Very Low Energy Office Buildings in Sweden

Simulations with low internal heat gains

Kajsa Flodberg

Division of Energy and Building Design
Department of Architecture and Built Environment
Lund University
Faculty of Engineering LTH, 2012
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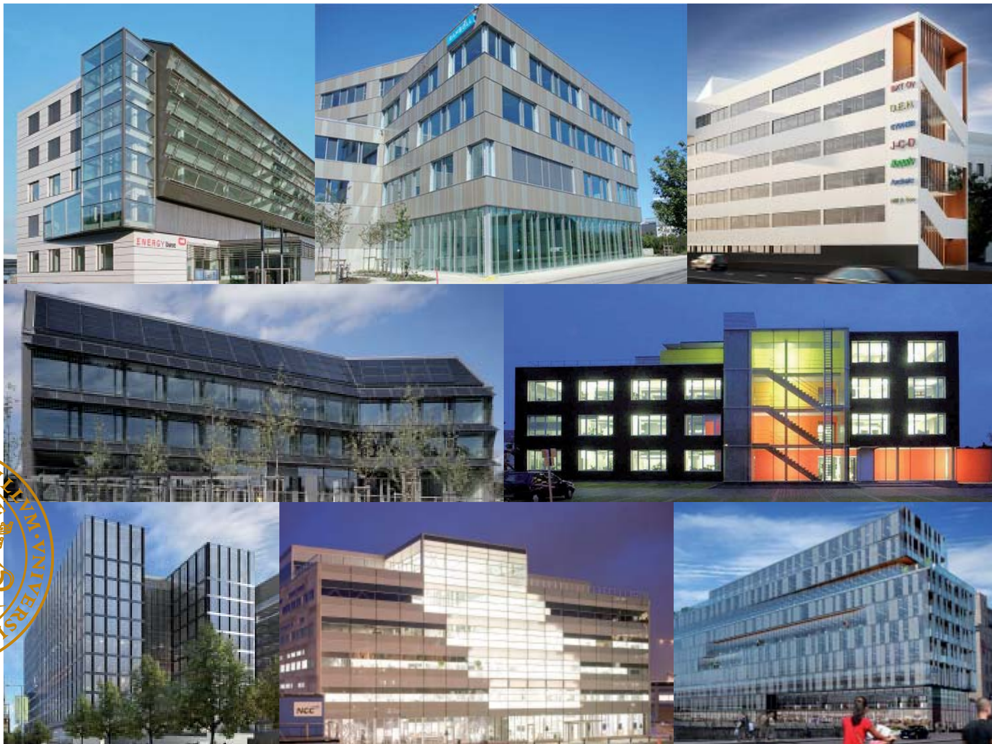

Lund University

Lund University, with eight faculties and a number of research centres and specialized institutes, is the largest establishment for research and higher education in Scandinavia. The main part of the University is situated in the small city of Lund which has about 112 000 inhabitants. A number of departments for research and education are, however, located in Malmö. Lund University was founded in 1666 and has today a total staff of 6 000 employees and 47 000 students attending 280 degree programmes and 2 300 subject courses offered by 63 departments.

Division of Energy and Building Design

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Licentiate Thesis

Keywords
Low energy, office building, dynamic simulations, end-use energy, user related electricity, internal heat gains, nearly zero-energy

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Abstract

According to the Directive on Energy Performance of Buildings, all new buildings must be nearly zero-energy buildings by the end of 2020. The most recent statistics for Sweden show that the total end-use energy to existing office buildings was around 210 kWh/m²yr in 2005. Out of this total average energy use, approximately half was electricity and half of this total electricity use was user related electricity for lighting and office equipment. These statistics indicate that there is a great saving potential in reducing the user related electricity in office buildings.

Dynamic simulations of energy use were carried out with the software IDA ICE 4 on a typical office building with perimeter cell rooms. The total end-use energy for the reference building is 139 kWh/m²yr including tenant electricity. A parametric study was carried out in order to see how different design features affect the energy use in the building. The results from the study show that airtightness, insulation levels and solar shading devices are important design features in order to decrease heating and cooling loads. However, the most crucial design features turned out to be window-to-wall ratio, demand controlled ventilation and lighting, low-power equipment and allowing a wider temperature range. The least crucial features turned out to be building orientation, thermal inertia and cooling with mechanical night ventilation.

The best practice of all parameters and scenarios were combined to a low energy office building which yields a total end-use energy of 73 kWh/m²yr for heating, cooling, facility electricity and user related electricity. The result shows that 49% energy can be saved compared to the traditional modern office building. Thus, it is possible, using a combination of simple and well-known building technologies and configurations, to have very low energy use in new office buildings. One aspect of the results concerns the user related electricity, which becomes a major energy post in very low energy offices and which is rarely regulated in building codes in Northern Europe today. This results not only in high electricity use, but also in large internal heat gains and unnecessary high cooling loads given the high latitude and cold climate.

Since this simulation study was carried out with proven technique, further research should involve simulations on an office building with the best available technique on the market. These simulations should contain also the study of different renewable energy concepts in order to see if the remaining energy demand could be covered, and a net zero-energy building achieved in Sweden.

Contents

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Lund, May 2012

Kajsa Flodberg

Abbreviations

Ach	Air changes per hour
CAV	Constant air volume flow
COP	Coefficient of performance
DHW	Domestic hot water
EPD	Equipment power density
EPS	Expanded polystyrene insulation
GHG	Greenhouse gas
GWR	Glazing-to-wall ratio
HVAC	Heating, ventilation, air conditioning
LPD	Lighting power density
Met	Metabolic rate
PMV	Predicted mean vote
PPD	Predicted percent dissatisfied
SFP	Specific fan power
SHGC	Solar heat gain coefficient
TABS	Thermo-active building systems
TSENS	Thermal sensation
VAV	Variable air volume flow
WWR	Window-to-wall ratio

1 Introduction

1.1 Background

One of the greatest environmental challenges in the world today is the fight against continuously emissions of greenhouse gases (GHGs) from human activities and the influence these have on global warming. CO_2 is the most important anthropogenic GHG which has been released in great quantities in more than 150 years of industrial activity. The major source for CO_2 emissions is the burning of fossil fuels in the production of electricity and heat. In order to stabilize the concentration of GHGs in the atmosphere at a harmless level, the United Nations Framework Convention on Climate Change (UNFCCC) was established and the Kyoto Protocol was adopted in Kyoto, Japan in 1997(UNFCCC 2012). In the protocol, industrialized countries (currently 191 states) agreed on collectively reducing the amount of GHG emissions by 5.2% compared to 1990 levels over the period 2008-2012.

1.1.1 European directive on energy performance of buildings

The Kyoto Protocol was an important starting point for energy saving initiatives taken within the European Union. In 2007, the European Union made a commitment to reduce its own GHG emissions by 20% by the year 2020 (in relation to 1990 levels), while increasing the share of renewable energy sources to 20% and reduce the total primary energy use by 20% (Europa 2012). Since buildings account for approximately 40% of the total energy use within the Union, the building sector plays a key role in achieving the climate policy. The reduction of energy use and contribution from renewable sources in the building sector are thus important measures needed to reduce the Union's energy dependency and GHG emissions. Therefore, the European Parliament and the Council of the European Union promoted the Directive on Energy Performance of Buildings (EPBD) in 2002, with a recast formally adopted in 2010, which is a legal framework for all member states aiming to improve the energy performance in buildings (European Parliament 2010).

The EPBD requires, among other things, that all member states shall:

- Apply a methodology for calculating the energy performance in buildings in accordance with the general framework.
- Take the necessary measurement to ensure that both new and renovated buildings meet the minimum energy performance requirements.
- Ensure that by 31 December 2020, all new buildings are nearly zero-energy buildings.
- Establish a system of certification of the energy performance of buildings.
- Establish a regular inspection of heating and air-conditioning systems in buildings.
- Ensure that independent control systems for energy performance certificates and building inspections are established.

It is each member state's responsibility to set minimum national standards on energy performance of buildings. This allows taking into account differences in outdoor climatic and local conditions as well as indoor climate requirements and cost-effectiveness. To comply with the EPBD, member states need to implement the directive in national building codes by 2013 at the latest (European Parliament 2010).

1.1.2 Zero-energy buildings

According to the EPBD, "*a nearly zero-energy building is a building that has a very high energy performance. The nearly zero or very low amount of energy required should be covered to a very significant extent by energy from renewable sources, including energy from renewable sources produced on-site or nearby*" (European Parliament 2010).

The nearly zero-energy building standard yet has to be defined in detail at both European and national level. However, this is not an easy task since many parameters must be considered. The concept has been described in the literature with a wide range of terms and definitions, according to a review and overview carried out by Marszal, Heiselberg et al. (2011). The first issue of consideration concerns the unit used as measurement (which must be "zero") in the balance. The unit can, for instance, be primary energy, end-use energy, exergy, CO_2 emissions or energy cost. The most frequent unit used so far is the primary energy. The next thing to discuss is whether the period of time for the energy balance is the entire life cycle, a year, a season or a month. Furthermore, the options for renewable on-site and off-site energy supply, as well as the connection options to the energy grid must be discussed. The authors also discuss whether all energy types should be included in the balance or not. A building's energy performance is often judged by the use of facility energy only. The user related energy use is seldom taken into account since it is difficult to predict and control, and since there is a lack of reasonable data. However, this approach will probably have to change in the future. There is a great potential for reducing overall energy by motivating an energy efficient behaviour. Furthermore, the user related energy becomes a more and more important part of the total energy use as the facility energy amount constantly reduces (Marszal, Heiselberg et al. 2011). Since the overall objective of the EPBD is to reduce the CO_2 emissions and primary energy use in European buildings, the most logical approach should be to include the user related electricity use. Electricity is associated with high primary energy use and a large amount of GHG.

1.1.3 Swedish directive on energy performance of buildings

The Swedish government has not yet established the national directive on energy performance of buildings that is supposed to comply with the European Directive. The building code BBR 19 (Boverket 2011b) is therefore the current regulation for energy performance of buildings.

In the Swedish building code, the energy performance is determined on the purchased (end-use) energy for heating, domestic hot water, cooling and auxiliary energy. The user related energy is not regulated at all. Primary energy is not limited and there exist no national primary energy conversion factors, which are considered as major hinders among stakeholders of the building and energy sector. However, for the last decade, an important aim of the Swedish energy policy has been to reduce the dependency of electricity in general and in particular the electricity used for heating in the building sector (Johansson, Nylander et al. 2007). This was clear when the building code was supplemented with much stricter requirements for buildings with electricity supplied heating, in 2009. Electric-heated buildings are allowed to consume only half the energy compared to buildings with other heat sources than electricity.

Until the new national energy directives are established, the only incitement for producing low-energy or nearly zero-energy buildings has been commercial or local interests. There are different voluntary energy classification concepts or rating systems for buildings such as Passive House, GreenBuilding, Breeam, Leed and Miljöbyggnad. Just recently, in January 2012, the Swedish Centre for Zero-energy buildings published a new non-residential definition of zero-energy buildings, passive houses and mini-energy buildings, the FEBY 12 (SCNH 2012). The definition of zero-energy, according to this voluntary criterion, is that on a yearly basis, the sum of delivered energy *to* the building (excluding user related electricity) must be below, or equal to, the sum of delivered energy *from* the building. The delivered energy, both to and from the building, is weighed with conversion factors developed by the Swedish Centre for Zero-energy buildings. The conversion factors are 2.5 for electricity, 0.8 for district heating and 0.4 for district cooling (SCNH 2012).

1.1.4 Energy performance of office buildings in Sweden

The most recent statistics for Sweden show that the total end-use energy to existing office buildings was around 210 kWh/m²yr in 2005. The statistics come from the "Step by step STIL" survey, an inventory of 123 existing office and administration buildings of different age carried out on behalf of the Swedish Energy Agency (Energimyndigheten 2007). The main objective of the survey was to determine the electricity use in office buildings. This data revealed that of the total average energy use, approximately half was electricity (108 kWh/m²yr) and half of the total electricity use (57 kWh/m²yr) was user related electricity for lighting and office equipment. The average lighting electricity use was 23 kWh/m²yr in the studied office buildings, ranging from 7 to 53 kWh/m²yr. This spread can be explained by differences in the number of lighting fixtures per m^2, type of fixtures used, different control systems and operation of the buildings. This result indicates, however, that there is a great saving potential only in the lighting systems in office buildings. Daylight can be utilized in a greater extent and modern efficient fixtures with control systems can be installed. Furthermore, the user related electricity can be completely shut off outside of normal office hours. The user related electricity contributes to large internal heat gains which must be cooled a great part of the year.

Regarding new office buildings, designed and constructed after the "Step by step STIL" survey, the energy performance has been significantly improved. Particularly the heating demand has been reduced because of increased insulation and airtightness levels in building envelopes, and increased heat recovery in the ventilation systems. This improvement is likely a result of the major revision of the energy regulation in the building code established in 2006 (BBR 12, BFS 2006:12), combined with the introduction of the GreenBuilding programme. However, the facility energy for cooling and ventilation and the user related electricity use for lighting and equipment has not been improved the last years. Recent statistics for non-residential buildings actually indicate that the facility energy and the user related electricity increased with approximately 30% between 2004 and 2009 (Energimyndigheten 2011). One possible explanation is the general increase in office equipment, which is not regulated in the building code or in any of the voluntary energy classification concepts. This electricity use affects the internal heat gains and generates a cooling demand. Together with the popular design of highly glazed office buildings with large solar heat gains, the cooling demand is unnecessarily high given the high latitude and rather cold climate of Sweden.

In summary, there is a great saving potential in office buildings, through reducing the electricity use for lighting and equipment, and the cooling and ventilation energy use. In Germany, a number of passive and low-energy office buildings has been constructed and evaluated. Also, research on energy efficiency potential for a passive office building has been carried out with dynamic simulations by Knissel (2002). These German experiences are clearly important for the development of future zero-energy office buildings. However, German building techniques must be adapted to the Swedish context, as climate conditions and indoor comfort criteria differ between the two countries. In Sweden, good examples of low-energy and nearly zero-energy residential houses have been built during the past decade. However, there is yet no example of a nearly zero-energy office building.

In order to bridge this gap, the project '*Energy-efficient office buildings with low internal heat gains: simulations and design guidelines*' was initiated at the Division of Energy and Building Design at Lund University. The results from this project are mainly reported in the present thesis.

1.2 Objectives

The main objective of this research is to provide knowledge to the Swedish building industry, supporting the development of cost-effective office buildings with good indoor climate and very low energy use.

By identifying important design features, possibilities and limitations for Swedish conditions, the main goal of this thesis work is to show that it is possible to reduce the total annual energy use by 50%, compared to the current requirements of the Swedish building code. This goal shall be achieved with proven technique and an investment cost of the same order of magnitude as that of a traditional modern office building.

1.3 Method

There are different methods for evaluating the energy use in buildings, for instance case studies, measurements and simulations. Within this research, thermal simulations have been performed on a reference building in order to be able to test a number of different design features in a parametric study, which would have been difficult to achieve in a real building or in a laboratory environment. It would also have been difficult to compare the performance of different case buildings, since no building design and building operation are ever the same.

In the first phase of this research, a literature review was carried out, with the main purpose to describe the current knowledge in design of low-energy office buildings. Previous studies and evaluations regarding building shape, size, envelope performance, solar protection, HVAC systems and lighting techniques were studied and the method is further described in Chapter 2.1. Secondly, existing low-energy office buildings were studied in order to identify general and specific solutions regarding building design, HVAC systems and techniques for lighting and office equipment. The approach of this study is further described in Chapter 3.1.

The results from both the literature review and the state-of-the art review of existing office buildings were used as valuable input for the parametric study, carried out on a fictive office building with the dynamic simulation software IDA ICE 4. This simulation tool was selected because it is considered the most frequently used tool for thorough energy simulations of office buildings in Sweden today. The method and the software are further described in Chapter 4.1. In the simulation study, important design features were revealed and a potential office building with a good indoor climate, which uses less than half the energy compared to a new office building, including user related electricity was presented.

1.4 Limitations

This study was carried out with a holistic approach, considering many different design parameters and a whole building energy balance. The research is therefore broad, covering architecture, building physics and building services engineering, without getting into specific technical details.

The research is limited to refined office buildings with standard operation, and new production only. There are no deeper studies of moisture risks or thermal bridges, these features are just briefly mentioned and considered. The energy performance has been analysed regarding the actual energy demand in the building. Thus, the efficiencies of different energy supply sources have not been evaluated. The purchased end-use energy was used as evaluating metric instead of primary energy. Life cycle analysis and embodied energy have not been studied and no life cycle cost calculations have been carried out in this part of the project.

1.5 Thesis disposition

A part from this introduction chapter and a final chapter with ideas for future research, this thesis contains three main chapters and a conclusion:

Chapter 2 gives a theoretical framework based on the literature review regarding different design strategies and features for energy efficient office buildings.

Chapter 3 presents the state-of-the-art review of 24 existing low-energy office buildings in Northern Europe.

Chapter 4 presents the results of the parametric simulation study where different design features were studied in detail in order to analyse their impact on the building's energy use.

Chapter 5 sums up the main results from the previous three chapters and discusses them in relation to the objectives of this thesis.

2 Theoretical framework

This theoretical framework is based upon a literature review which was carried out with the main objective to describe the current knowledge regarding the design of low-energy office buildings. Previous studies and evaluations about building shape, size, envelope performance, solar protection, HVAC systems and lighting techniques are presented. The results from this review will give valuable insight and information for the simulation study presented in Chapter 4.

2.1 Method

An extensive literature search was undertaken in 2009 by Leroux (2010), and completed with additional searches by Flodberg in the years 2010-2012, to identify studies addressing design parameters in low-energy office buildings. The electronic databases searched were mainly SAGE and ScienceDirect, additionally Web of Knowledge and Google Scholar. These electronic databases were searched for full text papers published in English from 1990 and forward. The following keywords were used for the search: building performance, energy use, indoor climate, indoor environment, thermal comfort, building simulations, glazed office buildings, mechanical ventilation, solar shading devices, computer simulation, energy simulation, thermal mass, heating, cooling, natural ventilation, office building, low-energy, passive office buildings, passively cooled buildings, energy efficient buildings, computer simulation modeling, primary energy, end energy, net zero energy, CO_2 and greenhouse gas emissions.

Reviewed journal articles, thesis and conference proceedings from countries in Europe and North-America were selected for further study due to similar climate and building techniques. Journal articles from Asia were excluded from the study because of very humid and warm climate conditions in most of these countries. The next selection was made by reading the titles and abstracts of the texts and the final selection was made by reading the complete texts to see whether they were relevant to the study.

2.2 Regulations and definitions

This section briefly presents different regulations, concepts and underlying terms used in this thesis.

2.2.1 Current Swedish regulations

In the Swedish building regulation, the annual energy use is defined as the end-use energy (purchased energy) for space heating, space cooling, domestic hot water (DHW) and facility electricity (fans, pumps, elevators, some general lighting etc.). The user related electricity, for lighting and plug loads, is not included. The specific energy use is the annual end-use energy divided by floor space. The space taken into consideration is the sum of all heated floor areas within the external walls (heated to more than 10°C), internal walls and chimneys included. This area is called tempered area (A_{temp}) and differs from the more common expression heated net floor area (NFA). The NFA is defined in many different ways, but the most common definition is that the NFA is the sum of all heated floor areas excluding the internal walls and partitions (CEN 2007b).

Recently, in January 2012, an updated, and 20% stricter, version of the Swedish building code was released (BBR 19) (Boverket 2011b). However, in this thesis, the second recent code BBR 18 (Boverket 2011a) is used since the BBR 19 code was not yet available when this thesis was initiated and since the code will not be fully implemented until 2013. According to BBR 18, non-residential buildings in the south climate zone are allowed to use maximum 100 kWh/m^2(A_{temp}),yr. An additional 0-45.5 kWh/m^2(A_{temp}),yr can be added depending on how large the ventilating airflows are during the heating season.

2.2.2 Primary energy and end-use energy

Many European countries calculate and compare primary energy instead of end-use energy. End-use energy is the final delivered energy to the building, required for heating, hot water, cooling and electricity, often also referred to as final energy. Primary energy is defined as the total amount of a natural resource needed to produce a certain amount of end-use energy, including extraction, processing, transportation, transformation and distribution losses down the stream (Sartori and Hestnes 2007; Schimschar, Blok et al. 2011). Primary energy therefore gives an indication of how resource-efficient for example a certain heating system is (Hernandez and Kenny 2010) and it gives a simplified picture of the environmental impact and resulting GHG emissions (mainly CO_2) but it does not deal with other environmental issues such as resource scarcity, acidification and ecotoxicity (Levin 2010). The final end-use energy is converted into primary energy using standardised conversion factors. These multiplicative coefficients vary for each energy carrier and country (Sartori and Hestnes 2007). In Germany, for example, electricity is multiplied by 3.0 and biomass by 0.1 (DIN 4701) and in Switzerland electricity is multiplied by 2.0 and biomass by 0.7 (MINERGIE 2010), all depending on the country's energy production system and mix. In Sweden, there are no national conversion factors at this time. A weakness with primary energy is the difficulty to determine accurate conversion factors. According to Johansson, Nylander et al. (2007), end-use energy is more exact and easier to calculate and measure since it is in fact the purchased energy. Persson, Rydstrand et al. (2005) claim that end-use energy is considered a better and more precise approach when describing a building's energy performance and comparing energy-efficiency of different building envelopes.

2.2.3 Heating and cooling degree days

The outdoor temperature has a great impact on the building energy use. Degree days are simplified historical weather data, widely used among energy consultants and energy managers for calculation, gross predictions and comparison of energy use in buildings. Degree days are often used for weather normalisation of monitored energy data to compensate for the variation in outdoor climate in order to compare different operating years and buildings on similar grounds (BizEE 2011). There are a number of various ways to calculate degree days. The most accurate way is by using hourly weather data and integrating the difference between the ambient temperature and the balance temperature of the building (Layberry 2008). Degree days provide a measure of how much (in degrees) and for how long (in days) the ambient temperature was below or above the balance temperature. The balance temperature is also called the equilibrium or base temperature, which is the external temperature at which the building starts to be heated or cooled (Mitchell and Beckman 1989; Layberry 2008). In reality, each building has its own balance temperature, but the general default base temperature, when not calculating the exact losses and gains, has for many years been 15.5°C in the UK (Layberry 2008) and 17°C in Sweden (Boverket 2009b). However, the true value can be even lower than 10°C for well insulated buildings and office buildings with high internal gains (Jardeby, Soleimani-Mohseni et al. 2009). Moreover, the base temperature of most buildings varies throughout the year. The gains in a building are affected by the sun, wind, and patterns of occupancy (BizEE 2011). Due to the difficulties in deciding the accurate base temperature, degree day based calculation methods are simple and inaccurate tools to use. In this thesis heating and cooling degree days are not used for calculation of energy use. They are simply used to describe and compare different climates in chapter 3 and to give an indication of the required heating and cooling energy.

2.3 Important design principles of low energy office buildings

A well-known design strategy for low-energy buildings and passive houses is the so called “Kyoto Pyramid”, which was introduced by Rødsjø and Dokka and presented internationally for the first time as part of IEA Task 37 (Jansson 2010). A modified version, adapted for office buildings, is presented in this report in Figure 2.1 with inspiration from “Guidelines for energy efficiency concepts in office buildings in Norway” by SINTEF Building and Infrastructure (Haase, Buvik et al. 2010). The strategy is based on the principle “the most energy-efficient kilowatt-hour is the one we never use” and works as guidance for how to prioritise when designing low-energy buildings. It stresses the importance of reducing the energy demand before adding systems for energy supply. This paradigm promotes robust solutions.

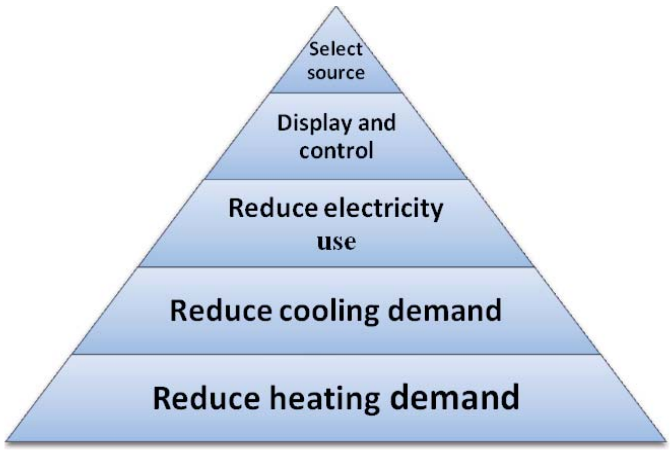

Figure 2.1 Modified version of the Kyoto Pyramid for office buildings as presented by Haase, Buvik et al. (2010)

Step 1 Reduce the heating demand

The first and most important step is to reduce the transmission and ventilation heat losses as much as possible since the heating energy is the most dominating energy type in the North European climate. The key elements of this strategy are: a good building design, a well-insulated and airtight building envelope, an optimized window design, efficient heat recovery in the ventilation system, and demand based airflows.

Step 2 Reduce the cooling demand

The cooling demand can be reduced by a good solar control strategy and by reducing internal heat gains from equipment and lighting. Further cooling reductions can be obtained by allowing a larger temperature variation in the indoor air and by using passive cooling and free cooling to a high degree.

Step 3 Reduce the electricity use

Electricity shall be minimized by reducing the facility and the user related electric energy with efficient pumps and fans (low specific fan power), demand based airflows and low installed power for lighting and equipment and by shortening the hours of operation and avoiding standby losses.

Step 4 Display and control the energy use

Further reductions can be obtained by choosing easy and user-friendly control and monitoring systems, and by designing for demand-controlled ventilation and lighting and wider temperature set-points.

Step 5 Select energy source

The last step consists of selecting energy sources to cover the remaining energy demand. Examine to what extent renewable sources like solar energy and geothermal energy can be used and make sure to reduce the emissions of GHG.

In this thesis, the emphasis is clearly on the first three steps, i.e. reducing heating, cooling and electric energy.

2.3.1 Building envelope and building shape

Regarding building design and energy saving measures in the building envelope, a majority of the conducted studies have been carried out on dwellings and residential buildings with a predominant heating demand.

For office buildings, which struggle with both heating and air conditioning issues, the literature mainly addresses the design of HVAC systems.

Shape and compactness

It is generally known that the shape of a building has an impact on the transmission heat losses and the uncontrolled air leakage through the building envelope. A relatively large envelope surface increases the exposure to the environment and the ambient air. Building compactness (C) is generally defined as surface-to-volume ratio, $C=S/V$ [m^{-1}], where S is the envelope surface [m^2] and V is the internal volume of the building [m^3] (Depecker, Menezo et al. 2001; Gratia and De Herde 2003). Typical good values for compact office buildings are 0.1-0.3 according to guidelines by Haase, Buvik et al. (2010). Different geometrical shapes have different surface-to-volume ratios where the sphere has the lowest S/V and the pyramid has the highest S/V. The size of the overall volume has a great effect on the surface-to-volume ratio where a large size results in a small surface-to-volume ratio. Take, for example, a cube with the side "a". The surface-to-volume ratio is in this case $6a^2/a^3$ and it will decrease with an increased "a". Therefore, building compactness is sometimes expressed as the relative compactness, $RC= C/C_{ref}$ [-], where C_{ref} is the compactness of an ideal reference building with the same volume (for orthogonal buildings, the ideal shape is a cube) (Ourghi, Al-Anzi et al. 2007). Hence, the most compact building has a relative compactness close to 1.0 and different shapes with the same volume can vary between 0.6 and 1.0 (Pessenlehner and Mahdavi 2003). According to a simulation study performed on an office building in Belgian climate (Gratia and De Herde 2003), the shape of the building plays a significant role for the energy use, and a non-compact building shape results not only in more exposed surface but also in more joints which cause larger thermal bridges. The authors claim that it is even preferable to reduce surface area rather than to add insulation since compactness decreases both energy and construction costs. Multiple floors and a cubic shape bring compactness.

