and Trigeneration	14

Table D1 Typical values for system heat gains

Parameter	Units	Conditions
Ambient air temperature (for air cooled)	°C	27
Ambient air (wet bulb) (for water cooled)	°C	20
Compressor Efficiency (Vapour Compression)	%	60
Super-heat ΔT	K	5
Sub-cooling ΔT	K	5
Evaporator ΔT (Vapour Compression)	K	3
Evaporator ΔT (Absorption)	K	5
Generator Temperature	°C	100
Refrigerant Flow Rate	kg/s	0.8
ΔT across Heat Exchanger-Ground Condenser	K	5-11
ΔT across Heat Exchanger-Water Condenser	K	8-20
ΔT across Heat Exchanger-Air Condenser	K	10-19
Forced Air System Delivery Temperature	°C	7
Climatic System Delivery Temperature	°C	14
Radiant Slab System Delivery Temperature	°C	16

Table D2 Key parameters for calculating chiller CoP

Figure D1-D3 shows the CoP of vapour compression chillers at different temperatures using three different refrigerants. Figure D4 shows the CoP of absorption chillers at different temperatures using lithium bromide. Figure D5 shows indicative borehole cooling CoPs.

Figure D1 Vapour compression CoPs at different temperatures using R134a

Based on central plant CoP for refrigerant R134a and varying condenser temperature differences ($t_{coolant} - t_{refrigerant}$).

(Note water cooled referred against wet bulb temperature, and air cooled referred against dry bulb temperature).