Depecker, Menezo et al. (2001) discovered, in a simulation study of 14 different building shapes in two different French climates, that the colder the climate (>2500 heating degree days, which corresponds to Paris), the stronger the correlation between shape and energy use. An increase in compactness by 0.1 m^{-1} increases the energy use with almost 4 kWh/m^2yr for the simulated apartment buildings with rather poor insulation compared to today's standard. No correlation was found for the warm climate in Southern France. This study indicates that the building shape effect may be significant in Swedish climate, at least for residential buildings. In another context, Pessenlehner and Mahdavi (2003) examined whether the simple correlation between compactness and heating load is reliable regardless of building shape (self-shading aspect), glazing amount and building orientation. The authors concluded that more compact buildings indeed result in somewhat smaller heating loads, when it comes to residential buildings in Austrian climate. Furthermore, the correlation between RC and heating load is strong despite different shapes, glazing designs and orientations. On the other hand, the study showed that the overheating tendency increases with increasing RC, however with a relative week correlation. This indicates that the correlation between compactness and total energy use may be week, or even reverse, for office buildings with cooling loads.

Insulation levels

The insulation levels, mainly in residential buildings but also in office buildings, have increased greatly during past decades. It has come to a point where building professionals are asking whether they should go even further or if more insulation only leads to higher material and construction costs, to unused floor space and to higher risks. One risk with more insulation is the increase in overheating hours, which is particularly severe in office buildings with active cooling. Gratia and De Herde (2003) found, in a simulation study of an office building in Belgian climate, that for the same level of internal gains, a better-insulated and a more airtight building gets warmer in the summer than a similar building with less insulation and therefore needs more cooling energy. On a yearly basis though, they showed that the total energy consumption is much smaller for a well-insulated office building.

Another risk with high insulation levels is the potential risk of moisture problems and mould growth in wooden constructions due to a different micro climate within the elements (Berggren, Stenström et al. 2011). Thicker insulation will lead to colder outer parts of walls and roof structures, partly because of the increased heat resistance, but also because of the natural convection that will occur within a continuous, thick insulation layer. The moisture distribution in the wood frames follows the temperature distribution in the structure, and lower temperatures correspond to higher relative humidity (Geving and Holme 2010; Uvslökk, Skogstad et al. 2010). Geving and Holme (2010) carried out simulations and laboratory experiments on different envelope constructions in order to determine the risk of moisture in well-insulated constructions. The authors observed an increase in relative humidity in the constructions during winter due to thicker insulation, and a negligible increase during the summer. On the other hand, they found that other factors, like resistance in the vapor barrier and the humidity in the indoor air, actually influenced the relative humidity more than increased insulation thickness. This result indicates that the risk of mould growth in well-insulated office constructions may not be severe since office buildings in general have dryer indoor air compared to residential buildings, because of a low internal moisture production and high ventilation rates. It is important though, to be aware that it takes longer time to dry out moisture in wood frame walls when the insulation is thick. Not only is the total amount of built-in moisture higher due to more wood in a thicker wall, but the insulation increases the average vapor resistance from a point in the structure to the outdoor air (Geving and Holme 2010). Well-insulated constructions are not as forgiving as constructions with less insulation are. It is therefore crucial to protect the structure from water during the construction phase and allow it to dry to a reasonable level before closing it with a vapor barrier (Samuelsson 2008).

For a large office building with many floors, it is more important to focus on the insulating performance of walls and windows than roof and floor since the façade represents a large portion of the total envelope surface. There are no specific requirements for insulation thicknesses in the Swedish building code today. The passive house recommendations might therefore represent a useful starting point in order to find suitable insulation levels for low-energy office buildings. There are rules and recommendations for U-values both in the International passive house standard and the Swedish passive house criteria. According to the Passive house Checklist ((Passive House Institute, PHI 2012a) the opaque envelope elements must be super-insulated with U-values of maximum 0.15 W/m^2°C and if possible 0.1 W/m^2°C. The Swedish passive house recommendation also strives for 0.1 W/m^2°C in the same building elements. Windows must have a U-value of 0.8 W/m^2°C or less (frames included) according to the most recent criterion (Nollenergihus 2012). The former criterion required a maximum U-value of 0.9 W/m^2°C (FEBY 2009).

Airtightness

An important parameter in terms of energy use for heating and cooling a building is the airtightness of the envelope. Uncontrolled air leakage yields higher energy consumption since the air that leaks into and out of the building envelope does not pass the heat exchanger in the air handling unit. Additionally, uncontrolled air leakage can contribute to comfort problems in terms of draught, which can result in raised indoor temperatures in order to improve comfort. Airtightness in large and complex buildings is difficult to measure, and the knowledge of actual airtightness in Swedish office buildings and its effect on the energy balance is generally very low. In 2009, Blomsterberg completed measurements in a modern glazed office building, The World Trade Center, in Malmö. The measured airtightness (blower door EN 13829) was 0.61 l/sm^2 at 50 Pa pressure difference which is well below the former requirement in the Swedish building code BBR of 1.6 l/sm^2 at 50 Pa pressure difference (Blomsterberg 2009).

The envelope airtightness is not regulated in the Swedish building code today, but the Swedish passive house criterion requires an airtightness of maximum 0.3 l/sm^2 at 50 Pa pressure difference (SCNH 2012). The international Passive House Institute requires maximum 0.6 ach at 50 Pa pressure difference (PHI 2012a). For comparison of the two criteria, 0.3 l/sm^2 (q_{50}) corresponds to 0.6 ach (n_{50}) when the compactness is approximately 0.55 m^{-1}, which is a rather poor compactness. The more compact a building is, the stricter is the Swedish requirement. For a really compact building with a compactness of 0.1 m^{-1}, the Swedish requirement corresponds to only 0.1 ach. The different quantities and methods are defined in European Standard EN 13829 (CEN 2000).

Thermal mass

Opinions diverge whether a high thermal mass and thermal inertia can actually save heating and cooling energy. Many claim at least that thermal mass prevents overheating at critical hours and creates a better and more stable indoor climate with smaller temperature swings. The desired effect is that heat from solar gains and internal gains during the day is stored in the construction and then slowly released into the room at a later time, reducing both heating peak loads in the winter and cooling peak loads in the summer. The effect is greater when it comes to saving cooling energy since the cooling peak load has a diurnal variation and effectively can be smoothened with high thermal mass (Kalema, Jóhannesson et al. 2008). The heating load variation is mainly annual. Thermal mass is therefore more effective in non-residential buildings which have large heat gains during the day and no operation during the night when the heat is released. Thermal mass is the construction mass incorporated into floors, external walls and partitions (Balaras 1996) and it describes the ability to provide inertia against temperature variations (Dodoo, Gustavsson et al. 2012). For the material to effectively store heat, it must have a high density and thermal capacity in order to absorb and store heat, and a proper thermal conductivity which determines the time lag for absorbing and releasing heat (Balaras 1996; Dodoo, Gustavsson et al. 2012). The effect of thermal mass also depends on the actual heating and cooling loads which are affected by building design, insulation levels, outdoor climate, solar radiation through windows, building orientation, ventilation rate, occupancy patterns and internal heat gains (Balaras 1996; Kalema, Jóhannesson et al. 2008). This makes it very difficult to measure the real effect of thermal mass since it is almost impossible to ensure that the conditions in the compared buildings or rooms are exactly the same. Many researchers claim that only the mass and heat capacity of the innermost layers in a building plays an active role in heat accumulation and temperature reduction (Balaras 1996; Gratia and De Herde 2003; Di Perna, Stazi et al. 2011). Diurnal temperature variations penetrate maximum 10 cm in a material (Isfält and Bröms 1992). This parameter is called internal thermal inertia or internal areal heat capacity. Suspended ceilings and carpets reduce the internal thermal inertia since these materials have low heat capacity compared to, for example, concrete.

Results from a variety of experimental and simulation studies around the world report very different energy savings due to thermal mass and thermal inertia, ranging from just a few negligible percent up to more than 80 percent according to a recent review (Aste, Angelotti et al. 2009). Södergren, Isfält et al. (1992) simulated the energy demand and thermal climate in industry buildings with different thermal capacity. The simulation results showed that the influence of thermal capacity is inferior other parameters, such as thermal insulation, window area, solar shades, ventilation, airtightness and internal heat gains. Dodoo, Gustavsson et al. (2012) compared the effect of thermal mass on space heating energy and life cycle primary energy between concrete- and wood-framed residential buildings in Sweden. Their results indicated that the influence of thermal mass on final space heating demand is small (0.5-2.4%) and that this small saving is outweighed by the larger life cycle primary energy use for the concrete alternative. Høseggen, Mathisen et al. (2009) studied the potential energy savings of exposing concrete in the ceiling compared to a suspended ceiling in a passively cooled office building in Norway. Their results show that there are only minor differences in total heating energy demand (<3%). On the other hand, the exposed concrete reduces the hours of excessive temperatures (>26°C) by a factor of two, and the maximum indoor air temperature was reduced with more than 1°C for the warmest day of the year. The effect was greater if the internal heat gains were larger. Aste, Angelotti et al. (2009) carried out a parametric study in EnergyPlus on the effectiveness of thermal inertia in 24 different external walls in a model of a residential building in Milan in Northern Italy. They varied the operational parameters (ventilation rates and solar shading devices) in order to get maximum effect. The results showed that for the design when the maximum heating energy saving potential of 10% occurred, the cooling energy saving was only 1% and for the design when the maximum cooling energy saving potential of 20% occurred, the heating energy saving was non-existent. Kalema, Jóhannesson et al. (2008) investigated the effect of thermal mass in an actively cooled apartment building in a Nordic climate. The simulations were carried out with seven different calculation programs. The results indicate that going from extra-light to massive constructions decreases the need for cooling energy (13-21%) and also, slightly, the need for heating energy (5-7%) in well-insulated Nordic buildings. The authors also showed that the effect of thermal mass on heating energy is clearly higher in south Sweden (Malmö) than north Sweden (Luleå). Furthermore, the simulations indicated that the larger solar gains and internal gains, the larger the effect of thermal mass. Similar results were established by Di Perna, Stazi et al. (2011) who carried out an experimental and parametric study of a school building with different thermal internal inertia in different climates. In Loreto in central Italy, the discomfort hours were reduced from 21% to 15% but in London no difference was observed because there was not really a problem with overheating from the beginning. According to a review by Balaras (1996), heat storage is most effective when the diurnal variation of ambient temperature exceeds 10°C. Balaras also claimed that creating a time lag between the peak load and the peak in room temperature is most important in rooms towards the south and west. An eight hour time lag is sufficient to delay the heat transfer from midday until evening hours.

A couple of studies indicate that medium mass construction levels have the best energy-saving performance and that further improvement in thermal mass, from medium to high mass, generally has a negligible effect (Morgan and Krarti 2007; Kalema, Jóhannesson et al. 2008). Artmann, Manz et al. (2008) studied the effect of thermal mass on cooling with natural night ventilation in a model of a standard office room with the building simulation programme HELIOS. They found that the impact of thermal mass in internal walls depends on room geometry. In a large open plan office, the ratio of wall-to-floor area is small and the effect of the walls' mass thus becomes less important. However, thermal mass in the ceiling is always favourable. A concrete ceiling in direct contact with the room air reduced overheating (>26°C) by a factor of two in the study compared to a suspended ceiling.

Potential disadvantages when it comes to high thermal mass and internal thermal inertia are seldom discussed in literature. As mentioned above, Dodoo, Gustavsson et al. (2012) discussed that the savings in heating and cooling energy due to higher mass can be outweighed by the larger life cycle energy use for concrete compared to wood-frame constructions. Other weaknesses can be higher material costs and comfort problems due to radiation from cold surfaces in the morning. Furthermore, indoor temperatures can continue rising after a heat wave even though the ambient temperature is cooler because of the stored heat that is released. Finally, exposed internal thermal inertia often conflicts with the placing of sound absorbers in an office environment since ceiling absorbers and floor carpets are not used. Without ceiling absorbers, ventilation ducts are visible, which might have a negative influence on the interior design.

Glazing, daylight and solar control

The positive effects of fenestration and daylight access in buildings are both esthetical and physical. Glazed facades give the design a light and open appearance and provide a view out for the occupant. It also allows the occupant to keep track of time and weather conditions. In a literature review, Dubois and Blomsterberg (2011) stress the importance of daylight for occupants' health and well-being and claim that most people prefer daylight to electric lighting. In addition, windows offer a visual rest center to relax eye muscles on a distant point (Gratia and De Herde 2003). On the other hand, too much glazing has the opposite effect. It often results in unwanted solar gains and direct sunlight with both thermal and glare discomfort. Thus the shading devices will be used much of the time, which will reduce the amount of daylight and all its positive effects, and in addition increase the electric lighting. Excessive glazing will also increase the energy use for heating and cooling due to transmission heat losses in the winter and unwanted solar gains in the summer. Poirazis, Blomsterberg et al. (2008) carried out dynamic simulations with IDA ICE on a typical large office building in Sweden in order to study the impact of different glazing-to-wall ratios (GWR) on energy use. The simulation results showed that both heating and cooling energy increased strongly with increased GWR. The total energy use increased with 23% when GWR was increased from 30% to 60% and with 44% when GWR was increased from 30% to 100%. Furthermore, a larger GWR does not necessarily reduce the electricity use for lighting because of glare problems and more frequent use of shading devices.

One important design aspect is thus to optimize the size, shape, position and orientation of windows in low-energy office buildings, securing adequate daylight but preventing glare and overheating problems. Dubois and Flodberg (2012) carried out a parametric study in the dynamic daylight simulation program DAYSIM in order to find reasonable glazing-to-wall ratios (GWR) for peripheral office rooms at high latitudes. A typical single office room was modeled and parameters studied were, among others, climate, orientation, GWR, surface reflectance, and solar shading control. The main metrics for evaluating available daylight were "continuous daylight autonomy" (DA_{con}) and "daylight autonomy maximum" (DA_{max}). Daylight autonomy is defined as the percentage of the working hours in a year when the illuminance requirement is met by daylight alone and DA_{con} gives partial credit to the amount of daylight that is available at a given timestep relative to the required amount of daylight illuminance.

Thus, if 500 lx is required and 400 lx is provided by daylight, DA_{con} is 400/500=80% for that timestep. Levels of more than 80% represent "excellent" daylight designs and levels of 60-80% represent "good" daylight, as introduced by Rogers and Goldman (2006). DA_{max} is defined as the percentage of times during a year when the illuminance is at least 10 times higher than the benchmark value, which indicates direct sunlight and a high risk of glare discomfort. The proposed acceptable limit is maximum 5% and above this limit, the occupants are expected to use solar shading devices (Rogers and Goldman 2006).

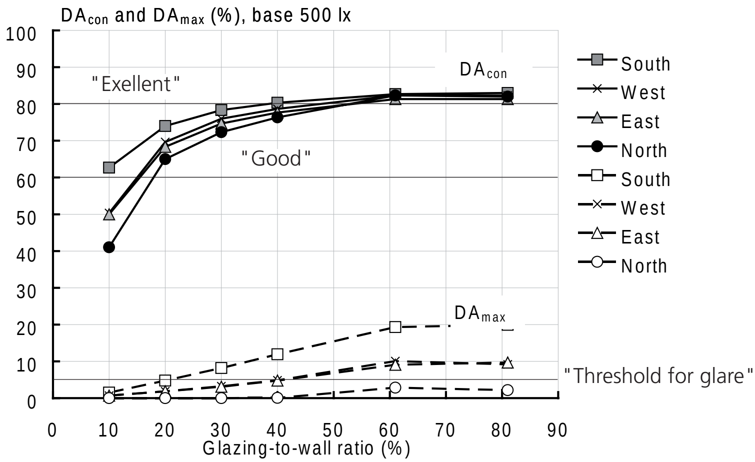

Figure 2.2 *DAcon and DAmax as a function of GWR in relation to orientation for a single office in Stockholm. A floor average during office hours, no blinds. With permission from Marie-Claude Dubois 2012.*

Some of the simulation results for Stockholm are shown in Figure 2.2. This figure shows that the south orientation has the highest DA_{con} and the north orientation has the lowest DA_{con}. East and west orientations have similar DA_{con} and DA_{max}. The same trend was found for all studied climates. All orientations show the same interesting relationship between GWR and available daylight. The DA_{con} rises steeply when GWR is increased from 10% to 30% and almost stabilizes for GWR larger than 40%. The benefits of increasing GWR from 40% to 60% are marginal and nonexistent for GWR larger than 60%. Regarding direct sunlight and glare, the south orientation has the highest risk of glare, already at GWR 20%. For east and west orientations, the DA_{max} limit is reached for GWR 30% and for north orientation there seems to be mainly diffuse daylight and no glare problem for any GWR. The authors' general design advice was to strive for GWR 20% on the south façade, GWR 30% on east and west facades and finally GWR 40% on the north façade, considering daylight aspect only. These glazing ratios will provide "good" daylight autonomy (DA_{con} = 70%) and meanwhile keep the risk of glare below the acceptable limit (DA_{max}< 5%).

The authors also performed additional thermal simulations of the peripheral office room in IDA ICE for analysis. The result indicates that the smallest GWR always yields the lowest total energy use on all facades, even for the south orientation with a lighting system controlled with daylight dimming. Furthermore, the study shows that there are negligible differences in DA_{con} between Stockholm, Malmö and Gothenburg. Östersund has slightly more limited daylight autonomy. The main conclusion of the study reveals that although DA_{con} is more limited in the Swedish cities compared to cities at lower latitude (here Montreal), it is still possible to achieve good to excellent daylight design with reasonable glazing-to-wall ratios of 20%-40%, depending on orientation, glazing visual transmittance and inner surfaces' reflectance in a peripheral office space.

An additional, similar study was carried out by Dubois and Du (2012) for a landscape office with four rows of work stations. This study shows that the good and excellent levels achieved in peripheral office rooms are more difficult to achieve in deep landscape offices in Stockholm. For the first work station, right next to the window, DA_{con} is "good" to "excellent" for all orientations and glazing-to-wall ratios above 20%. For work stations further into the room on the other hand, DA_{con} decreases significantly and large GWRs are needed to achieve "good" daylight. GWR 80% is required to obtain "good" daylight autonomy at the third work station and no GWR can provide "good" daylight autonomy at the forth work station from the façade, regardless of orientation. The study also shows that a south orientation provides significantly more daylight than a north orientation. However, the risk of glare at the first work station is very high for all orientations except the north, and a high DA_{max} will trigger the use of blinds which will reduce daylight autonomy, especially for work stations located further away from the window. Dubois and Du (2012) gave the advice to place circulation or informal meeting spaces along the south, east and west façades, and computer work stations further into the room. This would encourage keeping the window view open and free from shading devices. On the north façade, work stations can be positioned directly close to the window since there is no direct sunlight. Instead, the authors suggested that deep landscape offices perhaps should not be planned at all on north facades since they require large GWR which will increase heat losses. The study also shows that an increase in ceiling height and additional glazing in the upper part of the facade has a positive effect on

DA_{con} for work stations located in the back of deep rooms. In addition, separated solar shadings for lower and upper parts of the windows can provide daylight further back in the room even when blinds are down on the lower part in order to prevent glare discomfort. Another interesting result from the study is the large impact furniture has on daylight autonomy in deep landscape offices. Typical office furniture can reduce DA_{con} with up to 35%, and this aspect must therefore be considered when studying and planning landscape offices.

One important parameter to consider when performing daylight and energy simulations is the operation of blinds. The blinds have a large impact on heating, cooling and lighting energy use and the usage can be difficult to predict when the blinds are manually controlled. Many occupants are so called “passive” users and forget to pull up the blinds again when they are not required. Dubois and Blomsterberg (2011) discuss that a number of researchers have attempted to investigate whether occupants in office buildings use their shading devices according to predictable patterns and if these patterns are dependent on window orientation, time of day, sky conditions, season, latitude and workstation position. Leslie, Raghavan et al. (2005) claim that it has been found that occupants’ decisions to manually close their blinds correlate with the solar beam irradiance on an interior task plane, but that the actual irradiance threshold value is under debate. They refer to two different blind control models, by Reinhart and Newsham. In Reinhart’s model, blinds are lowered if beam irradiance exceeds 50 W/m^2 and they remain down until the following morning. In Newsham’s model it is assumed that occupants open their blinds in the morning and close them during the day if beam irradiance exceeds 233 W/m^2. Dubois and Blomsterberg (2011) found in their review that solar radiation levels above 250-300 W/m^2 on the glass normally are reported to trigger blind utilization and for radiation below 50-60 W/m^2, occupants do not use shading devices. In various simulation programs used in Sweden, default solar radiation values are 100 W/m^2 (inside glass, IDA ICE), 150 W/m^2 (ParaSol) and 250 W/m^2 (VIP Energy), showing that there is not yet any general agreement on the appropriate threshold level. Automatic blind management was studied by van Moeseke, Bruyère et al. (2007) in TRNSYS. They studied the impact of management strategies for external shading devices in low-energy buildings in Belgium. The results showed that a control mode based on irradiation level only causes an important increase in energy demand for heating due to the decreased solar gains during winter. The authors suggest a combination of both irradiation and temperature control. Having a temperature set-point of 23-24°C combined with an irradiation level of 200-300 W/m^2 is ideal in order to reduce both over-heating hours and closed mode hours. Goethals, Breesch et al. (2011) carried out thermal simulations of an office building with

movable external blinds automatically lowered when the incident solar radiation exceeded 150 W/m^2.
Gratia and De Herde (2003) presented various guidelines for good daylight design. They claim that the higher the position of the window is, the better the back of the room is lit and the deeper the naturally lit zone is. Furthermore, ceiling height and ceiling reflection plays an important role for the daylight distribution further into the room. The importance of ceiling reflectance is also mentioned in the review by Dubois and Blomsterberg (2011), which stresses Reinhart's findings in 2002, that the majority of daylight that penetrates beyond the 1st work station is reflected from the ceiling at least once and that increased ceiling reflectance leads to a more uniform distribution of daylight throughout the space. Gratia and De Herde (2003) recommend the following inner surface reflection factors (R):

Walls	$R > 0.5$
Ceiling	$0,7<R<0,8$
Floor/desk	$R >0.5$

Tables and desks often represent a great part of the office space and therefore their reflectance can have as much influence on indoor daylight levels as the floor. To improve the penetration of light in a room it is preferable to keep floors and desks relatively clear (Gratia and De Herde 2003). A bright desk color is also beneficial because it helps reducing the contrast between paper and desk surface, which improves the visual comfort. On the other hand, too reflective horizontal surfaces can lead to disturbing reflections and glare (Dubois and Blomsterberg 2011). Dubois and Flodberg (2012) showed that the effect of inner wall reflectance for daylight penetration can be significant and even as important as the effect of orientation, especially for small GWR.

Orientation

The impact of building orientation on energy use and thermal comfort highly depends on the design of the facade. Orientation must be considered when designing glazing areas, solar shading devices and active solar energy systems. Poirazis (2008) showed, that for an office building with identical short sides and long sides, orientation has a negligible impact on energy use. It is possible that the impact of building orientation is negligible when performing a whole building annual energy balance. However, orientation ought to have great impact on thermal and lighting comfort in the rooms along the façade due to direct solar radiation. Gratia and De Herde (2003) claim that for a rectangular building, a north-south building orientation is better than an east-west orientation when it comes to reducing the total heating and cooling demand. They showed that having the largest window area towards north reduces the cooling demand more than it increases the heating demand. Artmann, Manz et al. (2008) argue that if solar gains are low compared to internal heat gains, the effect of façade orientation on overheating degree hours is relatively small. However, for an office room oriented to the north, the overheating hours can almost be half compared to the other orientations. Haase, Buvik et al. (2010) claim that windows on the east and west facades often result in overheating hours because of the low solar angles in these directions, which are difficult to shade.

2.3.2 HVAC

There are a number of different supply and distribution strategies for heating, ventilation and air conditioning (HVAC) in office buildings. The role of the HVAC system is to secure a healthy indoor environment with a good air quality and thermal climate. The design of the HVAC systems highly affects the building's energy use. Efficient supply and distribution strategies have been studied in several low-energy office buildings in Europe. Natural ventilation, cooling with night ventilation, thermo-active building systems (TABS), earth-to-air heat exchangers and geothermal bore holes are common techniques which are reviewed in this section. In Sweden, usage of such innovative supply systems and HVAC techniques are still limited. The district heating and cooling network is well developed and according to recent statistics (Boverket 2010), more than 80% of the Swedish non-residential buildings use district heating. As much as 90% of the 123 existing office buildings in the investigation performed by the Swedish Energy Agency use district heating. The remaining buildings are mainly heated with electricity and gas. Regarding cooling supply, compressor chillers still dominate in Sweden (68%) but district cooling is getting more and more frequent in new office buildings (24%) (Energimyndigheten 2007). Regarding ventilation, 95% of the non-residential buildings in Sweden have a mechanical balanced ventilation system (Boverket 2010).

Heating

Hot water central heating systems are most common in Swedish buildings today, in particular radiators with central control of the water temperature (depending on ambient temperature) and individual control of the water flow to each radiator (Jardeby, Soleimani-Mohseni et al. 2009). Other hydronic systems are fan-coil batteries and floor heating. A fan-coil battery is a room unit with a fan and a battery which is supplied with warm or cold water. Room air is circulated through the unit where it is heated or cooled with a rather fast reaction time. A floor heating system has much larger heat-emitting surface compared to a radiator, which admits a lower water temperature. However, the floor heating system reacts slowly to adjustments. Heating with ventilation air is possible when the heating demand is rather small. The air is heated with heating batteries in the supply ducts. The system is more difficult to control, but in return it allows a faster temperature adjustment. The normal strategy in office buildings is to have a combination of air and water distribution, with a central heating battery in the air handling unit, for pre-heating the supply air, and a hydronic room unit for additional heating (Jardeby, Soleimani-Mohseni et al. 2009).

Cooling

There are other cooling supply systems beside district cooling and conventional electric compressor chillers. Absorption chillers resemble the compressor chillers but they are run on a heat source instead of electric power. For instance, district heating, combustion heat or excess heat from the building can be used as heat source. Absorption chillers require very little electricity, but in return the coefficient of performance (COP) is low. Evaporative chillers are an alternative when all-air is used for cooling distribution. The device cools the warm and dry air by making it pass liquid water and evaporate while heat is consumed. The cooling efficiency is further improved if the air is first dehumidified. This combination of sorptive dehumidification and evaporative cooling is called desiccant cooling and is only possible for airborne cooling (Jardeby, Soleimani-Mohseni et al. 2009).

For cooling distribution, both water and all-air systems are common in Swedish office buildings (Jardeby, Soleimani-Mohseni et al. 2009). Hydronic cooling systems are not as space consuming as airborne systems which requires large ventilation ducts. The most common hydronic system is having active cooling baffles which are placed under the ceiling. The warm air in the room is transferred to the cold water in the baffles with natural convection. The baffles are normally designed with supply and return water temperatures of 14 and 17°C. The surface temperature of the cooling baffle must always be warmer than the dew point of the room air in order to avoid condensation. As mentioned previously, hydronic fan-coil batteries can be used both for heating and cooling. The fan-coil battery has an enhanced cooling efficiency compared to the cooling baffle but on the other hand, it makes more noise (Källman, Hindersson et al. 2004). Cooling by removing heat surplus with air is convenient since fresh air needs to be provided to the building with the ventilation system anyway. Moreover, the ambient temperature in Sweden is colder than the indoor temperature a large part of the year and free cooling with outdoor air can be utilized to a great extent. The remaining cooling is provided by the cooling coil in the air handling unit. However, the specific heat capacity of air is low and large airflows and great amounts of fan energy are required to meet the cooling load (Källman, Hindersson et al. 2004).

Free cooling

Free cooling is defined as cooling when a natural heat sink is used for cooling, for instance the outdoor air, geothermal bore holes and lake water. With an airborne cooling system, the cooling demand can be met by the outdoor air as long as it is colder than the supply air temperature in the air handling unit (approximately 16°C) which actually occurs most of the time in Sweden (80-90%) (Nilsson 2001). Cooling towers with free cooling from outdoor air can be used for hydronic cooling systems when the ambient temperature is colder than 7-10°C. Reversible heat pumps can be used both for heating and cooling production. Geothermal heat pumps are efficient for cooling since free cooling from the bore hole can be extracted while the bore hole is charged with heat for the winter season. When the free cooling from the bore hole is insufficient, the pump is activated to raise the cooling efficiency (Jardeby, Soleimani-Mohseni et al. 2009). One form of free cooling is night cooling where the thermal mass in the building construction is used as heat sink. Cooler night air is stored in the interior materials and some of the excess heat during day will be consumed for re-heating the materials. Night cooling is often improved with increased airflows during night. Another free cooling system exploiting the building thermal storage, is thermo-active building systems, TABS. TABS cool and heat the building structure using tube heat exchangers integrated with building elements (commonly in the concrete floors). TABS are thermally activated by either water or air, and operate with temperatures close to the room temperature. Thus free energy from surrounding heat sinks such as the ground, ground water and ambient air can be used. The cooling water temperatures are often 18-22°C and the heating water temperatures no more than 27-29°C. TABS can also be called slab cooling and heating, underfloor cooling and heating, concrete core temperature control, hydronic radiant heating and cooling. In buildings with TABS, room temperatures cannot be individually or quickly adjusted. TABS were introduced in office buildings in Switzerland in the early 1990s. During the last decade TABS have been gaining an increasing market share in Western Europe. (Bine 2007; Henze, Felsmann et al. 2008).

Mechanical ventilation

A conventional mechanical ventilation system can be designed with constant or variable airflows. In order to make the fans more energy-efficient, the total pressure drop in the ventilation system must be reduced. To reduce the overall use of electricity, the size of the airflows and hours of operation are crucial. The energy efficiency of a mechanical ventilation system is often characterized by the specific fan power value (SFP). SFP is a measure of the electrical power that is needed to drive all the fans in the ventilation system, relative to the amount of air that is circulated through the fans [kW/m^3s^{-1}]. The building code recommends that the SPF value for a new building project should not exceed 2.0 kW/m^3s^{-1} (Boverket 2011b).

In a constant air volume flow (CAV) system, the airflow is kept constant but the supply air temperature is allowed to vary depending on room temperature or ambient temperature. The supply air temperature can also be constant, as long as the rooms are equipped with separate room units for heating and cooling (Jardeby, Soleimani-Mohseni et al. 2009). The airflow rate is determined by the maximum heat surplus and number of occupants, according to design conditions, and will therefore bee too large long periods of the year. CAV systems can be designed with two-speed motors which enables a reduced speed when the current load is small (Källman, Hindersson et al. 2004).

In a variable air volume flow (VAV) system, the airflow to each room varies but the supply temperature is kept constant. However, the supply air temperature can be varied with the seasonal ambient temperature. The indoor temperature determines the required airflow, and the airflow varies between 100% the warmest day and 20% the coldest day, when only the hygienic ventilation flow rate is required (Nilsson 2001). Having variable airflows can save heating energy and electric energy, since only the essential amount of air is distributed to each zone and hence less air needs to be distributed and treated with room units. VAV systems are often combined with demand controlled ventilation systems (DCV). A DCV system is mainly a control system, which requires a VAV system and regulates the airflow rate according to a measured demand indicator (Maripuu 2009). This demand indicator can be for instance CO_2 level, temperature, occupant presence or humidity. However, it is usually the temperature requirement that determines the airflows rather than the CO_2 limit in office buildings (Jardeby, Soleimani-Mohseni et al. 2009).

Natural and hybrid ventilation

Natural ventilation, or a hybrid of both natural and mechanical ventilation, can be adopted in order to save auxiliary energy for fans. This ventilation strategy is not as common in Swedish office buildings as in Germany, Belgium and Denmark for example. The technique is often combined with passive night cooling and it has been evaluated in many European low-energy office buildings. The challenge with natural ventilation is to achieve a sufficient air change rate with buoyancy forces or wind forces only, but if this is not secured, a small mechanical system can be added as back-up. The flow path of the air depends on the design and placement of openings in the façade and within the building. The single-sided ventilation strategy implies that openings are placed at different heights in the external wall, creating a stack effect and natural ventilation within the room. Cross ventilation requires openings within the building, creating cross flows from one façade to the other.

Nì Riain, Kolokotroni et al. (1999) investigated the cooling effect of various ventilation flow paths in an existing naturally ventilated office building in the UK. The three floor office is L-shaped with both individual and open plan offices. The main components of the natural ventilation system are operable windows, ventilation stacks to extract stale air, and a sinus shaped concrete ceiling with internal channels for air distribution and night cooling. At night, windows are automatically opened and so are the ducts in the slab in order to cool the slab. During the tests, different ventilation paths were opened in sequence and the airflow rate was estimated. The initial measurements during the first summer indicated that acceptable ventilation was provided, the CO_2 levels peaked just below 800 ppm and generally the concentrations were below 600 ppm. The indoor temperature sometimes exceeded 25°C but only when the outdoor temperature exceeded 30°C. Night ventilation coupled with exposed thermal mass and minimisation of solar and internal heat gains effectively reduced the effect of high external temperatures. The authors concluded that cross-ventilation, either directly to the office space or indirectly through the concrete slab, can provide the necessary day ventilation to satisfy cooling purposes. During hot and calm days though, the passive chimneys, exploiting the stack effect, can provide more ventilation than the cross-ventilation system.

Gratia, Bruyère et al. (2004) compared different strategies for natural ventilation. Simulations were carried out in the simulation tool TAS, on a rectangular five floor office building with peripheral individual office rooms with weather data for Belgium a sunny summer day. Internal walls between the office modules and the corridor were modeled with operable windows above the doors to facilitate the air flow between northern and southern spaces. Each office was modeled with four windows, two in the superior and two in the inferior part of the wall, to allow natural ventilation. The efficiency of natural day ventilation, natural night ventilation and ventilation rates due to different positions of the openings were studied. The authors found out that natural day ventilation is most efficient with a single-sided strategy rather than a cross ventilation strategy, since it allows double air inlet. At a mean airflow rate of 4 ach, the single-sided ventilation reduces the cooling load by 31% but the cross ventilation only by 11%. During night, cross ventilation is almost as efficient as single-sided ventilation because of the length of the ventilation period. At a mean air flow rate of 8 ach, the single-sided strategy reduces the cooling load by 38% and the cross ventilation strategy by 36%. Cross ventilation is not possible when the building is wind protected or when wind direction is parallel to windows. The study also showed that the position of openings is as important as the area of the openings. A tall window uses the stack effect better than a horizontal window. If the ventilation is single-sided, it is preferable to dispose of two openings on different heights of the wall, and with cross-ventilation the opening levels should be at different height at each side of the building. Finally, Gratia, Bruyère et al. (2004) claimed that since wind and temperature differences are the driving forces causing air flows through the building, there will be times, even with the best design, when ventilation will not be sufficient enough.

Van Moeseke, Bruyère et al. (2007) studied the impact of cooling by intensive natural ventilation in low-energy office buildings. Various control rules were simulated with TRNSYS and Belgian weather data was used. A heat wave was simulated for the natural ventilation set. A south-oriented office room with 40% GWR and exposed concrete in external wall, ceiling and floor was modeled. The day ventilation rate was constantly 4 ach in one simulation and 1.5-4 ach in another, varying with the outdoor temperature. According to the results, outdoor temperature control mode is not efficient enough to limit over heating hours, and compared to the model with constant air flow, it only leads to small savings in heating energy (3-5%). The authors concluded that since the choice of management and parameters strongly affects the cooling performance, designers must carefully consider the control systems in order to build high comfort, low energy buildings.

Hummelgaard, Juhl et al. (2007) recorded and compared occupant satisfaction and indoor environment characteristics in four naturally and five mechanically ventilated open plan office buildings in Copenhagen. Air temperature, air humidity and CO_2 concentration were logged and occupant responses were collected simultaneously in the different buildings during a working day in October. The questionnaires focused on occupants' overall assessment of the indoor environment, the thermal sensation, their perception of personal control, and the frequency of symptoms occurring during the past three months. The results from the indoor climate measurements showed that temperatures, relative humidity and CO_2 concentration varied more among the naturally ventilated buildings while the mechanically ventilated buildings were more alike. The highest temperatures were found in two of the naturally ventilated buildings with a peak around 4 o'clock pm. The temperature varied between 22.1-26.3 °C in the naturally ventilated buildings, and between 21.3-24.8 °C in the other buildings. The relative humidity was 28-45% in the naturally ventilated and 28-47% in the buildings with mechanical ventilation. The concentration of CO_2 was constantly low in the mechanically ventilated buildings (405-555 ppm) while it varied between 425-1000 ppm in the naturally buildings. Despite the higher concentration of CO_2 and the higher temperatures with more variation, 70% of the occupants in the naturally ventilated buildings were satisfied with the indoor environment, whereas only 59% were satisfied in the mechanically ventilated offices. Overall symptoms, like "difficult to concentrate" and "dry, itchy or red skin", as well as building related symptoms, like "eyes itching/irritation" and "dry, itchy or red skin", occurred more often in the buildings with mechanical ventilation. The occupants' thermal sensation (rated from -3 to +3 on the ASHRAE scale) was in average -0.2 for the naturally ventilated offices and +0.1 for the mechanically ventilated buildings, thus both results were near neutral. These contradictory results have, according to the authors, been found in earlier studies as well, and one possible explanation is that occupants in naturally ventilated buildings have lower expectations of the indoor environment than people in climate-controlled buildings with less fluctuating pollutions and temperatures.

Night ventilation and passive cooling

Cooling with night ventilation and passive cooling with TABS or earth-to-air heat exchangers are often combined in low-energy office buildings in order to improve the cooling efficiency. Pfafferott, Herkel et al. (2005) state that passive cooling is one promising approach in moderate climates to reduce the energy demand for cooling without reducing thermal comfort and without increasing facility electricity. However, the performance depends on complex correlations between heat gains, heat losses and heat storage. Night ventilation can affect the daytime internal conditions by reducing the peak air temperatures, reducing slab temperatures and creating a time lag between external and internal peak air temperatures. Night ventilation has almost become a standard in the UK for "green" office buildings using natural ventilation (Kolokotroni and Aronis 1999). Kalz, Herkel et al. (2009) claim that cooling from ambient air with mechanical night ventilation is harvested with a rather poor efficiency due to the high electricity use for the fans. The cooling effect is particularly limited during persistent heat waves. The required air change rates and the actual cooling effects have been investigated by several researchers, which are reviewed in this section.

Kolokotroni and Aronis (1999) investigated the applicability of night ventilation in air-conditioned office buildings in order to determine if it can also be a good strategy for a mechanically ventilated building, considering the increased consumption of fan energy. The simulated building was a standard air-conditioned office building in the UK with medium thermal mass and the cooling season was chosen as simulation period. A parametric study was carried out, varying internal gains, thermal mass, glazing ratios, solar shadings, building orientation, night cooling strategy (balanced mechanical ventilation or natural ventilation) ventilation rates and operation time. The simulation results showed that mechanical night ventilation can lead to an increased energy use because of the fan operation. The use of a natural, single-sided night ventilation concept in the reference building, on the other hand, yielded a 5% reduction in energy consumption, corresponding to approximately 1 kWh/m^{2}yr. According to the parametric study, the maximum effect from night ventilation is achieved when the building has more exposed thermal mass, followed by improved airtightness, reduced glazing-ratio and reduced internal heat gains. An optimized building; heavyweight with exposed concrete ceilings, airtight with an infiltration rate of 0.1 ach, a glazing-ratio of 20%, a reduction of internal gains by 10 W/m^2 and with natural stack ventilation during night with a ventilation rate of 10 ach, can save up to 9 kWh/m^{2}yr compared to the reference case.

Pfafferott, Herkel et al. (2003) carried out full-scale experiments in an existing German office building (Fraunhofer ISE) in order to determine the efficiency of night ventilation dependent on air change rate, solar gains and internal heat gains. The building has a hybrid ventilation system with a minimum air change rate of 1 ach during working hours and a night ventilation air change rate of up to 5 ach. The experiments were evaluated by using both a parametric model and a simulation program in order to develop a method for data evaluation in office buildings with night ventilation. During the experiments, meteorological data, air change rates, air temperatures, surface temperatures and the operative room temperature were measured in two rooms, one with and one without night ventilation. The results show that room temperatures exceed 25°C in less than 8% of the working hours. Due to thermal stratification and solar radiation, there is an increase in temperature of 0.5°C from one floor to the next. As expected, the night ventilation efficiency increases with the air change rate and decreases with the ambient temperature. The comparison between the measurements and results from the parametric model shows that the parametric model is correct to use when calculating the mean air temperature but not so accurate when calculating the temperature amplitude. The result from the building simulation shows a good agreement between measurements and simulation results when the input parameters and boundary conditions are well known. However, different user behaviour results in energy and temperature variations of great magnitude. A simulation with standardized input shows that night ventilation reduces the mean air temperature by 2-3°C.

Pfafferott, Herkel et al. (2004) evaluated the night ventilation concept in an existing low-energy office building in Germany (DB Netz) in order to quantify the cooling capacity and study the thermodynamic phenomena. The office building was designed, constructed and monitored for two years within the German research program SolarBau with the general benchmark of a total primary energy demand below 100 kWh/m^{2}yr. The building has a central atrium for cross ventilation and daylight inlet. The ventilation strategy during office hours is hybrid with both natural and mechanical ventilation. Night ventilation is automatically activated during summer nights (2 a.m.-8a.m.) and the airflow depends on stack effects due to the atrium. In addition, the ventilation system has an earth-to-air heat exchanger for pre-cooling the supply air. The monitoring results show that general comfort criteria were not strictly matched since the operative room temperature exceeded 25°C during 11-15% of the working hours. Tracer gas technique was used to get more detailed information about airflow rates and flow patterns in different opening states. The experiments showed that the air change rate is higher during night than during day (due to stack effect) and higher with open rather than closed doors (small flow resistance). Furthermore, the effect of the night ventilation is higher in the peripheral rooms than the rooms close to the atrium because the rooms closest to the façade get more benefit from the cool outdoor air. The simulations indicated that the most efficient strategy is hybrid day ventilation in combination with pre-cooled supply air from an earth-to-air heat exchanger.

Jaboyedoff, Roulet et al. (2004) presented some of the work within the frame work of the European project AIRLESS. The main objective, of the project part concerned with energy, was to assess the impact on energy consumption by the use of natural and mechanical ventilation in administrative buildings. A three-storey building, with offices facing south and an atrium facing north, was modelled with TRNSYS. The natural ventilation system consisted of automatic controlled pivoted window parts and interzone openings. To investigate the influence of window openings, three different opening sizes were simulated; 2%, 4% and 8% of the façade area. Other parameters studied were airflow rates, thermal mass, humidity, heating and cooling energy, heat recovery, airtightness, cooling set-point temperatures, duration of the fans and climate (Oslo, Zurich and Rome). The results from the study show that the annual duration of the temperatures above 25°C is about 200 h for a light building with small openings, and only 20 h for a heavy building with large ventilation openings. Furthermore, the airtightness is a parameter of great importance; a leaky envelope can more than double the heating energy use. Changing the cooling set-point temperature from 26 to 24°C increases the cooling energy by more than 50%. Operation of the ventilation 24h per day increases the heating demand by about 25% in Oslo but also allows a reduction of cooling energy by about 25% in Rome. The use of heat recovery allows a reduction of heating energy by about 50% in Oslo. For a building in Zurich, with high performance envelope and low airflow rate for high-energy efficiency, it is not possible to remove the heat accumulated during the day when the ventilation does not operate at night. Humidification and mechanical cooling are significant energy users and should therefore be avoided whenever possible without reducing the comfort. An efficient and economical cooling strategy is to combine a mechanical ventilation system designed for the minimum hygienic airflow rate with passive cooling using natural night ventilation.

Breesch, Bossaer et al. (2005) evaluated the passive cooling effect and thermal comfort in the existing low–energy office building SD Worx in Belgium, with natural night ventilation and an earth-to-air heat exchanger. This well-insulated building consists of two office floors and an atrium on the south side. During the cooling period, the earth-to-air heat exchanger pre-cools the supply airflow daytime and the natural ventilation system cools the exposed surfaces during night time with ambient air entering from openable windows. Measurements during summer 2002 were used to show outdoor and indoor temperatures, airflow rates in the mechanical ventilation system and control parameters in the cooling season. In addition, simulations were carried out in TRNSYS and COMIS in order to estimate the relative importance of the different techniques. The measurements showed that the night ventilation was in operation during 60% of the nights in the cooling season. The temperature drop was higher on the first than on the second floor because of stack effects. The ambient air temperature peak was on average postponed by 5h and therefore the indoor air temperature peaks occurred after the office hours. The earth-to-air heat exchanger secured that the maximum temperature of the supply air never exceeded 22°C. During days with a maximum external temperature between 12 and 22°C, the cooling effect was limited. A heating demand was noticed when the maximum outdoor temperature was below 12°C. Thermal comfort was evaluated and according to the authors, an excellent thermal summer comfort was reached. A temperature of 26°C was only exceeded in 0.3% of summer working hours and 25°C was exceeded in 8.2% (operative temperatures). The simulations and comparisons with measurements showed that the actual outdoor climate was slightly warmer than the simulation weather data. Yet, the simulation model showed a slightly worse thermal comfort with more working hours exceeding 25 and 26°C. Furthermore, in contrast to the measurements, the simulated temperatures hardly differed between the floors. The impact of natural night ventilation versus earth-to-air heat exchanger was estimated by comparing the thermal summer comfort of the building. Natural night ventilation appeared to be much more effective than an earth-to-air heat exchanger. If the internal heat gains were kept low, the natural night ventilation alone could provide a good thermal comfort. An earth-to-air heat exchanger alone with no other cooling system performed poorly.

Eicker , Huber et al. (2006) evaluated the Lamparter office building in Germany, which is one of the first passive house office buildings. The building was constructed in 1999 and monitored over three years in order to analyze the summer performance of a highly insulated, well sun-protected and mechanically ventilated building. The cooling system consists of a passive night ventilation concept, whereby the user has to manually open the upper section of the windows, and by an additional earth-to-air heat exchanger which pre-cools the supply air during the day.

Monitoring results showed that during the typical summers of 2001 and 2002, the night ventilation concept was efficient with only 2% of all office hour room temperatures above 26°C (50-60h). In 2003 though, with a mean summer temperature 3.2°C higher than usual, 9% of the office hours had room temperatures above 26°C (230h). Air change rates were measured using tracer gas technique during 170 night hours in the summer of 2003. The average air change rate turned out to be 9.3 ach at an average wind speed of 1.1 m/s. The air exchange was strongly wind induced. Because of the night ventilation, the room temperature level dropped by 3°C from the daily peak during the hot month of August. Simulations were carried out with TRNSYS in order to see how to improve the night cooling efficiency. One solution could be automatic control of the window openings, postponing the opening until later in the evening when the ambient temperature is cooler. When the windows are manually opened by the users at the end of the working day (6 p.m.), the room first gets heated by the warm ambient air which can reduce the night cooling potential by 20-30%. The contribution of the earth-to-air heat exchanger during day time operation was also investigated, both experimentally and theoretically. Temperature sensors were placed inside the pipes and the air humidity was measured at the inlet and outlet of the pipes. The pipes lie in a depth of 2.8 m where the soil temperature is almost constant, closely matching the annual mean ambient temperature. By ventilating the ambient air through the system, the supply air is cooled in the summer and heated in the winter. The measurements showed that the heat exchanger performed very well in the warm summer of 2003 and the supply air was pre-heated and pre-cooled by around 10°C. The outlet temperatures were kept below 20°C 95% of the time and never dropped below 0 °C, which is excellent to prevent freezing of the heat recovery unit in the mechanical ventilation system. The annual COP was calculated from the sum of heating and cooling energy divided by the additional fan electricity required to run the supply air through the pipes. The calculated COP reached incredibly high levels, between 35 and 50 according to the authors, but only covered about 20% of the average internal loads. The earth-to-air heat exchanger could not fully remove the daily cooling load because the required ventilation rate was too small.

Pfafferott, Herkel et al. (2007) analysed room temperatures in existing, passively cooled low-energy office buildings in Germany. The 12 case buildings are all within the research program EnBau and designed for a primary energy demand below 100 kWh/m^{2}yr for heating, ventilation, lighting and technical services. All buildings have hybrid day-ventilation concepts and most have night ventilation for pre-cooling the building. Some have TABS (concrete slab cooling) and some earth-to-air heat exchangers. The weather at the building site and the room temperatures were monitored over 2-3 years. The comfort was evaluated for the hourly mean room temperature during weekdays and normal office hours. The study indicates that passively cooled low-energy office buildings provide a good thermal comfort in moderate European summer climate according to the European standard. Given extreme weather conditions, like the summer of 2003, buildings with night ventilation and earth-to-air heat exchanger exceed their capacity limits of thermal comfort. Water-driven cooling (TABS), using the ground as heat sink, provides a good thermal comfort even in extreme weather conditions. The new European standard take into consideration that occupants in naturally ventilated buildings perceive higher room temperatures as comfortable, supported by several research projects.

Haves, Linden et al. (2007) performed thermal simulations of a naturally ventilated office tower in San Francisco in order to evaluate different ventilation strategies for space cooling. The building is a narrow-plan, high-rise tower elongated in the NE-SW direction. Simulations were carried out with Energy Plus and COMIS with the assignment to determine whether there is a need to use buoyancy effects to supplement the wind. The paper also describes the airflow and temperature distribution in the occupied spaces arising from different combinations of window openings and outdoor conditions. Different ventilation configurations were simulated for the cooling season (April to October). The windows were opened whenever the indoor air temperature exceeded both the set-point and the ambient temperature. An adaptive comfort criterion model for naturally ventilated buildings was used (ASHRAE 55). The adaptive model has an upper limit for the operative temperature of 26-28°C and it assumes that occupants will change their clothing in response to changing conditions. The main observations from the study reveal that wind-driven night ventilation produces reasonable daytime comfort conditions and that a combination of wind-driven and internal stack-driven ventilation produces only a modest improvement in performance. Internal stack-driven night ventilation is less effective than the wind-driven case. Furthermore, additional external chimneys do not improve the performance of the combined case. The airflow study shows that the geometry of the user-controlled windows has a large impact on the airflow, the opening area and the ventilation efficiency. It is therefore desirable that the user operable opening has the maximum possible momentum flux which can be achieved by introducing a flow deflector. With this study, the authors show the importance of careful simulations in order to optimize the ventilation strategy and window geometry and thereby improving the ventilation efficiency and increasing confidence in the system.

Artmann, Manz et al. (2008) decided to identify the most important parameters affecting night ventilation in order to reduce uncertainties in the prediction of thermal comfort in buildings with night-time ventilation. The night ventilation concept is simple but the cooling effectiveness is affected by many parameters, which make predictions uncertain and architects and engineers hesitant to apply the technique. The HELIOS building simulation programme was used to model a standard office room, occupied by two persons as base case. The external façade, including two windows with external sunscreens was oriented to the south. The parameters studied were different levels of thermal mass, internal heat gains, air change rates, heat transfer coefficients and different sources of climatic data. The performance was rated by evaluating overheating degree hours of the operative room temperature above 26 °C. The study shows that cooling by night ventilation depends mostly on climatic conditions, building construction and internal heat gains. The external climatic conditions were found to have a very large impact on overheating. Not only local, but also annual climatic variability has a large affect. The weather data from the warm summer of 2003 clearly showed that simulations based on commonly used climatic data do not always allow reliable predictions of thermal comfort. The impact of thermal mass in internal walls depends on room geometry. In a large open plan office the wall-to-floor ratio is small and the construction of the walls thus becomes less important. However, the thermal mass of the ceiling is always favourable, a concrete ceiling in direct contact with the room air reduced overheating by a factor of two compared to a suspended ceiling. Varying the internal heat gains from persons, equipment and electric lights created effects of the same order as variations of the thermal mass. If high internal heat gains are combined with a low thermal mass, no air change rate will be sufficient to avoid overheating. As solar heat gains were generally low compared to internal heat gains, the effect of façade orientation on overheating degree hours was relatively small. A clear difference was found only for an office oriented to the north, where the overheating degree hours were almost halved. Regarding the night ventilation rate, the cooling effect changed rapidly when the air change rate was increased from 0.5 to 4 ach. When natural ventilation depends only on buoyancy forces, the airflow is small when the ambient temperature is high, making the cooling effect minor during warm periods. Therefore, the authors recommend that a mechanical system shall be used whenever natural forces are insufficient. When the airflow rate exceeds 10 ach, the cooling effect is not improved any more. The effect of the daytime ventilation rate was relatively small compared to the night time ventilation rate. Heat transfer between the internal surfaces and the room air was found to have only a minor effect.

Høseggen, Mathisen et al. (2009) carried out simulations with ESP-r on a real office building with the assignment to estimate potential energy savings and comfort performance of exposing the concrete in the ceiling. The building (Røstad) is located north of Trondheim in Norway and it has demand controlled ventilation with an earth-to-air heat exchanger for pre-cooling the supply air. In the simulations, the impact of exposed concrete, occupancy rate, ventilation strategies and night time airflows were studied. The results showed that the cooling effect with night ventilation increased rapidly with air changes between 1-5 ach. For larger air change rates, the cooling effect stabilised and air change rates exceeding 10 ach did not improve the performance further.