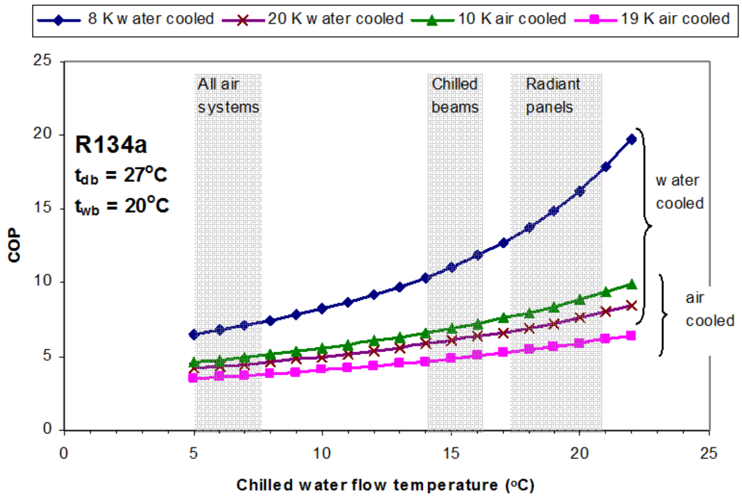


Figure D2 Vapour compression CoPs at different temperatures using R407c

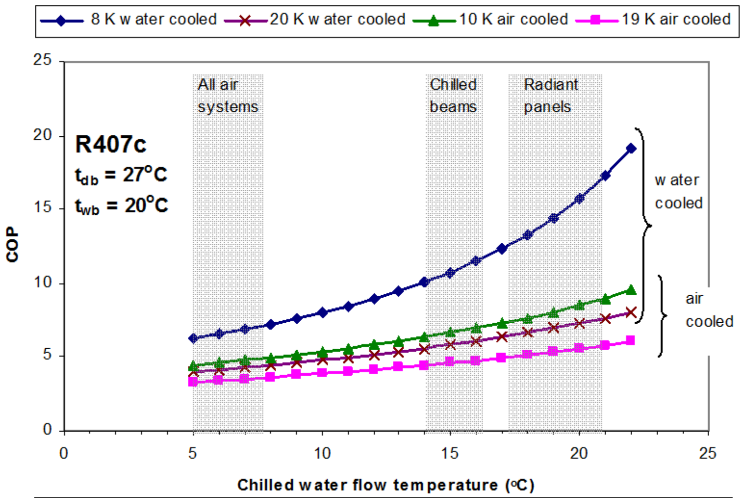


Figure D3 Vapour compression CoPs at different temperatures using R717

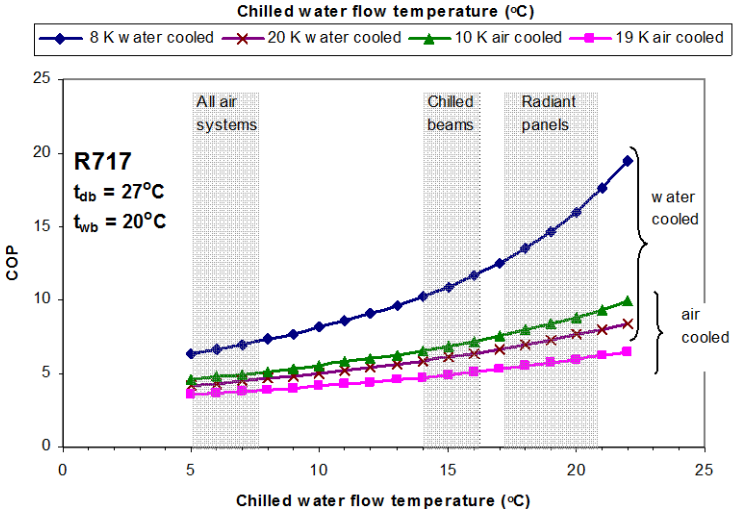


Figure D4 Absorption CoPs at different temperatures using Lithium Bromide

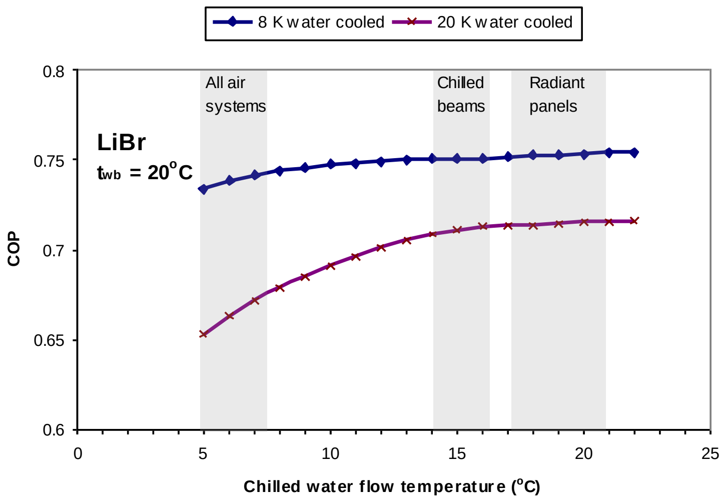
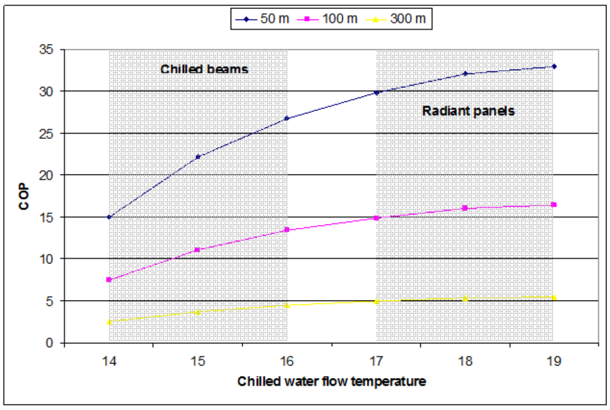


Figure D5 Indicative borehole cooling CoP.(where CoP = Cooling load/pump power) for different depths of borehole at a notional pipe pressure drop of 250 Pa/m



A range of thermal CoSPs – CoSPth – have been calculated using a mix Coolpack software (http://www.et.web.mek.dtu.dk/Coolpack/UK/index.html)and fundamental system equations. CoSPth is essentially the thermal efficiency of the system including plant CoP, and the additional gains due to delivery, distribution and plant operation.

Calculations for a range of system configurations were conducted at two external air temperatures, 23°C and 30°C, to represent design load and typical operating conditions. This resulted in 23,760 vapour compression cycle calculations, 66,978 vapour absorption cycle calculations and 79 borehole heat exchange cycle calculations.

The calculations were repeated for a fixed ambient air temperature of 27°C in order to provide a standard comparison of systems. The investigation looked at good practice delivery temperatures of 7°C for forced air systems, 14°C for climatic systems and 16°C for radiant slab systems, as well as the system delivery temperature ranges from Table D2.
Figures D1 to D5 show the results for vapour compression, absorption and borehole systems respectively.