Goethals, Breesch et al. (2011) carried out simulations of a night cooled office room in Belgium with TRNSYS in order to investigate the sensitivity of the night cooling performance to convection algorithms. Night cooling with mechanical ventilation and air change rates of 6 and 10 ach were simulated. The night ventilation was assumed activated when all of the following conditions were fulfilled:

- Monday – Sunday night, between 22.00 and 6.00
- Outdoor air at least 2°C colder than return air
- Return air warmer than 16°C
- Ceiling temperature warmer than 22°C.

2.3.3 User related electricity and internal gains

The user related electricity, or tenant electricity, is an important energy post in office buildings. Not only does it account for a large proportion of the total energy use, it indirectly increases the cooling energy use due to the high internal gains it causes. Gratia and De Herde (2003) claim that the internal gains have a great impact on cooling loads and that if half as much internal gains from lighting and equipment is secured, the indoor air temperature can be reduced by 3-4°C. Eicker, Huber et al. (2006) monitored and analysed office rooms in detail in a passive house office in Germany. The total hourly internal gains turned out to be 30-35 W/m^2 for an individual office room. Most of the gains were due to the office equipment (equipment 17 W/m^2, lighting 11 W/m^2 and occupant 6 W/m^2).

According to the "Step by step STIL" survey, the electricity use for lighting, computers and other user related office equipment was 57 kWh/m^{2}yr on average in 2005 (Energimyndigheten 2007). These statistics have been the base for the recommended standardized input for energy calculations in office buildings provided by the SVEBY programme, which stands for "Standardize and verify the energy performance of buildings" (SVEBY 2012). The SVEBY programme recommends 50 kWh/m^{2}yr as normal tenant electricity use in a modern Swedish office building (SVEBY 2010). The programme estimates that if the building is improved with "best practice" equipment, lighting and control systems, the user related electricity can be reduced to 39 kWh/m^{2}yr. Further improvements with new and efficient technique may reduce the user related electricity to 18 kWh/m^{2}yr in the future.

Lighting

Among the 123 office and administration buildings, of different age, studied in the "Step by step STIL" survey, lighting energy is one of the largest energy posts, with an average lighting energy use of 23 kWh/m^{2}yr. However, the spread was significant and the minimum value was 7 kWh/m^{2}yr and the maximum value 53 kWh/m^{2}yr. The studied buildings had an average installed lighting power density (LPD) of 10.5 W/m^2. The average LPD in individual office rooms was 13 W/m^2 and in landscape offices 12 W/m^2. This can be compared to the building industry's current guidelines of maximum 10 W/m^2 in individual rooms and 12 W/m^2 in landscape offices (Ljuskultur 2010).

An extensive literature review was carried out by Dubois and Blomsterberg (2011) in order to determine the energy saving potential for lighting in office buildings. The authors listed a number of different strategies to reduce energy use for lighting in office buildings, which are described in this section:

- Improvement in lamp technology, ballast technology and luminaire technology
- Use of task lighting combined with ambient lighting
- Reduction of illuminance levels
- Reduction of switch-on time
- Use of lighting control systems

Many existing office buildings in Sweden have T8 fluorescent lamps (26 mm), even though the thinner and more efficient T5 (16 mm) fluorescent lamps were introduced already in 1995. T5 lamps are being installed in almost all new office buildings and modern T5 lamps have luminous efficacy up to 104 lm/W which is 20% more efficient than T8 lamps (OSRAM 2012). The luminous efficacy of light emitting diodes (LED) is increasing rapidly and can today reach 100 lm/W. However, the authors believe that conventional light sources will have a major role to play for some time yet. Most existing office buildings in Sweden still use the conventional wire-wound ballast devices which consume 10-20% wattage of the lamp. High frequency (HF) electronic control ballast use less than half the energy required by the wire-wound types. Furthermore, HF lighting provides better lighting quality, flicker-free lighting, reduced power demand, longer life time and are compatible with lighting control systems. The luminary value describes the efficiency of the lighting fixture and how much of the lamp flux that is emitted into interior space (useful lumen). It depends on the quality of reflectors, diffusers, filters and ambient temperature of the lamp. Modern fixtures with coated reflectors and holographic diffusers can have luminary values of 75% and higher. (Dubois and Blomsterberg 2011)

One efficient way of saving lighting energy can be achieved by having separately controlled task lighting (desktop lamps) together with the ambient lighting. The task light ensures the required 500 lx immediately at the desk and the ambient lighting can be adapted according to available daylight. The literature indicates that 22-25% lighting energy can be saved compared to fixed general lighting. However, desktop lamps should never be used as the sole light source, because of the increased risk of visual fatigue. The level of background luminance is important since it influences visual, emotional and biological aspects. (Dubois and Blomsterberg 2011)

In Sweden, an illuminance level of 500 lx is recommended on the task area for individual office rooms while 300 lx is normally accepted as general lighting for landscape offices (Ljuskultur 2010). Several studies indicate that people generally prefer lower levels than 500 lx in office rooms, but the preferred illuminance level varies widely among individuals. By using 400 lx as a design criterion, a 20% decrease in energy consumption could be achieved without reducing the number of satisfied workers. One suggestion is to install a range of adjustable task illuminances for particular situations rather than a single level. Some people would probably choose lower levels than recommended. (Dubois and Blomsterberg 2011)

The lighting energy consumption is affected by installed power and the number of hours the lights are on. The European standard EN 15193 recommends a total utilization time for electric lighting in offices of 2500 hours per year. This corresponds to approximately 10 hours per day (5 days/week, some national holidays excluded), which is a reasonable value considering a small amount of flexible working hours. The recommended number of hours requires that the lighting system must be completely switched-off after operation. This will probably involve some kind of automatic power-break to avoid losses due to lights left on by mistake and in addition cleaning of the office during the day. (Dubois and Blomsterberg 2011)

Lighting energy can be considerably decreased by using lighting control systems for reducing switch-on time and power. Studies have shown that manual dimming can save 25% energy and switch-off occupancy sensors can save 20-35%, normally 25% with a sensor time delay setting of 20 min. Daylight harvesting in office buildings is not only important for the health and well-being of people. The utilization of daylight can be effective in order to reduce the electric lighting consumption. Direct savings in terms of reduced electricity for electric light and also indirect savings because of reduced internal heat gains and reduced cooling demand. Daylight controlled lighting systems with an automatic on/off switch or photoelectric dimming have the potential to reduce the electrical energy by as much as 30-60%. However, equipment for dimming is more expensive than occupancy switching systems. Dimming ballasts are less efficient than non-dimming ballasts and they consume 10-20% of the fixture's power even at the lowest possible light output. (Dubois and Blomsterberg 2011)

The review carried out by Dubois and Blomsterberg (2011), which is based on different monitoring and simulation studies, indicates that an energy use of 10 kWh/m^{2}yr is a realistic target for electric lighting in future low energy office buildings. This is a 50% reduction compared to the actual average lighting energy use in Swedish offices. Further savings are achievable by accepting lower illuminance levels (400 instead of 500 lx) and by using combined task/ambient lighting concepts.

Dubois and Flodberg (2012) investigated the effect of various switching and dimming strategies for electric lighting systems with the dynamic daylight simulation program DAYSIM and the user behavior control model Lightswitch. The model predicts when occupants will use their blinds and when they will switch on and off the electric lighting. Figure 2.3 shows the electric lighting consumption for different control strategies in relation to glazing-to-wall ratio (GWR) for a south oriented peripheral single office room in Stockholm. The slope of the curves indicates that the choice of electric lighting strategy has greater impact on electricity use than the GWR (for GWRs above 20%). One interesting finding is the fact that the system with occupancy sensor with automatic switch on/off actually yields more energy use than the ordinary manual switch near the door. The reason is that lights automatic switch on when the room is occupied, even if there is sufficiently available daylight. The occupancy switch-off, or so-called absence detector, is preferable since it, according to the study, yields around 25% savings compared to the manual switch by the door. This system automatically switches the light off when the room is empty and the occupant will have to switch it on manually when he or she returns. Hence, switching on demands effort while switching off is automatic. The most efficient system is photoelectric dimming with occupancy switch-off which allows savings of at least 50% compared to the manual switch. With this system, daylight sensors reduce the electric light when useful daylight is available, and the lights are automatically switched off when the room is unoccupied. The system makes it possible to achieve an annual electricity use below 10 kWh/m^{2}yr. Moreover, the study indicates that the initial lighting power density (LPD) is an important design feature. A LPD of 8 W/m^2, combined with a simple occupancy switch-off system, is also a valid overall solution in order to achieve an electricity use of 10 kWh/m^{2}yr.

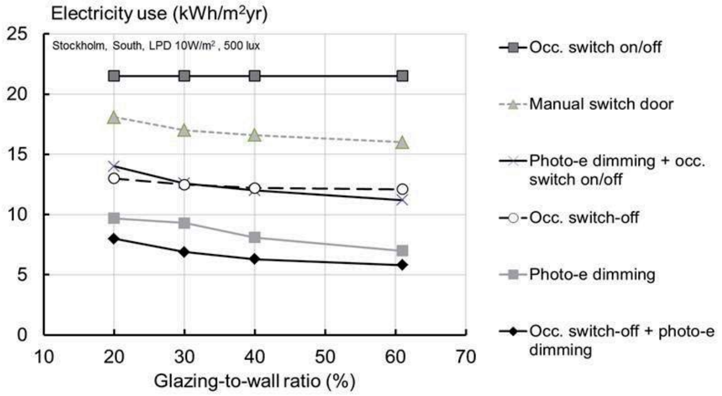

Fig. 2.3 *Electric lighting consumption as a function of switching and/or dimming strategy in relation to GWR for a south orientation in Stockholm with LPD 10 W/m2 and benchmark illuminance of 500 lx. Reproduced with permission from Marie-Claude Dubois 2012.*

Similar results were found for an open landscape office in a more recent study published by Dubois and Du (2012). Different lighting strategies were investigated for an open landscape office in Stockholm with varying GWR and orientation. In this second study, it was shown that the control system with occupancy switch on/off yields the highest electricity use, while a perfectly commissioned photoelectric dimming system can save more than 50% compared to a conventional manual switch near the door, and this for all GWR. The saving potential is still high at the third row from the façade, but deeper into the room it decreases because of limited useful daylight. The additional savings from an occupancy switch-off system are quite small.

Equipment

The “Step by step STIL” survey (Energimyndigheten 2007) revealed an average electricity consumption for computers of 15.4 kWh/m²yr and for server rooms of 10.7 kWh/m²yr. The electricity use for other equipment, such as printers, copy machines and mini-kitchens, was 8 kWh/m²yr on average. Hence, the total tenant electricity for office equipment was 34 kWh/m²yr. In addition, facility electricity other than fans (pumps and elevators for instance) was 9.5 kWh/m²yr.

There is great energy saving potential when it comes to office equipment. Modern computers and displays have lower equipment power density (EPD) and use less standby power. It is also important to reduce the operation hours by preventing equipment left on by mistake or left in standby mode outside office hours. Jagemar and Olsson (2004) carried out detailed measurements of electricity use in three Swedish office buildings built in 1998-1999 (two with individual rooms and one with open landscape office). The study showed that in two buildings, computers and other equipment were left in a sleep mode during night. Thus, the equipment power was 4 W/m^2 outside office hours. In the third building, computers were shut off at night and the equipment only consumed 0.5 W/m^2 during nights and weekends. Computers, displays and chargers consume power even when they are turned off. According to SVEBY (2010), 15% of the EPD can be assumed outside office hours. There is great saving potential in using power strips and multiple sockets which make it easy to turn off the equipment completely at night. Alternatively, modern equipment with low off-mode power can be used, for instance equipment qualified according to the ENERGY STAR Label from the US Environmental Protection Agency (EnergyStar 2012). Several computers with this label consume less than 2 W in off-mode, and all the displays consume less than 1 W in off-mode.

A realistic EPD for a conventional stationary workstation with display is 125 W according to SVEBY (2010). An energy efficient alternative is a modern laptop or notebook with EPD 12 W (EnergyStar 2012). Even with a separate display, this option can be really efficient. Modern suitable Liquid Crystal Displays (LCD) consume 20-35 W depending on their size (EnergyStar 2012).

Occupancy

The occupancy attendance in office buildings has a large impact on internal gains since it also affects the use of lighting and equipment. HVAC systems in modern office buildings must be able to adapt to the varying demands. The average occupancy pattern over time is often referred to as occupancy factor. The occupancy factor is defined as the actual number of occupied rooms, divided by the total number of rooms. It can also be expressed as the number of people that are present in the building divided by the number of people that the building was designed for (Maripuu 2009). The SVEBY programme suggests an average daily occupancy factor of 0.7 (weekdays 8:00-17:00) in energy simulations (SVEBY 2010). However, this value is of current debate and the general idea is that the real value is lower in reality.

Maripuu (2009) completed a study of occupancy patterns in office buildings as a part of a doctoral thesis about demand controlled ventilation in commercial buildings. In the literature review, Maripuu reports that there are relatively few studies conducted on occupancy patterns. There are also very few guidelines about the occupancy factor to be used in the design process. In addition, the occupancy factor is highly dependent on the type of operation in the building. The occupancy factors found in this review are summarised in Table 2.1. In addition, occupancy factors monitored by Blomsterberg (2011), Høseggen, Mathisen et al. (2009) and Maripuu (2009) are included in the table. Maripuu carried out own field monitoring in a university administration building in Gothenburg, Sweden. Patterns were monitored in different types of rooms with occupancy sensors installed to the supply air devices. The occupancy attendance was monitored during the period of September 2007 to September 2008. The results showed that the maximum occupancy factor occurring in the building was 0.7. The average occupancy factor during normal working hours (8:00-16:00) was about 0.4.

Table 2.1 Occupancy factors found in literature (Blomsterberg 2011; Høseggen, Mathisen et al. 2009; Maripuu 2009).

Report/Survey	Building	Method	Average Occupancy factor	Peak Occupancy factor	Time period
SBN 67, 1967 Swedish old building code (Maripuu 2009)	Fictive office	Proposed profiles	0.7 (>100 persons) 0.8 (11-100 persons) 1.0 (<10 persons)		
ASHRAE/IESNA 90.1-1989 (Maripuu 2009)	Fictive office	Proposed profiles	0.76	0.95	Weekdays 8:00-17:00
Keith and Krarti 1999 (Maripuu 2009)	Academic research facility	Monitoring	0.49	0.94 (10 rooms) 0.77 (50 rooms)	Weekdays 8:00-17:00
Johansson 2005 (Maripuu 2009)	University office (SWE)	Monitoring Sensors	0.33	0.49	Weekdays 8:00-18:00
	Municipality (SWE)	Monitoring Sensors	0.54	0.79	Weekdays 8:00-18:00
	Industrial office (SWE)	Monitoring Sensors	0.51	0.88	Weekdays 8:00-18:00
Halvarsson et al. 2005 Maripuu 2009)	Office (NO)	Monitoring Sensors	<0.35 (90% of time)	0.62	
	Education (NO)	Monitoring Sensors	<0.23 (90% of time)	0.47	
Mathisen and Halvarsson 2007 (Maripuu 2009)	Office	Monitoring Sensors	0.6	0.84	
	University office	Monitoring Sensors	0.2 <0.12 (90% of time)	0.3	
Bernard et al. 2003 (Maripuu 2009)	10 companies (FR)	Monitoring Sensors	0.4	0.7	Weekdays 10h
Jagemar and Olsson 2004 (Maripuu 2009)	Office	Evaluating electric lighting	0.3-0.5	0.7	Weekdays 8:00-18:00
Blomsterberg (2011)	WSP Office (SWE)	Monitoring Sensors	0.6		Weekdays 8:00-17:00
Maripuu (2009)	University Office (SWE)	Monitoring Sensors	0.4 <0.53 (90% of time)	0.7	Weekdays 8:00-16:00
Høseggen, Mathisen et al. (2009)	2 Office buildings (NO)	Monitoring Sensors (20 min delay)	0.4 and 0.6	0.65	Weekdays 8:00-16:00

Høseggen, Mathisen et al. (2009) discuss whether hourly averaging of the room occupancy is an adequate approach. In open landscape offices, with several people, it is probably applicable but in individual office rooms, persons are either present or absent (0.7 persons cannot be present). This simplified input approach can off course be a possible source of error in whole building energy simulations. An occupancy factor of 0.7 in the simulation model spreads out the internal gains evenly. In a real building, it is a fact that empty rooms can have a heating load while occupied rooms generally have a cooling load.

2.3.4 Thermal comfort

When a group of people are exposed to the same environment, they will experience a range of thermal sensations. A person's thermal response to environmental conditions is strongly influenced by clothing and activity. The thermal environment affects people's health and productivity and since the salary cost for workers in office buildings is higher than the operating cost, this is of great importance (Schiller 1988; CEN 2007a). There are a number of national and international standards and models for predicting and evaluating thermal comfort and thermal sensation. These predictive standards and models are often the basis for indoor thermal climate criteria and guidelines. In Sweden, the most common thermal comfort criteria TQ1 and TQ2 correspond to a predicted percent dissatisfied (PPD) of maximum 10%, according to the ISO 7730 model introduced by Fanger in 1970 (Ekberg 2006). The comfort criteria limit the operative temperature range in a building, and hence affect the total operation energy use. However, the following section indicates that the conventional models used for predicting optimal temperatures, might not always reflect the actual desired temperatures in modern office environments. Other indoor environmental parameters are air quality, humidity, lighting and acoustics but these are not discussed in this section.

Schiller (1988) studied the accuracy of different theoretical and laboratory based equations to predict occupant's thermal sensations in existing office buildings. Accepted international standards for thermal comfort are ASHRAE 55 and ISO 7730, which are both based on extensive research in laboratory facilities. From these experiments, equations have been developed to predict the average thermal sensation felt by a large group of people. These mathematical models describe the heat exchange between the human body and the environment, the physiological thermoregulation mechanisms of the body and the relationship between people's thermal sensation (psychological) and the physiological thermal strain on the body due to environmental and personal conditions. The data in this report (Schiller 1988) are based on a field study of 10 representative office buildings in San Francisco, where physical measurements and subjective responses were collected during one winter week and one summer week in 1987. A total of 2342 visits were made to 304 volunteers (62% females and 38% males). Each participant was visited at their desk 5-7 times and had to complete a thermal assessment survey addressing thermal sensation, thermal preference, comfort, mood, clothing and activity. Meanwhile, a mobile cart was placed at the workstation, measuring air temperature, dew point temperature, globe temperature, air velocity, radiant temperature asymmetry and illuminance. The subjects were asked to fill a seven-point ASHRAE Thermal Sensation Scale (TS) (-3 cold, -2 cool, -1 slightly cool, 0 neutral, +1 slightly warm, +2 warm, +3 hot). Schiller adopted the conventional approach of regarding the central three categories (slightly cool, neutral, slightly warm) as comfortable and that people voting outside these categories (cold, cool, warm, hot) were dissatisfied with their thermal state. Percentage of dissatisfaction was calculated by counting the number of votes where TS>1.5. Based on the responses of activity and clothing the total clothing insulation (clo) and metabolic rate (met) were computed according to the 1985 ASHRAE Handbook of Fundamentals. Schiller analysed thermal sensation predictions based on several models occurring in the literature; the original PMV and PPD introduced by Fanger in 1970, as well as PMV_G, PPD_G and TSENS introduced by Gagge in1986. The TSENS index was developed using responses from 1000 subjects tested in a University laboratory and a two-node transient heat balance model of the body. The results from the study showed that the mean "clo" of the occupants was 0.58 in the winter and 0.52 in the summer and the average "met" was 1.12 for the whole year. Meanwhile, the different predicted mean votes (PMV) were compared to the measured mean votes and the neutral temperature ($T_{neutral}$) was determined, which corresponded to the temperature for which a large group of people voted 0 on the ASHRAE scale.

	$T_{neutral}$
Measured	22.4°C
TSENS	23.8°C
PMV_G (Gagge)	23.9°C
PMV (Fanger)	24.8°C

The measured neutral temperature of 22.4°C was cooler than predicted by all of the other methods. Fanger's PMV model consistently predicted that people would feel cooler than they did. The best agreement between the actual thermal sensation and the predicted thermal sensation was in the region near neutral. As conditions moved away from neutral, predictions were more conservative and occupants voted at more extremes than predicted.

The results also show that the measured and calculated percent dissatisfied (PD) differed a lot. The optimum temperatures ($T_{optimum}$) where least people were dissatisfied occurred at:

	PD	$T_{optimum}$
Measured	12%	22.5°C
PPD_G (Gagge)	5%	23.9°C
PPD (Fanger, ISO 7730)	5%	24.8°C

The predicted values showed less dissatisfaction than the measured and the differences were even larger at warmer temperatures. This can be explained by the wide range of clothing worn in the offices, as compared to the standard uniforms in the laboratory experiments. The average “clo” was 0.55 for the whole year but the range varied from 0.23 to 1.14. However, additional simulations indicated that the over prediction of neutral temperatures rather reflected the workers’ preferences for cooler conditions than the researchers interpretation of clothing or activity levels.

Humphreys and Hancock (2007) studied the thermal comfort in university lecture halls in the UK to see if people really want to feel “neutral” according to the ASHRAE scale. In February and March 2004, 133 students of the Oxford School of Architecture took part in observations where they gave their thermal sensation on the ASHRAE scale during 5 lectures, and also indicated what their desired sensation would have been at that time, on the same scale. The scale contains 7 different scale units (-3 cold, -2 cool, -1 slightly cool, 0 neutral, +1 slightly warm, +2 warm, +3 hot). There were also questions about their recent activity and clothing. The air temperature was also measured in the lecture room. The results showed that more than 40% of respondents felt “neutral” and about 30% felt “slightly warm” while 15% felt “slightly cold”. The responses regarding the desired thermal sensation showed that 60% wished to feel “neutral” but almost 30% preferred to feel “slightly warm”. “Neutral” is therefore not necessarily the desired thermal sensation. The survey also showed that the respondents’ desired thermal sensation varied from occasion to occasion, typically with a range of two scale units. For example, a person who normally likes to feel “slightly warm” may on occasion like to feel “neutral” or “warm”. Notable is that neither differences in amount of clothing, nor differing levels of activity had a coherent effect upon the *desired* thermal sensation. Another result from the survey was that the optimal air temperature, with most people being satisfied, would have been 21°C but the measured mean air temperature was 19.3°C. The authors highly recommended that, when using the ASHRAE scale, to ask not only how the respondents feel but also how they would like to feel and then adjust the result by taking the actual sensation minus the corresponding desired sensation. The adjusted thermal sensation then indicates how much "too warm" or "too cool" the respondents feel.

Barlow and Fiala (2007) observed occupant comfort in a refurbished office building in the UK, as well as occupants' preferences when adopting low-energy strategies. The surveyed building is a three floor open landscape office in London, built in 1950 and refurbished in 2002. The building has natural ventilation and night time ventilation, double glazed windows, external awnings, both automatically and manually controlled, and an automatically controlled chilled beam cooling system. Eight surveys were conducted during March, April and June 2005. Between 15 and 25 persons responded on each survey day out of a potential office population of 87 people (N.B. only 17-29%). The occupants were asked to describe their subjective response to a range of thermal conditions; thermal sensations (using the ASHRAE scale to identify), air movement, visual comfort and the preferred changes in each case. They were also asked which adaptive opportunities they would use if available. Measurements of internal and external air temperatures, solar radiation levels, operative temperatures, air movement and relative humidity were recorded. The results showed that the mean clo decreased from 0.8 clo in late winter to 0.66 clo in early summer. People changed their clothing to reflect the external temperatures but less than 4% indicated a change of clothing to reflect the variations of the internal temperatures during a survey day. When occupants were asked to estimate indoor temperature they consistently underestimated the measured mean air temperature, on average by 3.2°C. When asked which adaptive opportunities they would support, 74% voted for openable windows, 69% for control of solar glare (even though occupants consistently voted they were not at all suffering from solar glare in the surveys), 47% for opportunities to control solar gain, 56% for turning lights off locally and 59% against turning lights off automatically, 55% for being able to increase levels of ventilation and 50% for control of room temperatures. The wish for solar glare control declined during summer months suggesting that the low-level winter sun was a greater problem than the high summer sun.

Wagner, Gossauer et al. (2007) carried out a survey on workplace occupant satisfaction in office buildings in Germany. Modern low-energy buildings are often designed with passive cooling instead of active cooling and the authors wanted to see if this can affect the occupant satisfaction. The objective was to determine whether there are significant differences in satisfaction due to building type, energy concept and season, and in addition develop a "satisfaction- index". The survey was carried out in 2004-2005 in 16 different office buildings with a range of size and energy concepts. A questionnaire with properties such as air quality, temperature, air velocity, humidity, acoustics and lighting was distributed to the participants. In addition, other general questions including office layout, well-being at work, health, amount of work, communication and the general acceptance of the workplace was asked. The questions were answered using a 5-point scale ranging from "very dissatisfied" to "very satisfied". In each building, surveys were carried out in the winter and summer in order to take into account the influence of diverse climate conditions on the occupants' judgement. As complement, room temperatures and humidity values were measured. A cluster-analysis was used to identify different possible groupings of building characteristics. Approximately 1300 questionnaires were evaluated. In the summer, the result of the mean satisfaction with the room temperature was 0.6 scale points below the mean satisfaction in the winter. The mean ratings ranged from "moderately satisfied" to "dissatisfied" in summer and from "satisfied" to "moderately satisfied" in winter. A comparison of the perceived room temperatures with the measured room temperatures gave a measured neutral temperature of 23°C in winter, which is almost 1°C above the recommendation of ISO 7730, and 23.5°C in summer, which is 1°C below the recommendation. In winter, the dissatisfaction with temperature often corresponded with being "too cool" and the feeling of draught. In summer, the dissatisfaction was mostly associated with the sensation of being "too warm" as well as with dissatisfaction of the indoor air quality. In both winter and summer, the most important factor turned out to be the ability to affect the room temperature. Since the potential of affecting the temperatures is higher in the winter, due to larger temperature difference between outdoor and indoor air conditions, this can explain why the occupants were more satisfied in the winter. The evaluation of different energy concepts in buildings and thermal comfort did not give any reliable results. The large variety of architectural and technical concepts only allowed a qualitative evaluation of their effect on the occupant satisfaction. However, the only office built according to the passive house standard, with a low glazing fraction, natural ventilation and without radiators, resulted in a very high satisfaction and with moderate temperatures even during warm summer days.

Pfafferott, Herkel et al. (2007) analysed room temperatures in 12 passively cooled low-energy office buildings in Germany, using and discussing four different comfort standards. The evaluated standards are the international standard (ISO 7730), the preliminary European standard (prEN 15251), the German standard (DIN 1946) and the Dutch code of practice (ISSO 74). The case study buildings are all within the research program EnBau and were designed for a primary energy demand below 100 kWh/m^{2}yr for heating, ventilation, lighting and technical services. The buildings are located in three different German climate zones; summer-cool, summer-hot and moderate. The weather at the building site and the room temperatures in several office rooms were monitored over 2-3 years. The comfort was evaluated for the hourly mean room temperature during weekdays and normal office hours. The four comfort criteria use different time periods of the outdoor air, different clothing levels and different temperature limits. The results for one of the example buildings (Fraunhofer ISE) showed that the upper comfort limit was exceeded during 6% for DIN 1946, 11% for ISO 7730, 1% for ISSO 74 and 4% for prEN 15251 during the summer of 2002. The comfort criteria can give different quantitative numbers (%) for comfort since the criteria are based on different studies, databases and consumptions. The authors observed that the qualitative assessment can differ from one criterion to the next; the most comfortable building according to one standard can be less comfortable according to another standard.

3 State-of-the-art

This chapter presents a state-of-the-art review of low-energy office buildings recently built in Northern Europe. This review allows identifying general and specific solutions regarding building configuration, HVAC systems and techniques for lighting and office equipment.

3.1 Method

In order to find suitable low-energy office buildings to study, universities and building research organizations in Northern Europe were contacted in order to obtain a list of the most interesting projects in each region. Subsequently, members of the reference group as well as key persons in large building companies in Scandinavia were contacted. Additional buildings were found through energy related web pages and real-estate news pages. Buildings of interest were office buildings completed, designed or completely retrofitted during the last decade. Geographically, the focus was on Sweden and Northern European countries with an outdoor climate similar to the Swedish climate. To qualify for this study, the building had to be energy efficient, by at least 25%, compared to other new buildings in the country concerned, and/or have some kind of green focus and certification such as GreenBuilding, Passive House, Minergie, LEED, BREEAM or Miljöbyggnad. At the end, fourteen low-energy office buildings in the Nordic countries and ten buildings located in other parts of Northern Europe were selected for further studies. In the next phase, the contact person for each project was asked to fill in a detailed questionnaire (see Appendix A). The requested material consisted of general information about the developer, contractor and architect as well as more specific information about building size, building envelope, materials, U-values, airtightness, glazing and solar shading devices. Furthermore, information about the operation, HVAC-systems, lighting strategy and energy use was requested. However, only three of these questionnaires were filled in properly. Most of the contacts handed in existing sales brochures and answered a couple of additional questions instead. This is likely to depend either on lack of time and interest or unwillingness to share company material with competitors. In addition, four recently completed projects in Sweden (Jungmannen, Hagaporten, Waterfront and Pennfäktaren) were visited in a field study with the intention to see how the low-energy design is perceived in real life and also to be able to get some questions answered. Both monitoring results and design values were obtained from the contact persons. The validity of the received information could not be verified to a greater extent but the information was analysed and compared to different guidelines, the Swedish building code and the existing building stock. The fact that the different countries have different building regulations and definitions makes the comparison to Swedish conditions more difficult. For instance, Sweden is one of few countries within the European Union that focuses on building performance and end-use energy instead of supply systems and primary energy use. To be able to compare the energy performance, the primary energy Figures was converted to end-use energy with actual primary energy conversion factors.

3.2 Existing low-energy office buildings in Northern Europe

In this section, examples of low-energy office buildings from Sweden, Norway, Denmark, Finland, Germany, Austria and Switzerland are presented in alphabetic order.

3.2.1 Sweden

Hagaporten 3, Solna

Location	Stockholm (N 59.36° E 18.02°)
Climate	HDD 3203/ CDD 261
Completion year	2008
Client/developer	Skanska
Architect	Strategisk Arkitektur
Contractor	Skanska
Tenant	ÅF
Tot. floor area	33 265 m^2 A_{temp} + car-park
Floors	7
Operation	Office, restaurant, car-park
Office hours	6.30-18.00
Plan type	Landscape
Space efficiency	15 m^2/employee
References	Skanska (2008a); Gräslund (2010); Persson and Arvidsson (2010)

Figure 3.1 Visualisation by Strategisk Arkitektur.

Building design

The open plan office space is located around an atrium with communication space, meeting rooms and natural daylight inlet. The building envelope has concrete sandwich walls with U= 0.34 W/m^{2}K, roof U=0.13 W/m^{2}K and windows U=1.4 W/m^{2}K (incl. frame). The airtightness was measured to 0.5 l/sm^2 at 50 Pa pressure difference. The glass facades towards south and west have SHGC of 15% and external, motorized sun shading devices.

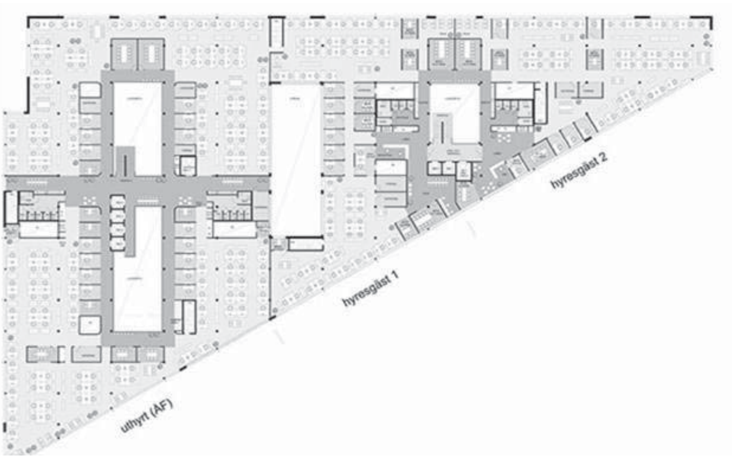

Figure 3.2 Plan by Strategisk Arkitektur.

HVAC+L

The target indoor temperature is 22-23°C. The building is provided with district heating and cooling. The air handling unit is equipped with a free-cooling battery which provides the cooling baffles with cold water when the outdoor air is below 15°C. In addition, the free-cooling battery pre-heats the incoming ventilation air. The CAV ventilation has a low-speed high-efficiency air handling unit with a ring-formed duct system. The specific fan power (SFP) is of 1.4 kW/m^3s^{-1} and the air-flow is 1.5 l/sm^2 with high speed facilities in meeting rooms. A coil heat exchanger with a measured efficiency of 67% recovers the heat from return air (including air from the garage). Occupancy sensors control the low-energy lighting system in spaces not regularly occupied, and the installed power for lighting is 5 W/m^2.

Energy performance

The specific end-use energy according to BBR was 79 kWh/m^2yr in 2009 (excl. tenant electricity) and the Hagaporten 3 building is certified according to EU GreenBuilding and Miljöbyggnad (Gold). Figure 3.3 shows the distribution of energy use for the different energy posts.

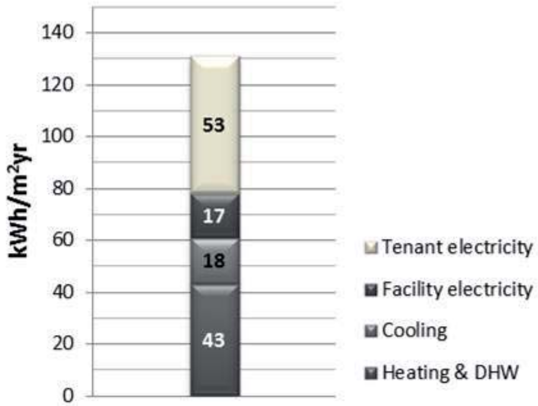

Figure 3.3 *End-use energy (monitored 2009). DHW stands for domestic hot water.*

Jungmannen 3, Malmö

Location	Malmö (N 55.61° E 12.99°)
Climate	HDD 2893/ CDD 215
Completion year	2010
Client/developer	Midroc Property Development
Architect	White
Contractor	Divided
Tenant	Ramböll
Tot. floor area	4800 m^2 A_{temp}
Floors	5
Operation	Office, restaurant, apartments
Office hours	Weekdays 8-18
Plan type	Landscape
Space efficiency	20 m^2/employee
References	Sjöqvist (2010); Herneheim (2011)

Figure 3.4 Photo by Midroc.

Building design

This building has a compact shape and an open plan office space with a central communication space. Room height is 3.0 m. The construction is heavy with concrete sandwich walls with metallic façade elements and a U-value of 0.25 W/m^2K. The U-values of the roofs are 0.13 and 0.22 W/m^2K. WWR is only 0.25 and the windows have a U-value of 1.3 W/m^2K (incl. frame) and a SHGC of 32%. In addition, there are external motorised blinds. The airtightness was measured to 0.7 l/sm^2 at 50 Pa pressure difference.

Figure 3.5 Plan by White arkitekter.

HVAC+L

The target indoor temperature is 22°C. The building is connected to district heating and cooling. Heating is distributed with radiators. Cooling is distributed with the supply air and night ventilation is possible for extra summer cooling. The ventilation system is a VAV-system with active ceiling air diffusers (Lindinvent TTD). Built-in sensors (occupancy and temperature) keep the airflow low and the supply temperature can be kept very low without causing draught problems. Cooling with ambient air is used most of the year. An efficient rotating heat exchanger with a measured efficiency of 80% recovers the heat from return air. The electric lighting system is controlled by the occupancy- and daylight sensors located in the air diffusers.

Energy performance

The specific end-use energy according to BBR is estimated to **43 kWh/m^{2}yr** (excl. tenant electricity), calculated with VIP Energy (see Figure 3.6). This building is certified according to EU GreenBuilding.

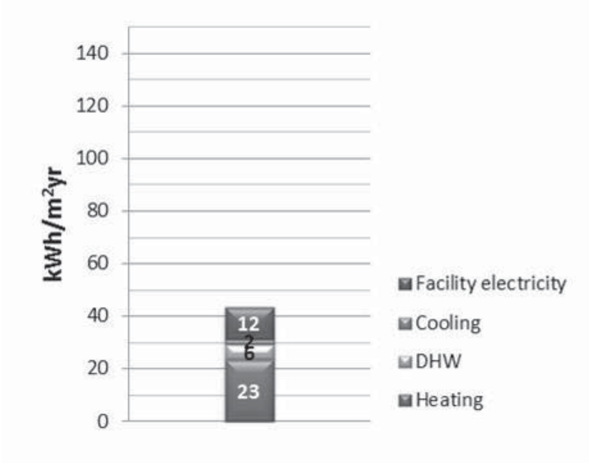

Figure 3.6 *End-use energy (calculated).*

Kaggen, Malmö

Location	Malmö (N 55.61° E 12.99°)
Climate	HDD 2893/ CDD 215
Completion year	2007
Client/developer	NCC Property development
Architect	Metro Arkitekter
Contractor	NCC
Tenants	NCC et al.
Tot. floor area	9400 m^2 A_{temp}
Floors	6
Operation	Office, café, hair dresser
Office hours	Weekdays 8-18
Plan type	Landscape
Space efficiency	13-20 m^2/employee
References	Söderling (2010)

Figure 3.7 Photo by Rafael Palomo.

Building design

The building has a square form and the open plan office space is located around a large atrium in the south with communication space and natural daylight inlet. The building is compact with a surface-to-volume ratio of 0.2 m^{-1}. The general room height is 2.7 m but along the façade, where there are no ducts, the height is 3.0 m. The Building envelope is airtight (not measured) and well insulated with an average U-value of 0.50 W/m^2K. The walls are concrete sandwich elements with a U-value of 0.31 W/m^2K. The WWR is 52% and the WFR is 20%. The windows have a U-value of 1.3 W/m^2K (incl. frame) and a SHGC of 31%. Internal sun screens are manually controlled.

Figure 3.8 Plan by Metro Arkitekter.

HVAC+L

The set-points for indoor air temperature are 21-25°C. The building is provided with district heating and cooling and an electric boiler for hot service water production. A VAV-system with active ceiling air diffusers (Lindinvent TTD) with built in sensors (occupancy and temperature) keeps the airflow very low, about 30% of maximum on a yearly basis. The air-flow varies from 0.35-1.5 l/sm². Because off the efficient rotating heat exchanger (measured efficiency is 83%) and the low airflow, there is no need for a heating battery in the air handling unit. The supply air temperature is 15-18°C and SFP is 1.9 kW/m^{3}s^{-1}. The electric lighting system is controlled by the occupant- and daylight sensors in the air diffusers.

Energy performance

The specific end-use energy according to BBR was 65 kWh/m^2 in 2009 (excl. tenant electricity) as shown in Figure 3.9. The building is certified according to EU GreenBuilding.

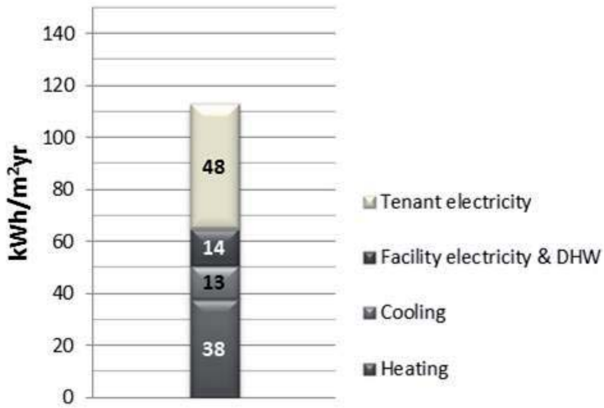

Figure 3.9 End-use energy (monitored 2009).

Kungsbrohuset, Stockholm

Location	Stockholm (N 59.33° E 18.05°)
Climate	HDD 3203/ CDD 261
Completion year	2010
Client/developer	Jernhusen Blekholmen AB
Architect	Strategisk arkitektur
Contractor	Divided contract
Tenant	Jernhusen, Schibsted, et al
Tot. floor area	21 000 m^2 (office)
Floors	12+ garage
Operation	Office, hotel, restaurant, garage
Office hours	18h weekdays
Plan type	Flexible
Space efficiency	10-18 m^2/employee
References	Larsson (2010); Sundholm (2010)

Figure 3.10 Visualisation by Strategisk arkitektur.

Building design

The narrow-shaped building has a flexible indoor plan with both open plan office space and individual office rooms. The room height is 2.85 m. The building has a double skin façade with an outer, tinted and ventilated, glass façade to keep the solar heat out and an inner façade with 50% WWR. The windows are well insulated with U-values between 0.7-1.1 W/m^{2}K. The U-value of the walls is 0.2 W/m^{2}K and the average U-value of the envelope is 0.42 W/m^{2}K. The envelope is very airtight with a measured airtightness of 0.3 l/sm^2 at 50 Pa pressure difference.

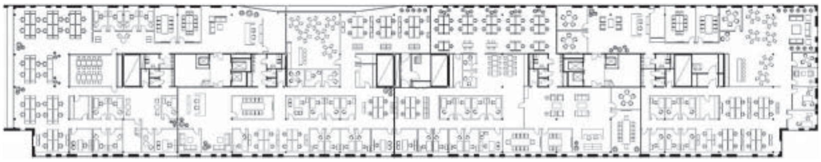

Figure 3.11 Plan by Strategisk arkitektur.

HVAC+L

The control set-points for indoor temperature are 20-26°C. The building is connected to district and geothermal heating (partly from Lake Klara). Kungsbrohuset will also to some extent (15-25%) be heated by the 200 000 people passing daily through the Central railway station, ensured with an air-to-water heat exchanger. The cooling system is connected to district and geothermal cooling (partly from Lake Klara). The cooling is distributed via active chilled beams and night ventilation is activated when needed. Each hour, the building receives detailed weather forecast via the GSM network, which helps optimize the heating and cooling systems. The ventilation is a CAV-system with high speed facilities in meeting rooms. The airflow is 1.5 l/sm^2 and the total SFP is only 1.0 kW/m^3s^{-1}. The efficiency of the heat exchanger is estimated to 75%. Installed power for electric lighting is 10-15 W/m^2 and stairwells are lit by daylight via fibre-optic cables. The power for television displays and mobile phone chargers is cut off during nights and weekends with a “green button”. The building’s energy use is displayed in real-time in the lobby, in order to inspire people to save more energy.

Energy performance

The specific end-use energy according to BBR is estimated to **47 kWh/m²** (excl. tenant electricity) as shown in Figure 3.12. The building is certified according to Miljöbyggnad (Gold target) and EU GreenBuilding.

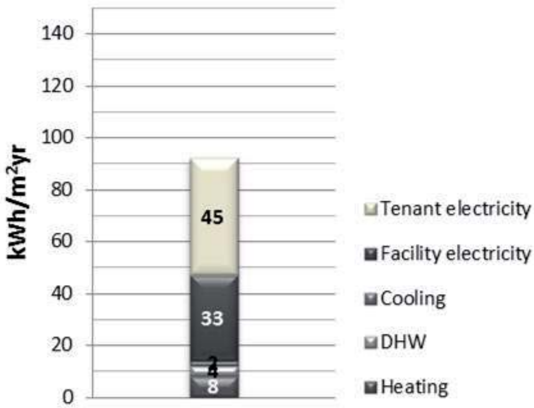

Figure 3.12 End-use energy (calculated).

Pennfäktaren (renovation), Stockholm

Location	Stockholm (N 59.33° E 18.06°)
Climate	HDD 3203/ CDD 261
Completion year	1977/2009
Client/developer	Vasakronan
Architect	Reflex Arkitekter
Contractor	Divided contract
Tenant	Many different
Tot. floor area	10 458 m^2 A_{temp} (office)
Floors	9+ garage
Operation	Office, restaurant, stores
Office hours	-
Plan type	90% landscape
Space efficiency	14 m^2/employee
References	(Zettergren 2010)

Figure 3.13 Visualisation by Reflex Arkitekter and Vasakronan.

Building design

The building was originally constructed in 1977 but completely rebuilt in 2009 with a high eco-focus. The retrofitting was limited because of the low room height (2.35-2.6 m) and a complicated load bearing system. A glass façade with an additional outer glass for sun and noise protection was installed on the north facades. The windows on the south facades were replaced with new ones, which are screen printed with a graphic pattern for sun protection. The overall window U-value is ≤1.2 W/m^2K.

Figure 3.14 Plan by Reflex Arkitekter and Vasakronan.

HVAC+L

The control set-points for indoor temperature are 20-26°C. The building is now provided with district heating and cooling and a new ventilation system. A total of 100 m^2 solar collectors on the roof provide DHW and a large share of the cooling demand via two sorption refrigeration machines (Desicool from Munthers) which cool the supply air. In addition, there are two conventional cooling machines. The ventilation is a VAV-system with a ring-formed duct system and heat recovery. The air flow is controlled by air temperature, CO2 and occupant sensors and the maximum air flow is 2.4 l/sm^2. Occupant- and daylight sensors control the lighting system, which has an average installed power of 7.2 W/m^2. There is also a natural daylight inlet in the stairwell. Some of the electric power is produced by 44 m^2 photo voltaic (PV) placed on the roof. Vasakronan offers their tenants a "green leasing" which means that the rent will be reduced if they consume less energy.

Energy performance

Before renovation, the end-use energy was approximately 257 kWh/m^{2}yr (excl. tenant electricity). The new end-use energy according to BBR is estimated to 98 kWh/m^{2}yr (excl. tenant electricity) as shown in Figure 3.15. Pennfäktaren is certified according to EU GreenBuilding and pre-certified according to LEED Core and shell (Gold).

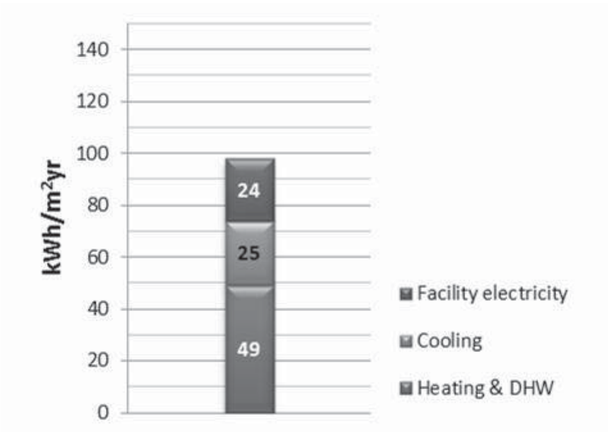

Figure 3.15 End-use energy (calculated).

Waterfront, Stockholm

Location	Stockholm (N 59.33° E 18.05°)
Climate	HDD 3203/ CDD 261
Completion year	2010
Client/developer	Jarl Asset Management
Architect	White arkitekter
Contractor	PEAB
Tenant	Many different
Tot. floor area	24 420 m^2 A_{temp} (office)
Floors	11
Operation	Office (+congress, hotel)
Office hours	Flexible
Plan type	Flexible
Space efficiency	7-22 m^2/employee
References	Waterfront (2009); Berglund (2010)

Figure 3.16 View by White.

Building design

This large office is one of three buildings in a large congress complex in the centre of Stockholm City. It has a load bearing construction of concrete floors and steel columns. The north facing walls have glass façades and the other facades have floor-to-ceiling narrow windows with tinted glass. The south façade is partly protected from the sun by the adjacent hotel and in addition there are internal sun-screens on all facades. The original plan was an open plan arrangement but most of the tenants preferred individual office rooms. The room height is 2.7 m.

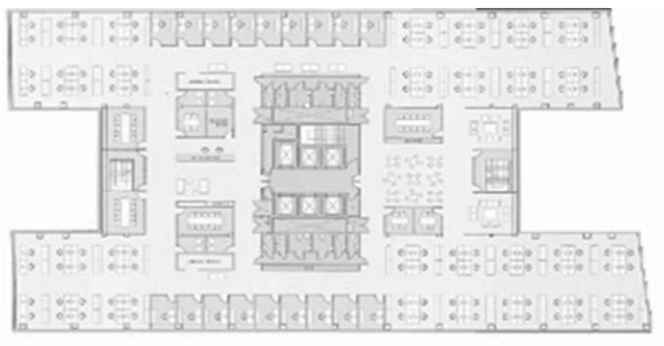

Figure 3.17 Plan by White.

HVAC+L

The HVAC system is designed to maintain an indoor temperature of 20-25°C. Heating is distributed in a concordant system, i.e. heat is moved and redistributed between the different buildings - from surplus to shortfalls- made possible because of the different operation hours and demands. The office is mainly heated with district heating and floor convectors. The building is cooled by water drawn from Lake Klara, stored in 250 tonne ice tanks in the basement. The sea water pump covers 40% of the cooling demand; the rest is produced in the ice tanks. Cooling is distributed with ceiling baffles and the cooling output is 85 W/m^2. The cooling and heating systems are controlled by a weather forecast feed forward system. The ventilation system is a VAV-system with four separate air handling units on each floor. The air flow is CO_2 controlled and can range from 20-100% with an average flow of 2.0 l/sm^2. Energy efficient fans and pumps are installed.

Energy performance

The end-use energy for heating and cooling in the office building is estimated to **42 kWh/m^{2}yr**. No information was found on other energy items so these figures are not presented in Figure 3.18. Stockholm Waterfront will be certified according to EU GreenBuilding and LEED (class unknown).

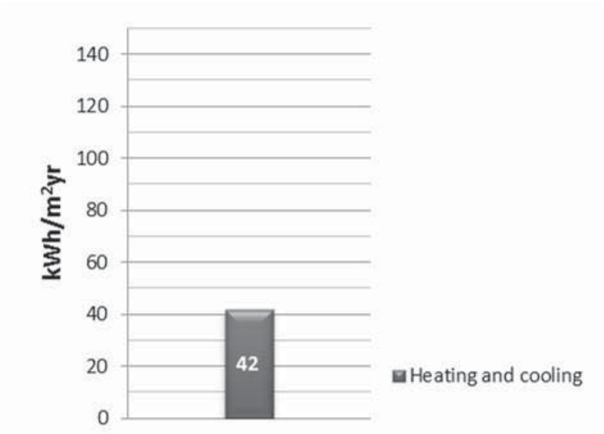

Figure 3.18 *End-use energy, heating and cooling only (calculated), other posts are not available.*

3.2.2 Norway

Aibel, Sandnes

Location	Stavanger (N 58.85° E 5.74°)
Climate	HDD 2663 / CDD 136
Completion year	2006
Client/developer	Seabrokers AS
Architect	Brandsberg-Dahls
Tenant	Aibel AS
Tot. floor area	23 300 m^2 A_{temp} (office)
Floors	6 + garage
Operation	Office and restaurant
Operation hours	85 h/week
Plan type	30/70 cell/landscape
Space efficiency	20 m^2/employee
References	Grini, Mathisen et al. (2009)

Figure 3.19 Photo by Johannes Marburg.

Building design

Aibel in Sandnes has a compact building shape with a 800 m^2 central atrium partly covered by glass, with a U-value of 1.6 W/m^{2}K. The façade has a concrete sandwich construction. The windows have a U-value of 1.25 W/m^{2}K and the SHGC is 33%. For sun shading there are internal Venetian blinds. The WWR is 54% but the glazing-to-floor ratio (GFR) is only 12%. The average U-value of the envelope is 0.41 W/m^{2}K and the design value of airtightness is 1.0 ach at 50 Pa pressure difference.

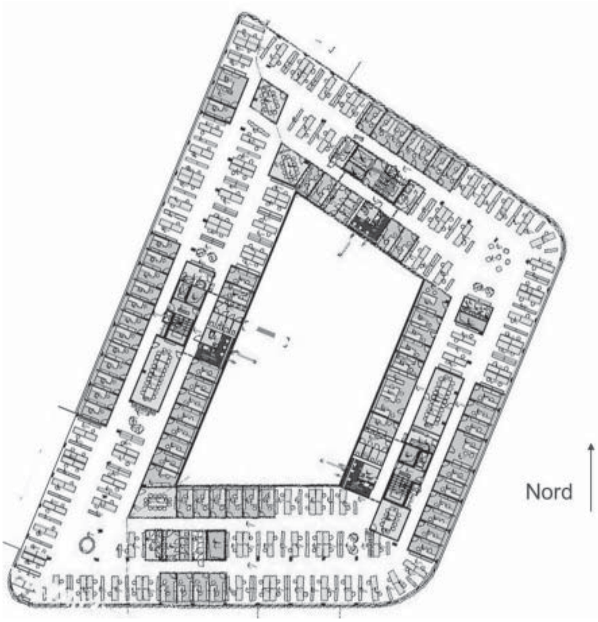

Figure 3.20 Plan (SINTEF Byggforsk).

HVAC+L

The building is connected to district heating and cooling. Heat is distributed by radiators but there are no room units for cooling. The control set-points for indoor air temperature are 20-23°C. At night, the indoor air temperature is allowed to drop to 19°C. The ventilation system is a VAV-system, controlled by occupant- and CO_2 sensors. The air is distributed via an aluminium "climate ceiling" which cools the air. The maximum air flow is 2.4 l/sm^2 during work hours and 0.24 l/sm^2 at night (as extra cooling). A liquid-coupled heat exchanger with an efficiency of 64% (calculated value) recovers heat from the exhaust air. The SFP is 2.0 kW/m^{3}s^{-1} (design value). Occupant sensors also control the lighting system which has an installed power of 10 W/m^2. Installed power for computers is estimated to 6 W/m^2.

Energy performance

The total end-use energy was **134 kWh/m^2** in 2008 (incl. tenant electricity) as shown in Figure 3.21.

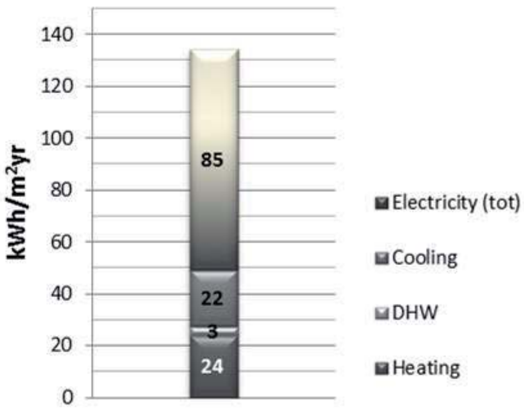

Figure 3.21 End-use energy (monitored 2008).