The following provides supporting information for Steps 8-13 of the cooling GGIF methodology, calculating Global Warming Potential (GWP).

Figure D9 provides information on systems refrigerant charge, Table D3 gives 100 year GWP and Table D4 provides information on likely refrigerant leakage rates all of which contribute to steps 8-13 of the method.

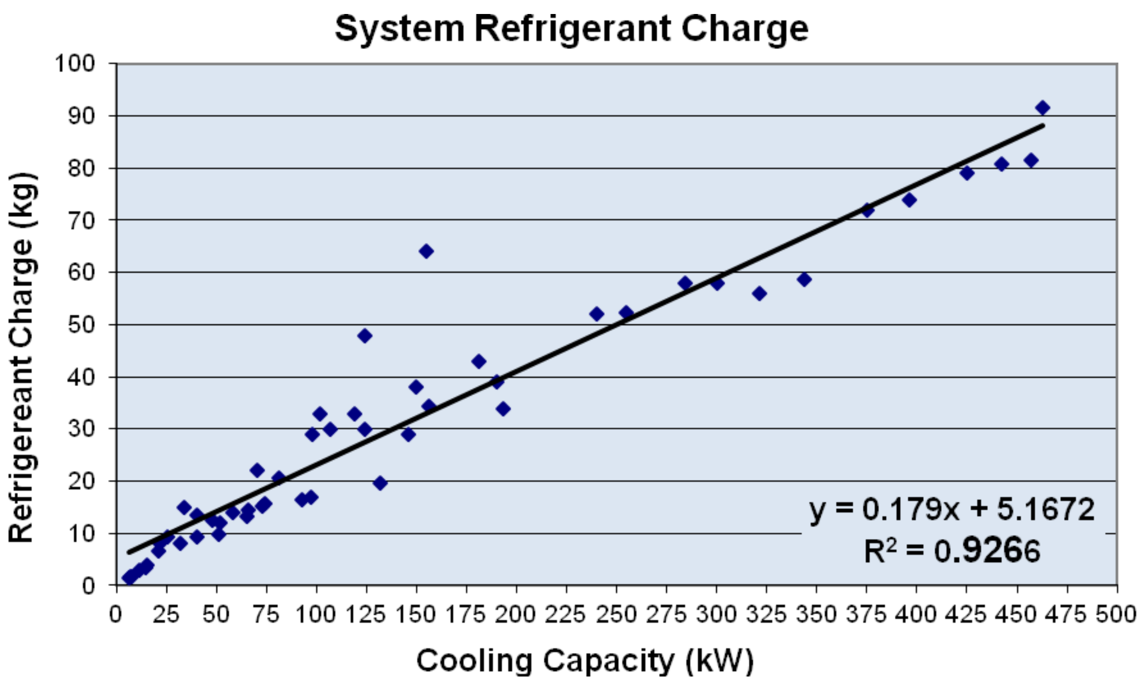


Figure D9 (STEP 10) System refrigerant charge in kg as a function of system cooling capacity from various manufacturer's literature[54,55]

Refrigerant		Global Warming Potential
Type	**Mix or Name**	**100 years**
R-134a	Tetrafluoruethane	1320
R-290	Propane	20
R-404a	R125-44%, R143-52%, R134a-4%	2314.4
R-407c	R32-23%, R125-25%, R143a-52%	1674
R-410a	R32-50%, R125 50%	1997
R507a	R125-50%, R134a-50%	2385
R600a	Isobutane	20
R-717	Ammonia	1
R-718	Water	0
R-1270	Propylene/Propane	20
LiBr	Lithium Bromide	0
CO_2	Carbon Dioxide	1

Table D3 (STEP 10) Global Warming Potential of common refrigerants[56,57]

Sector	Equipment	Reported Annual Leakage Rates (% of charge per annum)
Domestic		0.3-0.7
Retail		
	Integral Cabinets	3-5
	Split/Condensing Units	8-15
	Centralised Supermarket	10-20
Air Conditioning		
	Unitary/Split	8-12
	Chillers	3-5
	Heat Pumps	3-5

Table D4 (STEP 11) Annual refrigerant leakage rates[58]