Bravida, Fredrikstad

Location	Fredrikstad (N 59.22° E 10.93°)
Climate	HDD 3800 / CDD 182
Completion year	2002
Client/developer	Lillebæk
Architect	Multiconsult AS
Tenant	Bravida and others
Tot. floor area	6038 m^2 A_{temp}
Floors	3
Operation	Office
Office hours	8-16 weekdays
Plan type	Mostly landscape
Space efficiency	-
References	Grini, Mathisen et al. (2009)

Figure 3.22 Photo by SINTEF Byggforsk.

Building design

The two rectangular buildings are connected on the short sides by a glazed communication space, which has an East-West orientation. The concrete joist floor is exposed in the ceilings. External walls are wooden frame structures with a U-value of 0.2 W/m^{2}K. The average U-value of the envelope is 0.71 W/m^{2}K and the design value of airtightness is 1.5 ach at 50 Pa pressure difference. The windows have a U-value of 1.4-1.6 W/m^{2}K and the glass SHGC is 32-48%. The glass area is small, the WWR is 36% and the WFR is 19% including the glass atrium. Solar shading devices are manually controlled and consist of external Venetian blinds to the east and internal curtains to the west and south.

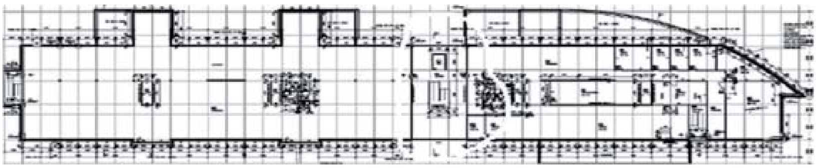

Figure 3.23 Plan by Multiconsult AS.

HVAC+L

Control set-points for indoor temperature are 22-26°C but at night, the indoor air temperature is allowed to drop to 20°C. A geothermal heat pump with 15 boreholes produces warm water for heating. Oil is used as back-up system, which also supplies the building with cooling when needed (peak load). In addition, there are 300 m^2 of solar thermal collectors on the south façade for extra heat production but these have not been working as planned. Heating and cooling is distributed to the rooms with the ventilation air through a "climate ceiling". The glass atrium is provided with hydronic radiant floor heating. The ventilation system is a VAV-system, controlled by occupant sensors. The maximum air flow is 2 l/sm^2 and the SFP is 2.0 kW/m^3s^{-1} (design value). The system operates 85 h/week. A rotating heat exchanger with a measured efficiency of 61% recovers heat from the exhaust air. Occupant sensors also control the lighting system which has an installed power of 7.1 W/m^2. The installed power for computers is estimated to 2 W/m^2.

Energy performance

The total end-use energy was **135 kWh/m²** in 2008, as shown in Figure 3.24.

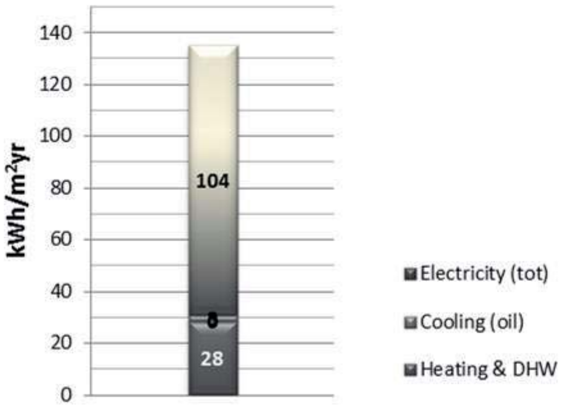

Figure 3.24 End-use energy (monitored 2008).

Stavanger Business Park H5

Location	Stavanger (N 58.96° E 5.72°)
Climate	HDD 2663 / CDD 136
Completion year	2013
Client/developer	NCC PD
Architect	Plank Arkitekter
Contractor	NCC
Tenant	-
Tot. floor area	9203 m^2 (heated BRA)
Floors	5 + garage
Operation	Office, garage
Office hours	-
Plan type	Flexible
Space efficiency	16 m^2/employee
References	(Haugland and Haugstad 2010)

Figure 3.25 Visualisation by Plank Arkitekter.

Building design

The two buildings are connected by a glazed communication space. The Building envelope is a well-insulated and airtight concrete construction. The average U-value is 0.30 W/m^{2}K and the design value of airtightness is 1.5 ach at 50 Pa pressure difference. The U-value of the walls is 0.18 W/m^{2}K. The windows have a U-value of 1.1 W/m^{2}K and the total SHGC including exterior solar shading devices is 12% (glass 35%). The glazing area is relatively small with WWR 32% and WFR 14%.

Figure 3.26 Plan by Rom & Design.

HVAC+L

The control set-points for indoor temperature are 20-25°C. The building is provided with district heating and cooling. The heat is distributed via radiators but there are no room units for cooling. Instead there is a cooling battery in the central AHU. At night, the indoor temperature is allowed to drop to 19°C. The ventilation system is a VAV-system, controlled by occupant sensors and indoor air temperature. The average air flow is 1.9 l/sm^2 during working hours and 0.55 l/sm^2 at night (night ventilation as extra cooling effect). A rotating heat exchanger with an estimated efficiency of 80% recovers heat from the exhaust air. The SFP is 2.0 kW/m^3s^{-1} (design value). Occupancy and daylight sensors control the lighting system, which has an installed power of 6.4 W/m^2.

Energy performance

The specific end-use energy according to BBR is estimated to **62 kWh/m^2yr** (excl. tenant electricity), calculated with SIMIEN (see Figure 3.27). Stavanger BP is aiming for a certificate according to EU GreenBuilding.

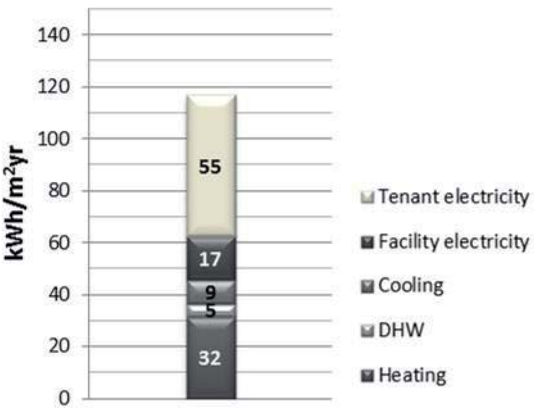

Figure 3.27 *End-use energy (calculated).*

UN House (renovation), Arendal

Location	Arendal (N 58.46° E 8.77°)
Climate	HDD 3001 / CDD 172
Completion year	1965/2006
Client/developer	GRID-Arendal
Architect	A7 Arkitekter
Contractor	Skanska
Tenant	GRID (UNEP)
Tot. floor area	2391 m^2 A_{temp} (office 428 m^2)
Floors	5+1
Operation	Office, school, health centre
Operation hours	50 h/week
Plan type	Landscape and cell
Space efficiency	19.5 m^2/employee (office)
References	Skanska (2008b); Grini, Mathisen et al. (2009)

Figure 3.28 Photo by SINTEF Byggforsk.

Building design

The building was originally constructed in 1965 but completely rebuilt in 2006 with a focus on energy efficiency and carbon neutrality. A double skin façade with 40 cm cavity was installed in order to insulate and ventilate the façade. Furthermore, 20-30 cm insulation was added to the roof and external walls. The envelope's average U-value is 0.66 W/m^{2}K. The airtightness was improved but because of the exposed position by the sea the design value of airtightness was estimated to 2.0 ach at 50 Pa pressure difference. The windows' total U-value is 1.0 W/m^{2}K and the g-value is 0.27 (double glass). The WWR is 50% and the WFR is 25%. Manually controlled solar shading screens are installed in the double skin facade cavity.

Figure 3.29 Plan originally by A7 Arkitekter. Reconstruction.

HVAC+L

The target indoor temperature is 21-23°C. Two new cooling machines, connected to seawater heat pumps with a 1.5 km long pipe system, produce 95% of the building's heating and cooling demand. An electric boiler covers the peak load. New solar thermal collectors (30 m^2) cover 50% of the domestic hot water demand. Radiators are used for space heating and ceiling elements provide both radiant cooling and supply air. The ventilation is a VAV-system controlled by occupant sensors. The airflow rate is 2.4 l/sm^2 and the SFP is estimated to 2.9 kW/m^3s^{-1}. The exhaust air is collected at a single point on each floor, to reduce the pressure drop, and a rotating heat exchanger with an estimated efficiency of 65% recovers the heat from the exhaust air. Occupancy sensors control the lighting system with an installed power of 7 W/m^2. The installed power for office equipment is 10.5 W/m^2. The building uses 100% renewable electricity according to the electricity provider.

Energy performance

Before renovation, the end-use energy was approximately 300 kWh/m^2yr. The new specific end-use energy according to BBR was 52 kWh/m^2 (excl. tenant electricity) in 2008, as shown in Figure 3.30. The building is now carbon neutral.

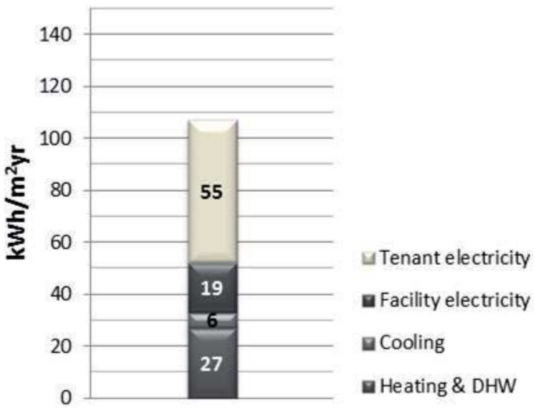

Figure 3.30 End-use energy (monitored 2008).

3.2.3 Denmark

Kolding Company House III

Location	Kolding (N 55.53° E 9.47°)
Climate	HDD 2415/ CDD 240
Completion year	2009
Client/developer	NCC Property Development
Architect	C. F. Møller Architects
Contractor	NCC Construction
Tenant	Alectia, Hjem-Is, others
Tot. floor area	5147 m^2
Floors	2 + basement
Operation	Office, restaurant
Operation hours	8-17
Plan type	Flexible
Space efficiency	20 m^2/employee
References	Ladekjaer (2011); NCC (2011a)

Figure 3.31 Photo NCC Property Development.

Building design

The building shape is square with a central, uncovered, courtyard for daylight access. The envelope is well insulated and very airtight with a concrete sandwich construction and an average U-value of 0.28 W/m^2K (incl. thermal bridges). WWR is 40% and WFR is 17%. The U-value of windows is 1.0 W/m^2K and the measured airtightness is 0.6 l/sm^2 floor area at 50 Pa pressure difference (w_{50}).

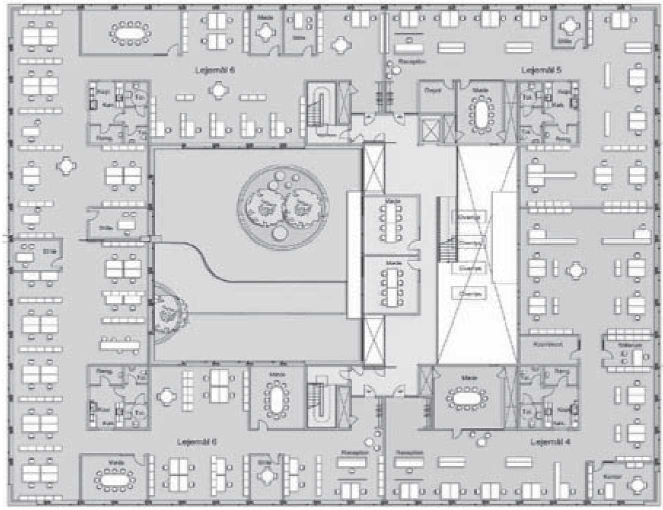

Figure 3.32 Plan by NCC Property Development.

HVAC+L

The target indoor temperature is 23°C and the cooling set-point is 25°C. The building is connected to district heating and heat is distributed with radiators. There are no room units for cooling but a cooling battery in the AHU cools the supply air. Night ventilation is possible for extra cooling during summer and the bought cooling energy can therefore be set to zero (Danish regulations). The ventilation is a VAV-system (20-100%) with a maximum air flow rate of 1.8 l/sm^2. A rotating heat exchanger with an efficiency of 84% (design value) recovers heat from exhaust air. The lighting system is according to the GreenLight Standard. It is controlled by occupant- and daylight sensors and the estimated installed power is only 4 W/m^2 according to the energy calculation input.

Energy performance

The specific end-use energy according to BBR is estimated to 36 kWh/m^2yr (excl. tenant electricity), calculated with Be06 (see Figure 3.33). Note that the basement area is included in this calculation and that a more correct specific energy use probably would be 37 kWh/m^2yr. The building is certified according to EU GreenBuilding and complies with Danish low energy class 1 (BR08).

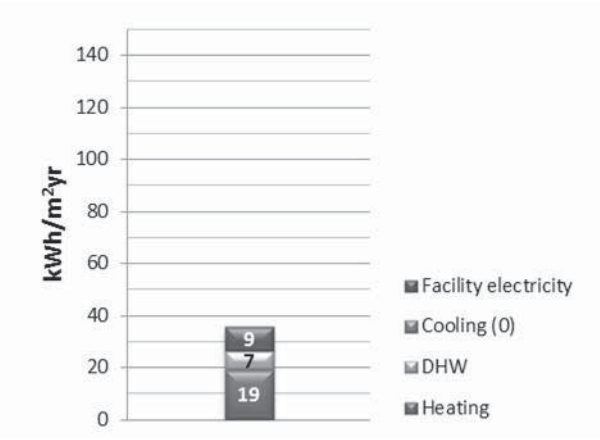

Figure 3.33 End-use energy (calculated).

Skejby Company House III

Location	Aarhus (N 56.19° E 10.18°)
Climate	HDD 2786/ CDD 191
Completion year	2011
Client/developer	NCC Property Development
Architect	C. F. Møller Architects
Contractor	NCC
Tenant	-
Tot. floor area	5900 m^2 A_{temp} (1-3)
Floors	3 + basement
Operation	Office, restaurant
Operation hours	8-17
Plan type	Flexible
Space efficiency	20 m^2/employee
References	Jensen (2011); NCC (2011a)

Figure 3.34 Photo by NCC Property Development.

Building design

This office is situated in the business area Skejby Park next to Aarhus. The building is well insulated with a quite heavy construction with load bearing internal concrete walls. The exterior walls are wooden wall elements with a U-value of 0.16 W/m^2K. The average U-value of the envelope is 0.29 W/m^2K (incl. thermal bridges). The WWR is only 18% and the WFR is 15%. The windows will have a U-value of 1.1 W/m^2K and the SHGC is 36%. Manually controlled internal venetian blinds are used to reduce solar gains.

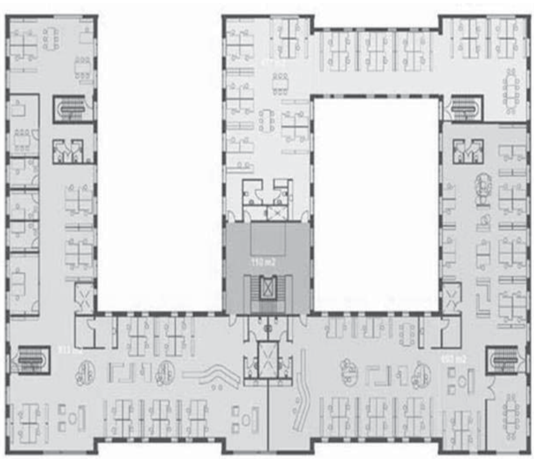

Figure 3.35 Plan by NCC Property Development.

HVAC+L

Control set-points for indoor temperature are 20-25°C. The building is provided with district heating and heat is distributed with radiators. Cooling is provided with cooling machines (COP 3.2) which cool the ventilation air. The ventilation system is a VAV-system with ceiling air diffusers for sub-cooled air (17°C) and low air-flows (30%). The average air flow is 1.5 l/sm^2 during work hours, otherwise the ventilation is off but night ventilation is possible during summer as extra cooling. A rotating heat exchanger with an efficiency of 80% (design value) recovers heat from the exhaust air. The lighting system is according to the GreenLight Standard. It is controlled by occupancy- and daylight sensors and the estimated installed power is 8 W/m^2. The installed power for computers is estimated to 6 W/m^2.

Energy performance

The specific end-use energy according to BBR is estimated to 46 kWh/m^2yr (excl. tenant electricity), calculated with Be06 (see Figure 3.36). The building will be certified according to EU GreenBuilding and has a pre-assessment according to BREEAM (Very Good).

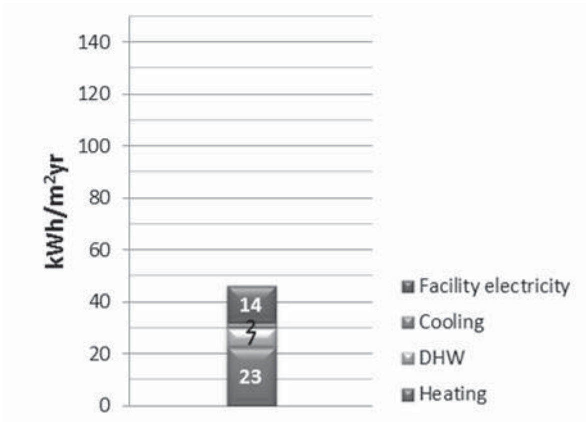

Figure 3.36 End-use energy (calculated).

3.2.4 Finland

Alberga Business Park (building A)

Location	Espoo (N 60.21° E 24.66°)
Climate	HDD 3921 / CDD 251
Completion year	2012
Client/developer	NCC Proprty Development
Architect	Brunow & Maunula
Contractor	NCC
Tenant	ÅF, SATS
Tot. floor area	8460 m^2 A_{temp} (office)
Floors	5 + underground garage
Operation	Office, gym, garage
Office hours	Weekdays 8-17
Plan type	Flexible
Space efficiency	18 m^2/employee
References	Utriainen (2011); NCC (2011b)

Figure 3.37 Visualization by Arkitekturbyrå Brunow & Maunula.

Building design

This will be the first building of five separate office blocks in Alberga Business Park. The Building envelope is well insulated with U=0.09 W/m^2K in the roof and U=0.17 W/m^2K in the walls. The average U-value is 0.36 W/m^2K. The windows have a U-value of 1.0 W/m^2K and a SHGC of 46% and the WWR is 34%. The design value of air leakage is 0.9 ach at 50 Pa pressure difference.

Figure 3.38 Plan by Arkitekturbyrå Brunow & Maunula.

HVAC+L

The control set-point for indoor temperature is minimum 21°C. The building is provided with district heating and a condenser chiller with COP of 5. The ventilation system is a VAV-system controlled by occupant sensors and indoor air temperature. The average air flow is 1.7 l/sm^2 during work hours and the SFP is 2.1 kW/m^3s^{-1} (design value). During summer, the Indoor Air Quality class is degraded from the highest class S1 to S2 in order to save cooling and ventilation energy. A rotating heat exchanger with an estimated efficiency of 74% (design value) recovers heat from the exhaust air. Occupancy and daylight sensors control the lighting system, which has an installed power of 7-15 W/m^2.

Energy performance

The specific end-use energy according to BBR is estimated to 62 kWh/m^2yr (excl. tenant electricity and gym) as shown in Figure 3.39. The office part of the building achieves Finnish Energy Class A according to calculations. The building will be certified according to EU GreenBuilding and BREEAM Very Good (goal).

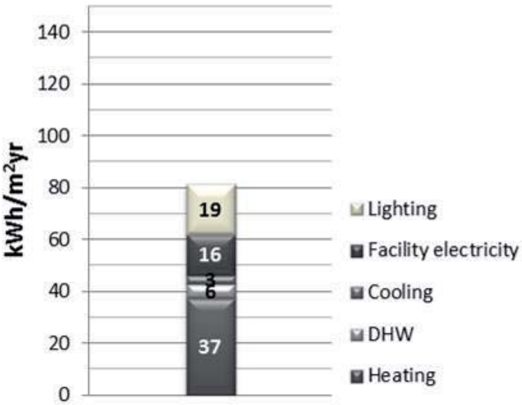

Figure 3.39 End-use energy (calculated).

Plaza Pilke, Vantaa

Location	Vantaa (N 60.29° E 25.04°)
Climate	HDD 3891/ CDD 221
Completion year	2011
Client/developer	NCC Property Development
Architect	Forma-Futura
Contractor	NCC
Tenant	Ramirent etc
Tot. floor area	6882 m^2 A_{temp}
Floors	7 + garage
Operation	Office, garage
Office hours	Weekdays 8-16
Plan type	Flexible
Space efficiency	20 m^2/employee
References	(Utriainen 2011)

Figure 3.40 Photo by Sini Pennanen.

Building design

Plaza Pilke is the first completed building of the third phase in Plaza Business Park near Helsinki Airport. The building shape is rather compact with a large atrium towards the north for daylight penetration. The layout is flexible and the tenants can choose both landscape and individual office rooms. Room height is 3.0 m. The Building envelope has an average U-value of 0.36 W/m^2K and the windows are well insulated with a U-value of 1.0 W/m^2K. The glass area is limited and the WWR is 27% while WFR is 17%. The design target for airtightness is 0.7 ach at 50 Pa pressure difference.

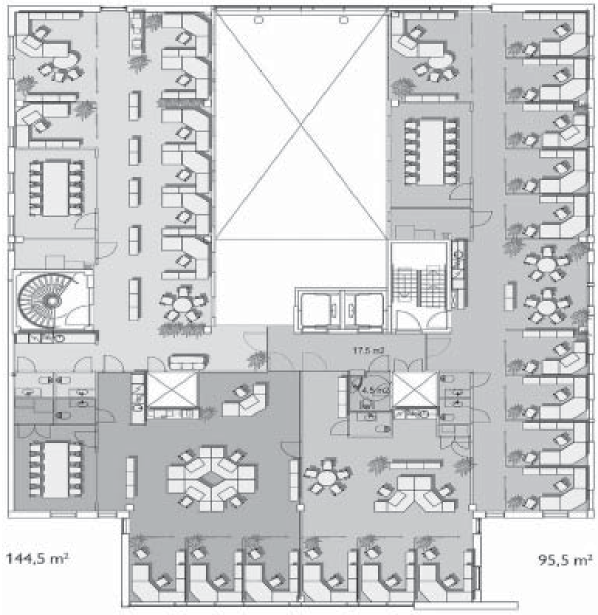

Figure 3.41 Plan from NCC Property Development.

HVAC+L

The control set-points for indoor temperature are 21-25°C. Heat is provided with district heating and radiators. Cooling is provided with a condenser chiller with a COP of 5 and distributed with cooling beams. The ventilation is a VAV-system, controlled by occupant sensors and indoor air temperature. The air flow is 1.76 l/sm^2 (1.56 ach) during work hours and the SFP is 2.45 kW/m^{3}s^{-1} (design value). Rotating heat exchangers with estimated efficiencies of approximately 75% recover heat from the exhaust air. Occupancy and daylight sensors control the lighting system, which has an installed LPD of 5-15 W/m^2. Heat balance simulations were carried out with IDA ICE for an office room and a meeting room to ensure that the cooling system is sufficient during a summer day.

Energy performance

The specific end-use energy is estimated to **82 kWh/m²yr** (excl. office equipment but incl. lighting) as shown in Figure 3.42. Plaza Pilke is the first commercial building complying with the requirements of Finnish Energy Class A. The building will be certified according to EU GreenBuilding and to BREEAM (target Very Good).

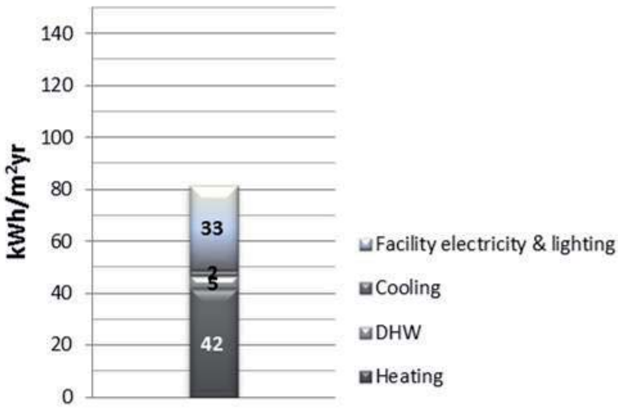

Figure 3.42 End-use energy (calculated).

3.2.5 Germany

In German buildings, primary energy is normally declared but end-use energy is sometimes declared in addition. In the cases where primary energy was declared only, these figures have been re-calculated to end-use energy according to German conversion factors (see Table 3.1).

Table 3.1 Primary energy conversion factors for Germany according to DIN 4701, 2003, index: p primary energy, e end energy (Voss, Herkel et al. 2007).

Type	Source	Primary energy conversion factor kWh_p/kWh_e
Fuels	Oil, natural gas	1.1
	Wood chips, pellets…	0.2
District heating (heating only)	Fossil fuel	1.3
	Biomass	0.1
District heating (CHP)	Fossil fuel	0.7
	Biomass	0.0
Electricity	German mix	3.0

Barnim Service and Administration Centre, Eberswalde

Location	Eberswalde (N 52.83° E 13.83°)
Climate	HDD 2505/ CDD 514
Completion year	2007
Client/developer	District of Barnim
Architect	GAP Architekten
Tot. floor area	17 131 m^2 NFA
Floors	3-4
Operation	Office + conference
Office hours	Weekdays 7-18
Plan type	Individual rooms
Space efficiency	23 m^2/employee
References	Bine (2009b); En0B (2011)

Figure 3.43 Photo by Martin Duckek, GAP.

Building design

This complex of four compact buildings in the North-east of Germany houses the local authorities of Barnim and the district administration centre. In each building, the office rooms are arranged around an unheated glass-covered interior courtyard. The buildings have a concrete skeleton with prefabricated wooden wall elements with cellulose insulation. The U-values of the walls and roof are 0.2 and 0.12 W/m^2K respectively. The windows are triple glazed with U-values of 1.0 and 1.4 W/m^2K. The solar protection consists of automatically controlled two-section exterior blinds which make it possible for daylight penetration in the upper part of the windows even when they are closed. There are also manually controlled interior glare protectors. The buildings' airtightness is estimated to 0.8 ach at 50 Pa. Room height is 3 m and there is no suspended ceiling.

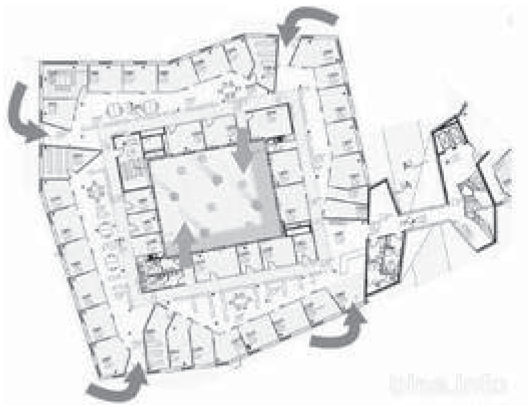

Figure 3.44 Plan by GAP Architekten. 1st floor building D.

HVAC+L

The heating set-point for room air temperature was planned to be 20°C but during 2008, when the building was monitored, the actual room temperature was around 23-24°C. Heat pumps provide the basic heat supply via absorbers installed in the buildings' 9 m deep foundation piles. The absorbers extract geothermal heat and cold from the ground in a hydronic system with buffer storage tanks. When the ambient air is warmer than 8°C, the heat pumps use outdoor air as a heat source instead. Heat is distributed with radiators in the office rooms and floor heating in the communication space. In the summer, the reversible heat pumps use the ground as cold source in combination with a water-glycol re-cooler. Additional cooling is provided with automatic night ventilation via windows. Domestic hot water is provided with a decentralised electrical system. The rooms have high thermal inertia and additional phase change materials (PCM). The ventilation is a conventional balanced system with a rotating heat exchanger (estimated efficiency 80%). Daylight- and occupancy sensors control the electric lighting system and the installed LPD for lighting is 8-12 W/m^2 in office rooms and only 2 W/m^2 in corridors.

Energy performance

Building D was monitored the first two years and the systems are still in a trimming phase. Total monitored primary energy in 2008 was 62 kWh/m^{2}yr (excl. tenant electricity), as shown in Figure 3.45. From this, the specific end-use energy according to BBR was estimated, with German primary conversion factors, to **21 kWh/m^{2}yr** (excl. tenant electricity). In 2009, the District of Barnim received a German Golden quality label for sustainable building.

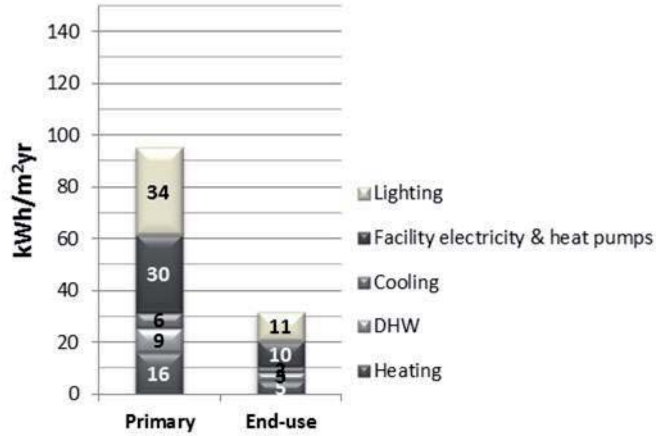

Figure 3.45 *Primary and end-use energy (monitored 2008).*

BOB, Aachen

Location	Aachen (N 50.78° E 6.08°)
Climate	HDD 2156/ CDD 412
Completion year	2002
Client/developer	VIKA Ingenieur
Architect	Hahn Helten
Contractor	B. Walter
Tenant	Vika, Helten, Walter et al
Tot. floor area	2076 m^2 NFA
Floors	4
Operation	Office
Plan type	2-3 persons/room
Space efficiency	22 m^2/employee
References	Kalz, Herkel et al. (2009); BOB (2011); En0B (2011)

Figure 3.46 Photo by Jörg Hempel.

Building design

"Balanced Office Building" (BOB) is a low-energy office concept in Germany. The building has a compact shape and a heavy construction with concrete floors, concrete columns and precast façade panels with concrete interior surface (U=0.17 W/m^2K). There are no loadbearing interior walls, mainly glass walls for daylight penetration. The envelope has an average U-value of 0.48 W/m^2K. The windows are triple glazed with a U-value of 0.8 W/m^2K and SHGC of 50% and internal venetian blinds are controlled by daylight sensors. The WWR is 41%. The building is very airtight with a measured airtightness of 0.3 ach at 50 Pa. Surface-to-volume ratio is 0.37 m^{-1}.

Figure 3.47 Plan by Hahn Helten. Reconstruction.

HVAC+L

For generating heat and cold, there are 28 boreholes and a heat pump (COP 4.3). Heating and cooling is distributed with concrete core temperature control (CCTC) which means that hot and cold water circulate in the concrete floors. The water supply temperature varies between 19-26 °C. The ventilation is a CAV-system with timer. The nominal airflow is only 20 m^3/h and person (~0.26 l/sm^2) and in addition, windows are openable. The ventilation heat exchanger has an efficiency of 75% (measured). Daylight sensors control the lighting system which has an installed LPD of 7.5 W/m^2.

Energy performance

In 2006, the specific end-use energy according to BBR was 19 kWh/ m^2yr (excl. tenant electricity), as shown in Figure 3.48, and the primary energy use was 86 kWh/m^2yr (incl. lighting). The saving with the heat pump is estimated to 40 kWh/m^2yr. BOB is GreenBuilding certified.

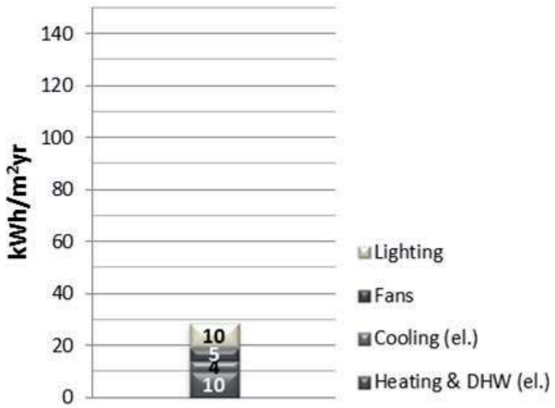

Figure 3.48 End-use energy (monitored 2006).

Energon, Ulm

Location	Ulm (N 48.42° E 9.94°)
Climate	HDD 2822/ CDD 413
Completion year	2002
Client/developer	Software AG Foundation
Architect	Oehler Faigle Archkom
Contractor	Freie Planungsgruppe 7
Tenant	Software AG Foundation
Tot. floor area	6911 m^2 NFA
Floors	5
Operation	Office + restaurant
Office hours	Weekdays 7-18
Plan type	3 persons/room
Space efficiency	13 m^2/employee
References	Kalz, Herkel et al. (2009); En0B (2011); Energon (2011); PHI (2012b)

Figure 3.49   Photo by G8w, 2012 (Wikimedia Commons)

Building design

This very compact, triangular building with a curved façade has a concrete skeleton construction with prefabricated wooden wall elements. There is a large central atrium with communication space, daylight access and ventilation openings. The envelope is well insulated with 350 mm insulation in the walls (U=0.13 W/m^2K), 500 mm in the roof and 200 mm in the slab. The windows are triple glazed with a U-value of 0.84 W/m^2K and an effective SHGC of 17% because of external blinds (glass SHGC is 50%). The WWR is 44%. The building is very airtight with a measured airtightness of 0.2 ach at 50 Pa pressure difference. The room height is 2.9 m and surface-to-volume ratio is 0.22 m^{-1}.

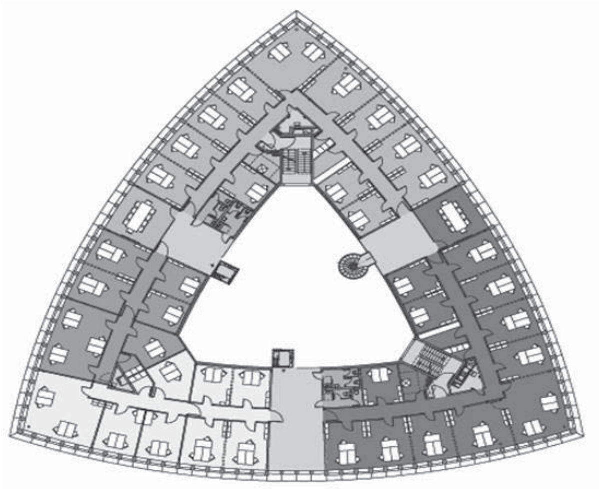

Figure 3.50 Plan by Oehler Archkom Solar Architektur.

HVAC+L

For heating and cooling, there are 40 borehole heat exchangers (100 m deep) in the ground but no heat pump. Heating and cooling is distributed with concrete core temperature control, which means plastic tubes for hot and cold water in the concrete floors. Waste heat from compression refrigeration machines in server rooms is collected and the remaining heat requirement is covered by district heating. The outdoor air is channelled through a 28 m long underground duct (earth-to-air heat exchanger) for preheating/cooling the supply air. When needed, the air is further heated/cooled by the borehole heat exchangers and finally by district heating. The airflow is approximately 1.1 l/sm^2 (30 m^3/h and person). The ventilation heat exchanger has an efficiency of 65% but together with the underground duct, the total system efficiency is 80%. There are 328 m^2 of PVs on the building with a power of 15 kW. Occupancy- and daylight sensors control the lighting system, which has an installed LPD of 14 W/m^2 in office rooms and 10 W/m^2 in corridors.

Energy performance

In 2005, the end-use energy according to BBR was **47 kWh/ m^{2}yr** (excl. tenant electricity), as shown in Figure 3.51, and the total primary energy use was 82 kWh/m^{2}yr. However, the office was not fully occupied that year. Energon is certified as "Quality Approved Passive House".

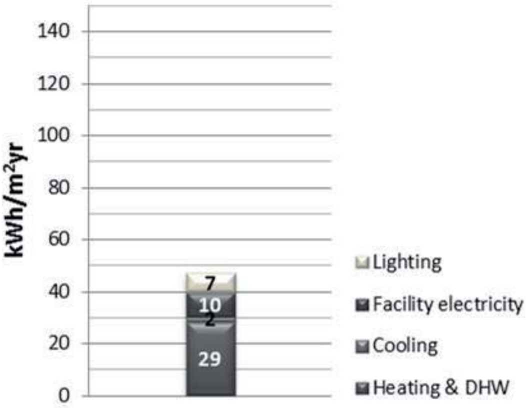

Figure 3.51 End-use energy (monitored 2005).

Lamparter, Weilheim

Location	Weilheim (N 48.62° E 9.54°)
Climate	HDD 2563/ CDD 458
Completion year	2000
Client/developer and tenant	Ingenieur- und Vermessungs-büro Hans Lamparter GbR
Architect	weinbrenner.single.arabzadeh
Tot. floor area	1000 m^2 NFA
Floors	3 (+ underground car park)
Operation	Office
Office hours	Weekdays 7-18
Plan type	2 persons/room (flexible)
Space efficiency	29 m^2/employee
References	(Bine 2001; Eicker, Seeberger et al. 2005; Eicker , Huber et al. 2006; En0B 2011)

Figure 3.52 Photo by weinbrenner.single.arabzadeh architects.

Building design

Lamparter is one of the first and smallest office buildings based on the German Passive House principle and it was built with a cost effective approach. The building has a central open stairwell with a large skylight for natural ventilation and daylight. The building has a steel/concrete skeleton construction with prefabricated wooden wall elements (U=0.14 W/m^2K). The envelope is well insulated with 240-350 mm insulation and an average U-value of 0.3 W/m^2K. The windows are triple glazed with a U-value of 1.1 W/m^2K. The windows are split in two, with an upper part for air- and daylight access. There are external louvres for solar protection. The WWR is 44% and the SHGC is 60%. The building is very airtight with a measured airtightness of 0.3 ach at 50 Pa. Surface-to-volume ratio is 0.4 m^{-1}.

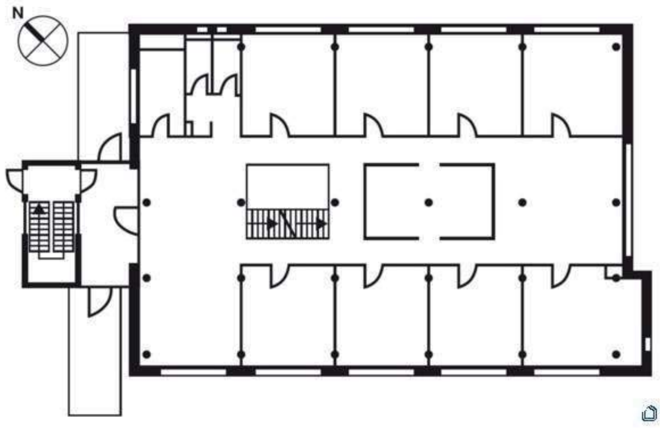

Figure 3.53 Plan by weinbrenner.single.arabzadeh architects.

HVAC+L

The target room temperature is 22°C. The building uses gas-fired condensing boilers for heating and the cooling system is passive. There are no radiators; heat is provided with the AHU. The supply air is drawn through an earth-to-air heat exchanger for cooling/preheating and is further preheated in the AHU rotating heat exchanger (measured efficiency 80%) if needed. The gas-fired condensing boiler system is used for backup heating. The cooling system is a passive night ventilation concept, based on thermal buoyancy and wind forces only. The workers have to manually open the upper sections of the windows when they leave in the evening. The mechanical airflow during the day is 30 m^3/h and person (~0.56 l/sm^2) and the pressure drop is small. A small (4m^2) thermal solar system facing south-south-west produces hot water (87%) and a PV-system on the roof (70 m^2, 8 kW) covers one third of the electricity demand for lighting and ventilation. Daylight sensors control the lighting system and the installed LPD is 11.6 W/m^2 in office rooms and 6.1 W/m^2 in corridors.

Energy performance

The building has been monitored for four years in a research study. Hourly internal loads, temperatures, air change rates, heating and cooling were measured and analysed. In 2000-2003 the average specific end-use energy according to BBR was 23 kWh/ m^2yr (excl. tenant electricity) with a large contribution (37%) from free solar energy (see Figure 3.54). The passive night ventilation system works satisfactorily during a normal central European summer climate but during the exceptionally hot summer of 2003, office temperature exceeded 25°C for too many hours.

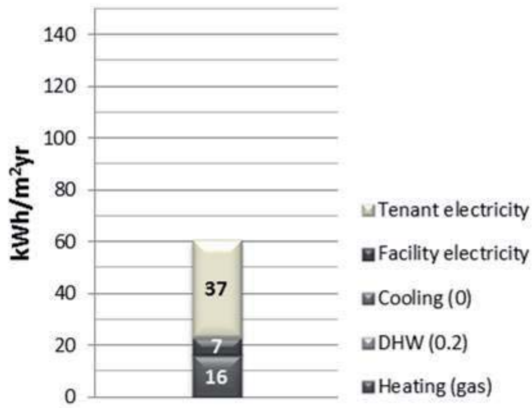

Figure 3.54 End-use energy (monitored 2000-2003, average).

Regionshaus, Hannover

Location	Hannover (N 52.37° E 9.72°)
Climate	HDD 2497/ CDD 397
Completion year	2007
Client/developer	Hanover Region
Architect	bünemann & collegen
Contractor	Bilfinger Berger
Tenant	Hanover Region
Tot. floor area	7134 m^2 NFA
Floors	6
Operation	Office + hall
Office hours	No information
Plan type	2 persons/room
Space efficiency	12 m^2/employee
References	Bine (2009a); En0B (2011

Figure 3.55 Photo by Bilfinger Berger.

Building design

The new "Regionshaus" is an additional building to a complex of existing buildings. A large hall building for 540 people sticks out from the facade on the first floor. The heavy, L-shaped building has a solid reinforced-concrete construction and exterior walls with 160 mm of insulation (U=0.23 W/m^2K). The windows are triple glazed with a U-value of 1.2 W/m^2K and window areas are moderate (WWR is only 30%). Dark anthracite-coloured granite on the facade makes the window openings appear larger. Intermediate sun protection with daylight redirection in the upper part makes it possible for daylight to enter even when the sun protection is closed. In case of strong solar irradiation on the façade, the solar shading is automatically pulled down but it can also be operated manually. The building is airtight with a measured airtightness of 0.4 ach at 50 Pa. The surface-to-volume ratio is 0.3 m^{-1}.

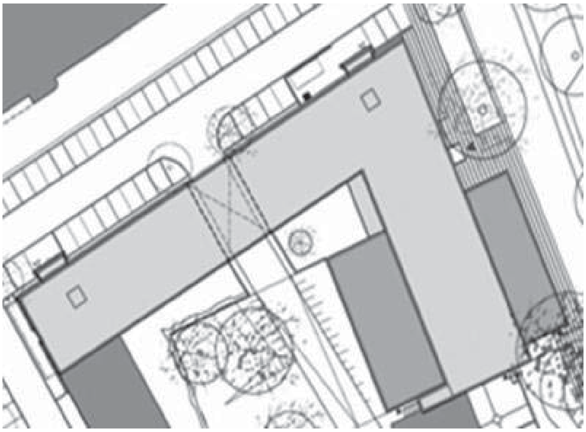

Figure 3.56 Plan by Bilfinger Berger.

HVAC+L

Office heating is supplied by district heating and radiators. The cooling system is nearly passive with a concrete core temperature control, which means that cold water is pumped through plastic tubes within the concrete floors. There are no suspended ceilings. The warm return water is cooled again in a heat sink system with 12 underground boreholes (70 m). A chiller is provided as a reserve. The borehole heat exchanger is also used for pre-heating the supply air in the winter. The hot water production is provided by electricity. A hybrid ventilation system provides the office rooms with natural window ventilation while the hall, meeting rooms and sanitary facilities have mechanical ventilation with heat recovery (unknown airflows and efficiency). Occupancy- and daylight sensors control the lighting system. The power supply to all equipment sockets can easily be switched off on each floor.

Energy performance

In 2008, the primary energy use was 81 kWh/m²yr (excl. tenant electricity). From this, the specific end-use energy was recalculated to 61 kWh/m²yr (excl. office equipment) as shown in Figure 3.57. Because of the window design, the effective solar protection and the moderate climate, no cooling was needed during the monitored years.

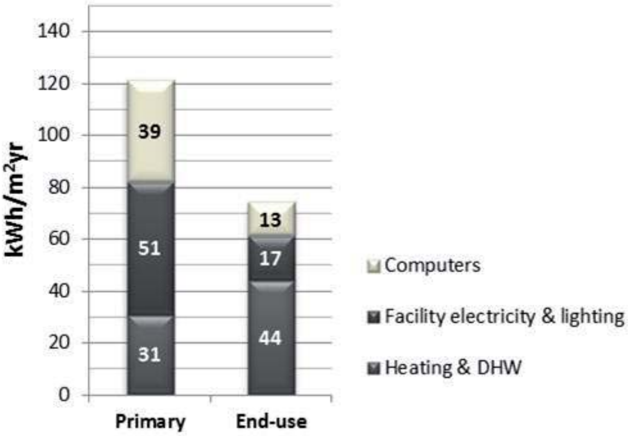

Figure 3.57 Primary and end-use energy (monitored 2008).

Solar Info Center, Freiburg

Location	Freiburg (N 47.98° E 7.85°)
Climate	HDD 2283/ CDD 599
Completion year	2003
Client/developer	PLB
Architect	Architekturbüro Epp
Contractor	No info
Tenant	Provinzial-Leben-Baubetreuung
Tot. floor area	13 822 m^2 NFA
Floors	6 + garage
Operation	Office + conference
Office hours	Weekdays 7-19
Plan type	Individual rooms
Space efficiency	22 m^2/employee
References	Bollin, Fernandes et al. (2008); En0B (2011)

Figure 3.58 Photo by Architekturbüro Epp.

Building design

This large innovation and conference centre lies at the foot of the Schwarzwald mountains in the south of Germany. The U-shaped building has a reinforced-concrete skeleton construction and exposed concrete ceilings with a room height of 2.99 m. The exterior walls are light with 200 mm insulation (U=0.19 W/m^2K). The windows are double glazed with a U-value of 1.3 W/m^2K and the average U-value of the envelope is 0.5 W/m^2K. The WWR is approximately 45% and the WFR is 23%. Venetian blinds are automatically closed when room temperature exceeds 24°C and solar irradiation exceeds 130 W/m^2. No information was found regarding the airtightness. The surface-to-volume ratio is 0.29 m^{-1}.

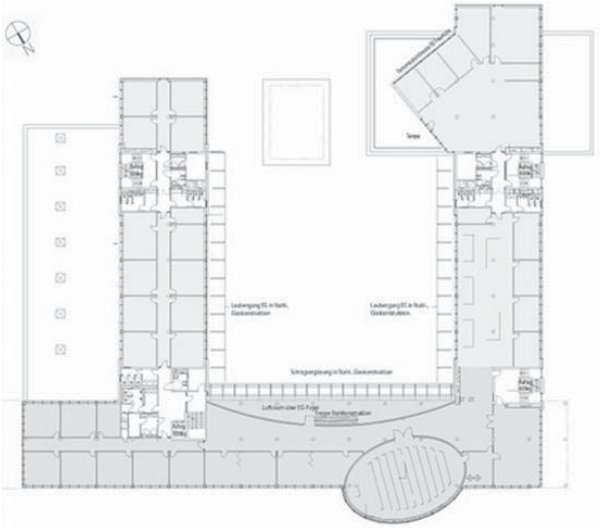

Figure 3.59 Plan by Architekturbüro Epp.

HVAC+L

The building is heated with radiators, which are supplied with district heating from a combined heat and power (CHP) plant at the nearby hospital. Five borehole heat exchangers (80 m deep) are available for cooling the conference area via a floor cooling system. The borehole heat exchangers are also used for pre-heating the supply air in the conference area. The ventilation is a mechanical exhaust air system which secures the necessary hygienic airflow of approximately 7 l/s,person (1-2 ach). Supply air penetrates through window ventilators except for the conference area where there is a balanced supply and exhaust air system with heat recovery. The office rooms are cooled in the summer with mechanical night ventilation (measured to maximum 1.25 ach). An intelligent dynamic operational management concept determines the necessary intensity of night ventilation. The installed LPD is 10 W/m^2 in both office rooms and corridors. A PV system (382 m^2) is installed on the roof and facade and contributes approximately 13 kWh/m^{2}yr of electric energy. The additional bought electric energy is almost 100% CO2 neutral. Four solar collectors are installed to cover the total hot water demand but due to large distribution losses they only cover 30%. Every tenant can control their own space separately via individual time programs.

Energy performance

In 2007, the specific end-use energy according to BBR was monitored to 42 kWh/m^{2}yr (excl. tenant electricity) as shown in Figure 3.60.

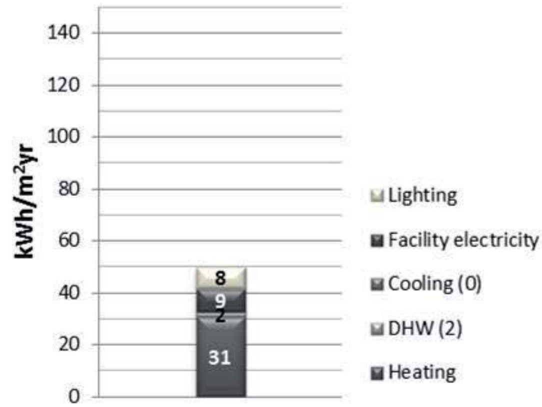

Figure 3.60 End-use energy (monitored 2007).

Wagner & Co, Cölbe

Location	Cölbe (N 50.85° E 8.78°)
Climate	HDD 2277/ CDD 563
Completion year	1998
Client/developer	Wagner & Co Solartechnik
Architect	Architektur Stamm
Contractor	No information
Tenant	Wagner & Co Solartechnik
Tot. floor area	1 948 m^2 NFA
Floors	3
Operation	Office, seminar, exhibition
Office hours	Weekdays 7-18
Plan type	Landscape/cell
Space efficiency	35 m^2/employee
References	Schneiders and Feist (2002); Wille, John et al. (2004); En0B (2011)

Figure 3.61 Photo by Hydro, 2009 (Wikimedia Commons).

Building design

Wagner & Co's administration building, in central Germany, was the first office building built according to passive house principles. The building has a rectangular floor plan with a round ending on the west side. The construction is a concrete skeleton with prefabricated wooden wall elements. The envelope is well insulated with 400 mm insulation in the walls (U=0.13 W/m^2K), 240 mm foam-glass under the slab (U=0.17 W/m^2K) and the roof U-value is 0.11 W/m^2K. The windows are triple glazed (low E with krypton gas fill) with a U-value of 0.8 W/m^2K and a SHGC of 46%. The average WWR is 45%. The automatically controlled external blinds have daylight redirection in the upper part, which makes it possible for daylight to enter even when the sun protection is closed in the lower part. The measured airtightness is 0.75 ach at 50 Pa pressure difference. The surface-to-volume ratio is 0.36 m^{-1}.

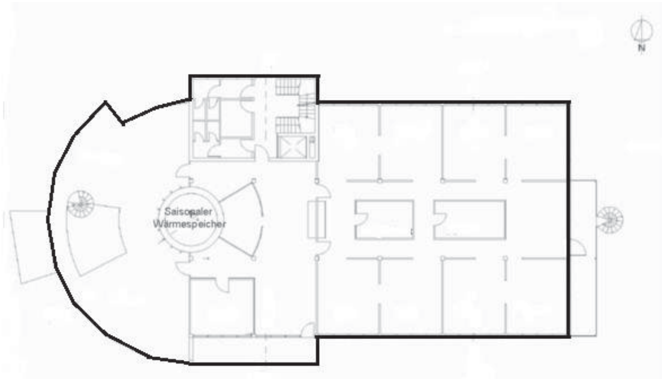

Figure 3.62 Plan originally by Architektur Stamm. Reconstruction.

HVAC+L

The control set-point for heating is 21°C. The building requires heating only from December to February. The small amount of heat is distributed via the supply air and no radiators are needed. The air can be heated to temperatures between 30 and 40°C. The outdoor air is preheated through four 32 m long underground ducts. The air is further heated with the heat exchanger in the ventilation system, a four-way-cross-flow heat exchanger with 80% efficiency (design value). There are additional small heat exchangers which are supplied with solar heating. The solar heating (64 m^2 collectors on the roof) is collected in the warm months and then stored in a huge seasonal storage tank (87 m^3), placed in the centre of the rotunda. For back-up heating, the gas-driven power plant, mainly providing electric power, can be used as a heat plant as well. The balanced ventilation system has an average airflow of 0.5 ach (~0.5 l/sm^2), which is necessary for hygienic purposes. The cooling system is passive. The supply air is pre-cooled in the ground-coupled ducts with a measured cooling capacity of up to 6K during a warm summer day. The building is also cooled at night using natural night ventilation, driven by thermal buoyancy forces. The airflow is approximately 4 ach and the measured cooling capacity is about 3K. Daylight sensors control the lighting system with an intensity set point of 500 lx. The installed LPD of 20 W/m^2 is relatively high compared to current praxis.

Energy performance

The office was monitored and analysed in detail for three years by the Passivhaus Institut. In the season 2000/2001, the total end-use energy was 83 kWh/m^{2}yr (incl. tenant electricity), as shown in Figure 3.63. The experiences have been very positive so far and the occupants are pleased with the indoor climate.

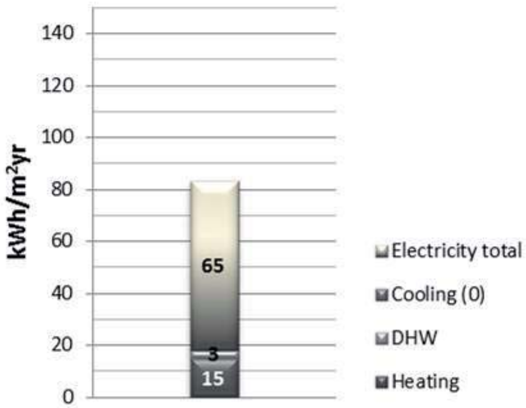

Figure 3.63 End-use energy (monitored season 2000/2001).

3.2.6 Austria

In the office buildings from Austria, information was received on both primary energy and end-use energy. Primary energy conversion factors for Austria are shown in table 3.2.

Table 3.2 Primary energy conversion factors for Austria, index: p primary energy, e end energy (BuildUp 2010).

Type	Source	Primary energy conversion factor kWh_p/kWh_e
Fuels	Gas	1.1
Electricity	“Wienstrom”	2.7

ENERGYbase, Vienna

Location	Vienna (N 48.2° E 16.37°)
Climate	HDD 2394/ CDD 623
Completion year	2008
Client/developer and tenant	Vienna Business Agency
Architect	POS architekten
Contractor	Divided contract
Tot. floor area	7500 m^2 lettable area
Floors	5+garage
Operation	Office and research
Office hours	Weekdays 8-18
Plan type	Mixed
Space efficiency	15 m^2/employee
References	Rauhs, Schneider et al. (2008); ENERGYbase (2009); BuildUp (2010); Greenbuilding (2011); Pos (2011)

Figure 3.64 Photo by Hertha Hurnaus.

Building design

This award-winning office and research centre was built according to the passive-house standard with a great focus on renewable energy and sustainability. The compact and narrow building has a construction of concrete floors and prefabricated wooden wall elements with 26 cm insulation (U= 0.22 W/m^2K). The U-value of the roof is 0.13 W/m^2K and the windows are triple glazed with a U-value of 0.9 W/m^2K and a SHGC of 42%. The extraordinary south façade has a saw-tooth shape with integrated PVs and solar panels. These work as effective passive solar and glare protections in the summer, but allow direct solar radiation from lower standing sun into the building during the winter. The conventional windows have light redirecting venetian blinds which reflect daylight deep in the rooms. The WFR is approximately 36%. The layout is open on the south façade, allowing daylight penetration deep into the building, and contains individual office rooms on the north façade. No information was found regarding the airtightness. The surface-to-volume ratio is 0.29 m^{-1}.

Figure 3.65 Plan by POS architekten.

HVAC+L

The control set-points for indoor temperature are 20-26°C. Geothermal energy and solar energy provide heating and cooling. Ground water heat pumps supply the concrete core temperature control system with warm or cold water, circulating within the concrete floors. Heat is also generated on the south façade when direct solar radiation heats the air, which is transported to colder areas via heat exchangers. For cooling, the air conditioning system has a solar sorption cooling unit supplied with heat from 300 m^2 of solar thermal collectors. The balanced mechanical ventilation system has a rotating heat exchanger with 75% efficiency (design value). The airflow is 30 m^3/h and person. Electric lighting is hardly needed but the installed LPD is 10 W/m^2 in the north office area and 5 W/m^2 in the south office area. There are 400 m^2 of PVs generating about 42 MWh per year (19% of total electricity use). For extra user comfort, there is a so-called green buffer zone, containing 500 plants (Cyperus Grass), humidifying the indoor air.

Energy performance

The specific end-use energy according to BBR is estimated to 20 kWh/m^2yr (excl. tenant electricity), with a contribution from the PV system estimated to 5 kWh/m^2yr (see Figure 3.66). Calculations were carried out with TRNSYS and CFD-simulations as part of a research project. The estimated primary energy for heating is 11 kWh/m^2yr and for cooling it is 15 kWh/m^2yr.

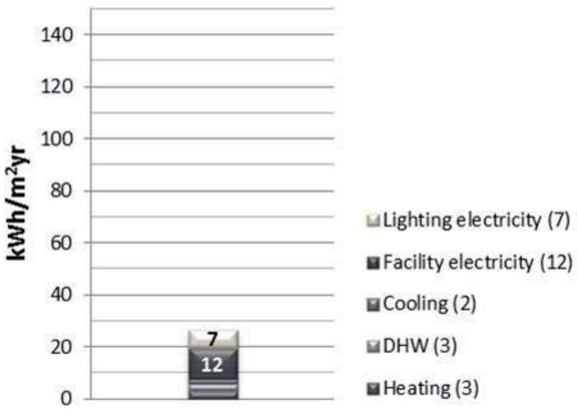

Figure 3.66 *End-use energy (calculated).*

SOL4, Mödling

Location	Mödling (N 48.08° E 16.27°)
Climate	HDD 2394/ CDD 623
Completion year	2005
Client/developer	BM Ing. Klausjürgen Kiessler
Architect	Solar4you Consulting
Contractor	No information
Tenant	Many small companies
Tot. floor area	2 740m^2 gross floor area (BGF)
Floors	4
Operation	Office, fitness centre
Office hours	-
Plan type	Flexible
Space efficiency	8 m^2/person
References	Kiessler, Stockinger et al. (2005); Kornadt and Wallasch (2008)

Figure 3.67 Photo:ThomasKirschner.com

Building design

This innovative training and business centre is situated in a nature reserve at the foot of the Eich Hill, south of Vienna and has a great ecological focus. The building is square and compact with a central atrium for daylight penetration and night ventilation. The loadbearing structure is made of cement-free concrete and brick masonry with optimized storage capacity. The external walls are made of clay blocks insulated with 30 cm of mineral foam (U=0.11 W/m^{2}K), except for the walls behind the "clip-on" PV façade system on the top floors which have 36 cm straw insulation (U=0.13 W/m^{2}K). The interior walls are made of unfired brick. The floor has 35cm insulation and the green roof system has 30 cm insulation (U=0.10 and 0.11 W/m^{2}K). The windows and the glass roof of the atrium are triple glazed with U-values of 0.9-0.97 W/m^{2}K. The windows have an advanced shutter system for solar shading. The measured airtightness is 0.56 ach at 50 Pa pressure difference.

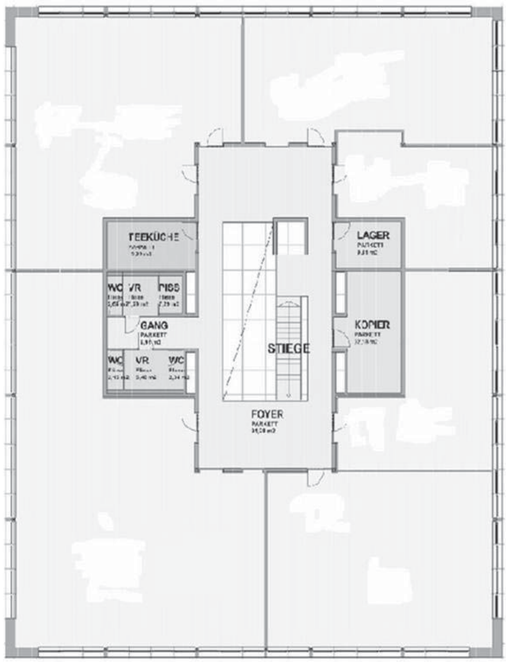

Figure 3.68 Plan originally by Solar4you Consulting. Reconstruction.

HVAC+L

Heating and cooling is supplied with two reversible ground water heat pumps (COP of 4.0) coupled with 7 boreholes, each 80 m deep. A concrete core temperature control system distributes and circulates the warm or cold water within the concrete floors. The building is also cooled at night using natural night ventilation, driven by thermal buoyancy through the atrium. The natural airflow is approximately 6-12 ach in the summer. Half of the large annual hot water demand is covered by 36 m^2 solar thermal collectors on the roof; the rest is covered by an electric heater. The PV system (210 m^2) on the facades produces roughly 6 kWh/m^2yr of electric power, which covers all the energy needs of fans and pumps. The ventilation is a VAV-system with a rotating heat exchanger with 85% efficiency (design value). The airflow is 0.5-2.5 ach which correspond to approximately 0.4-2.0 l/sm^2 (assuming 3 m room height). Daylight sensors control the lighting system and 80% of all work stations are placed within 5 m of a window.

Energy performance

The specific end-use energy according to BBR is estimated to 37 kWh/m^2yr (excl. tenant electricity), as shown if Figure 3.69. The high domestic hot water demand is due to the gym. No information was found on the tenant electricity. The primary energy for heating and hot water is 19 kWh/m^2yr (design value).

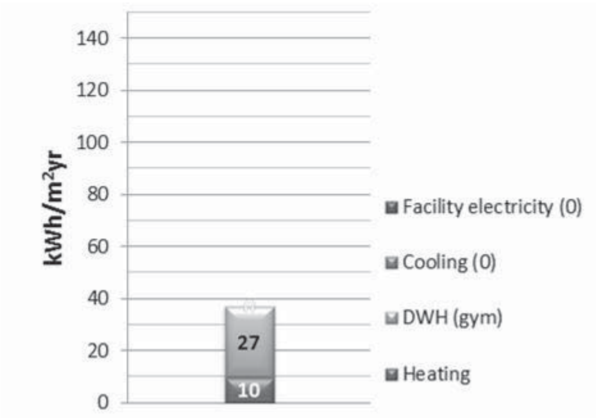

Figure 3.69 End-use energy (calculated).

3.2.7 Switzerland

Primary energy conversion factors for Switzerland are presented in Table 3.3.

Table 3.3 Primary energy conversion factors in Switzerland according to the Minergie standard.

Energy source	Primary energy conversion factor kWh_p/kWh_e
Solar and ambient heat	0
Biomass (wood, biogas)	0.7
Waste heat	0.6
Fossil fuels	1.0
Electricity	2.0

Dreieck GHC, Esslingen

Location	Esslingen (N 47.28° E 8.72°)
Climate	HDD 2600/ CDD 471
Completion year	2010
Client/developer	Rehalp Verwaltungs AG
Architect	Stücheli Architekten
Contractor	-
Tenant	Basler & Hofmann et al.
Tot. floor area	2621m^2 heated floor area (EBZ)
Floors	4+basement
Operation	Office+ boutiques
Office hours	-
Plan type	Flexible
Space efficiency	22 m^2/person
References	Filleux (2009); Braun, Filleux et al. (2009)

Figure 3.70 Visualization by Stücheli Architekten.

Building design

This is the third out of five office buildings (building C) in Esslinger Dreieck south-east of Zürich. All buildings on the site have a high sustainability focus and are aiming for the Minergie-P-ECO certificate. Building C is rectangular and compact with a loadbearing structure made of recycled concrete and prefabricated concrete elements. The exterior walls are prefabricated wooden wall elements with a U-value of 0.10 W/m^{2}K. The U-value of the roof is 0.11 W/m^{2}K. The windows are very well insulated with a U-value of 0.7 W/m^{2}K (incl. frame). The SHGC is 45% and the WFR is 27%. The spectacular south façade has a shell with an integrated PV system with a slope designed for excellent solar shading. In addition, the double skin protects the exterior venetian blinds. No information was found on the building's airtightness but it ought to fulfil the passive house standard (0.6 ach at 50 Pa pressure difference) since it is a Minergie-P certified building.

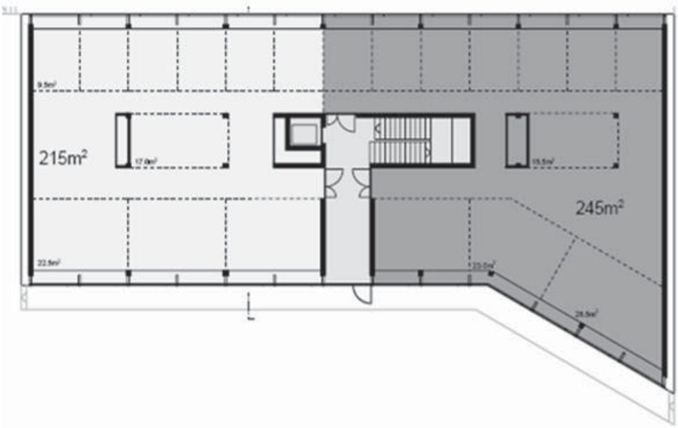

Figure 3.71 Plan by Stücheli Architekten.

HVAC+L

The control set-points for indoor temperature are 20-26°C. The heating concept is an innovative system completely supplied with solar energy. There are 95 m^2 of thermal solar collectors integrated on the roof, which store heat in the ground in the summer through 33 boreholes (35 m deep) for winter use. In the winter, the solar collectors are used for direct pre-heating of the warm water supply. The heat store in the ground heats the return water in the heating system. The system is new and not yet evaluated. By estimate, it takes about five years to fully load the ground with heat. Heating and cooling is distributed with convectors in the window parapets working with modest supply temperatures (26°C for heating and 20°C for cooling). The incoming cold water is used for evaporative cooling of the convector circuit. Heat from the server rack is used for heating the return water both in the heating and cooling seasons with en efficiency of 2°C. In addition, the temperature in the server room is reduced. The ventilation system is a VAV-system with CO_2 control. No information was found about the airflow rate or the heat exchanger efficiency. In addition, LED lighting is installed in the bathrooms. The 200 m^2 of PV panels on the south façade produce enough power to cover all lighting and fan electricity demand.

Energy performance

The specific end-use energy for heating is estimated to **9 kWh/m^{2}yr**, as shown in Figure 3.72. No other information was found on the energy use so the figures are uncertain. Building C was certified as a Minergie-P-ECO building in December 2010. Thus, the primary energy for heating and hot water should not exceed 15 kWh/m^2yr (design value).

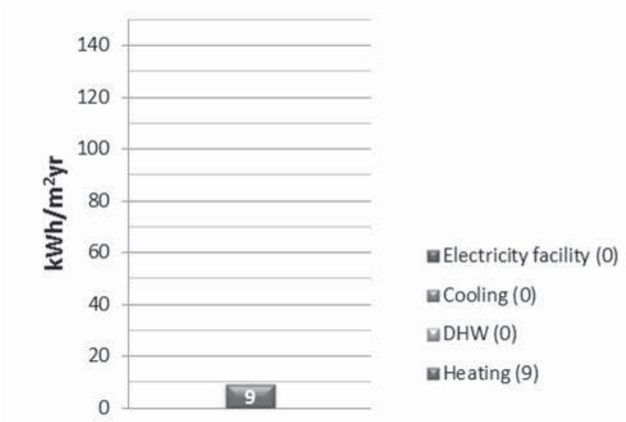

Figure 3.72 *End-use energy (calculated).*

3.3 Discussion

Detailed information was collected for 14 low energy office buildings in the Nordic countries and ten office buildings located in other parts of Northern Europe. Although the attempt was to list the most energy-efficient office buildings within this region, with a special focus on the Nordic countries, this study cannot claim to be comprehensive. The buildings presented are good examples but there are more buildings which, for different reasons, were difficult to document. There are also energy-efficient buildings currently in the design phase or in the pipeline which have not been studied. Furthermore, the selected buildings are not entirely representative for each country's building standard. For example, the examples from Denmark and Finland all represent the same developer and therefore they exhibit many similarities in the design. In this discussion, an effort is made to illustrate differences and similarities in building design, HVAC, lighting design, etc., for the described cases.

3.3.1 Building year

The most energy efficient buildings in the Nordic countries are obviously younger than the ones from Germany, which are older. All but one of the presented examples from the Nordic countries were constructed after 2006, while many good examples in Germany were built already in 1998-2002. This is likely to depend on the International Passive House programme with its origin in Germany. The Passive House Institute was founded in 1996 (PHI 2012b) and the first passive office building, Wagner & CO, was built shortly afterwards, in 1998. Another strong influence is clearly the demonstration programme EnBau, launched in 1995 by the German Federal Ministry for Economy. EnBau stands for "Forschung für Energieoptimiertes Bauen"(Energy-Optimised New Buildings, En0B) and was initiated in order to gain access to information on energy use in office buildings. For participating and sponsored buildings, the total primary energy limit for heating, lighting, ventilation and air conditioning is 100 kWh/m²yr (heated net floor area, NFA) (Voss, Herkel et al. 2007; En0B 2011). Furthermore, the European Commission initiated the GreenBuilding programme in 2004 (Greenbuilding 2011). In a pilot phase, in the years 2005-2006, the GreenBuilding infrastructure was set up in ten European countries, among them Sweden. It is clear that Sweden began to design GreenBuildings in this pilot phase and that other Nordic countries followed.

3.3.2 Location and climate

In this study, no low-energy office building further north than the 60th degree of latitude (the height of Helsinki) was found (see Figure 3.73). Although the North European region was studied because of the similarities in climate, there are some climatic differences within the region. According to heating and cooling degree days with base temperature 15.5°C (BizEE 2011), Finland has the largest heating demand and Austria has the largest cooling demand while Germany has the smallest heating demand and Norway has the smallest cooling demand (see Figure 3.74). As an example, Stockholm in Sweden has about 3200 HDD a year and 260 CDD compared to Freiburg in Germany with 2300 HDD and 600 CDD. This means a difference of 900 HDD and 340 CDD. Heating and cooling degree days are a rough indicator which should not be used for calculating heating and cooling demand. In this study, it is used primarily to indicate and compare climatic differences (see Figure 3.74).

Figure 3.73 Locations of the 24 studied office buildings (Google 2011).

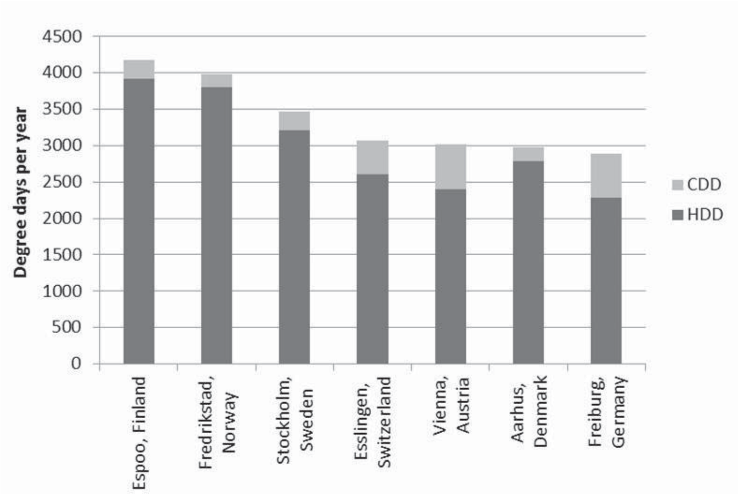

Figure 3.74 *Heating and cooling degree days (base temperature 15.5 °C) for locations representative for the office buildings studied. An average based on five years of weather data.*

The outdoor climate has less effect on heating and cooling demand than expected. Despite more significant cooling degree days in Germany and nearby countries, the purchased energy for cooling is almost negligible. This is possibly due to more sophisticated cooling strategies, using free cooling from the ground and from the ambient air to a greater extent, but also because of a larger range of acceptable temperatures. The effect from the climate is more obvious when it comes to heating demand. The Finnish buildings have the largest heating demand even though the building envelopes are well insulated. These climatic differences ought to be reflected either in building design or in heating and cooling demand but this is apparently not the case. Germany and nearby countries have a lower demand of *both* heating and cooling energy. One consequence might be seen in the use of free cooling, where the Nordic countries can benefit from cooling with ambient air while the Southern countries use the ground as a cooling source instead.

3.3.3 Building configuration

The Nordic buildings and Swedish ones in particular, are quite large in comparison with the rest of the studied buildings. The floor area varies mainly from 5 000-30 000 m^2 in the Nordic countries while many of the buildings further south are between 1 000-3 000 m^2. This could be the result of a more experimental and cost-reducing approach when building according to the passive house standard and the EnBau programme. The large buildings in the Nordic countries, with many floors, automatically yield a high compactness. Considering the shape of all the buildings, there are both rectangular/narrow buildings and square/deep ones. More than half of the buildings have a glazed atrium for daylight access and/or for natural ventilation. Half of the atria are placed along the façade and half have a central location within the building. In the Nordic countries, all the studied office buildings are open plan offices or at least have a degree of flexibility so that the tenant can choose between individual rooms and open plan or a mix of both. In Germany, all buildings are designed with office rooms for two or three people seem to be more common, which generates rather space-efficient buildings.

Several buildings in the study are designed with a loadbearing concrete skeleton construction with concrete floors, concrete columns and prefabricated wooden wall elements. About one third of the buildings have a concrete wall construction in addition and high thermal inertia. Most buildings in the Nordic countries have suspended ceilings, whereas many cases from other countries have exposed concrete floors and ceilings, which are used for heating and cooling distribution and heat storage. The average U-values of the structures in the Swedish buildings are slightly higher than the average in other regions (se Figure 3.75). The walls have U-values between 0.2-0.3 W/m^2K and the windows have U-values between 0.8-1.4 W/m^2K (frames included). In Germany and the nearby countries, the buildings are better insulated and the U-values of walls are 0.10-0.23 W/m^2K while U-values of windows are 0.7-1.4 W/m^2K. Thus, some of these buildings fulfil the basic features of the international passive house guidelines, suggesting that suitable U-values should be maximum 0.8 W/m^2K for windows (glazing and frames) and about 0.15 W/m^2K for other construction components in the envelope (PHI 2012b). For the cases where the average U-value of the building envelope is declared, it mostly varies between 0.3-0.5 W/m^2K. These values fulfil the Swedish GreenBuilding criterion, which is 25% below the BBR requirement in that was 0.7 at the time these buildings were designed (Boverket 2011a).

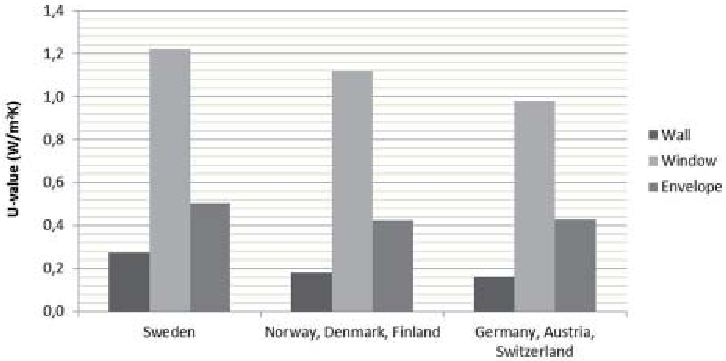

Figure 3.75 Average U-values of walls, windows and building envelopes (walls, windows, roof and ground) in the studied office buildings.

Regarding the airtightness of the envelope, various countries use diverse quantities and units from the European standard EN 13829 and different criteria. For example, the Swedish passive house criterion is 0.3 l/sm^2 (q_{50}) and the international passive house criterion is 0.6 ach (n_{50}) and these criteria were compared previously in chapter 2.4.1. In Sweden, test results were found for three buildings and one of them fulfils the Swedish passive house criterion. In Germany and the nearby countries, six buildings fulfil the international passive house criterion and the best declared airtightness is 0.2 ach (n_{50}). In Norway and Finland, none of the case buildings have been tested and the design values for airtightness are poor; 0.7-2.0 ach (n_{50}).

3.3.4 Solar control

There are relatively great variations in window amount and solar heat gain coefficients in the study (see Figure 3.76).

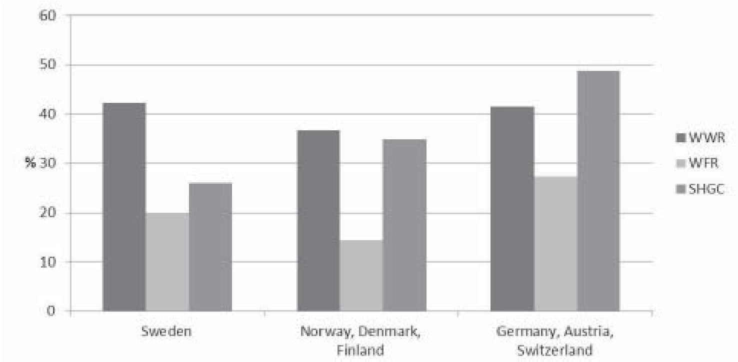

Figure 3.76 *Average window-to-wall ratio (WWR), window-to-floor ratio (WFR) and solar heat gain coefficient (SHGC).*

The window-to-wall-ratio (WWR) is quite small in the Nordic countries, often 20-40%. In Germany, the WWR is just below 45% in most cases. It was hard to find information about window-to-floor-ratios (WFR) but the declared values range between 12-36% with values below 20% in the Nordic buildings. The solar heat gain coefficient (SHGC) is difficult to analyse since in some cases the glazing SHGC is declared, and in other cases the total effective g-value inclusive solar shading is declared. Most buildings have both solar control glazing and solar shading devices. The SHGC in the Scandinavian cases is often 30-35%. In Germany and nearby countries, the studied SHGC vary between 42-60%. The best SHGC of the whole study is 27% and the best declared effective g-value (inclusive shading devices) is 12%. The current international passive house criterion suggests a SGHC around 50% (PHI 2012b).

In the Nordic countries, all types of solar shading devices are represented; external blinds, internal blinds and tinted glass. In Germany and nearby countries, solar shading devices are almost exclusively external, which is the most efficient position for reducing cooling loads. In some buildings, the shading devices are integrated in the façade as permanent passive devices, designed to let the low winter sun in but to prevent solar radiation from the high summer sun. Another characteristic in these countries are solar shadings with daylight redirection, i.e. the blinds consist of two parts which can be adjusted separately to permit daylight to enter through the upper part even when the blinds are closed. Combined with a high reflective ceiling, the natural light can be reflected deeper into the room. Many of the studied buildings are designed with glazed atria for daylight access. These atria are not equipped with solar shading devices in general.

3.3.5 HVAC

Design set-points for indoor air temperatures are 21-25°C in the Nordic countries in general, or 20-25°C in some cases, while other countries allow 20-26°C and often without an upper limit. For comparison, in Swedish guidelines for indoor climate, R1 (Ekberg 2006), the next most stringent classification, TQ2, requires operative temperatures of 20-26°C which is supposed to correspond to a PPD (Predicted Percentage Dissatisfied) index of 10%. The most stringent classification, TQ1, also requires operative temperatures of 20-26°C but in addition, an individual temperature control must be possible. However, the temperature control set-points are not always equal to real temperatures. From experience, target temperatures in reality in Swedish office buildings are often within 22-23°C throughout the year which, of course, increases the heating and cooling load.

In Sweden, Denmark and Finland, heating demand is exclusively provided by district heating. In Norway, half of the buildings have electric heat pumps. Heating is mainly distributed with radiators/convectors and cooling is mainly distributed with ventilation air. In Germany and the nearby countries, geothermal boreholes with or without reversible heat pumps are very common for heating and cooling. Heating and cooling is often distributed with a concrete core temperature control (CCTC) which is a hydronic radiant floor heating and cooling system with moderate temperature range. In addition, underground ducts (earth-to-air heat exchangers) are used for preheating and pre-cooling the supply air. There are two example buildings in which solar heat is stored over the year in the ground and in large accumulator tanks.

In the Nordic countries, most air handling strategies are demand controlled VAV systems with airflows changing with temperature and CO_2. The airflows vary from 0.35 to 2.4 l/sm^2 for buildings with large cooling demands. According to Swedish guidelines R1 (Ekberg 2006), the minimum hygienic airflow should be 0.35 l/sm^2 and the minimum person based airflow should be 7 l/s and person. However, the normal person based airflow is often larger, 15-20 l/s and person, due to additional internal gains from equipment and lighting (Enberg 2009). There are two Swedish buildings with CAV systems, characterized by low air velocity and low pressure drop. In both cases, the constant airflow is 1.5 l/sm^2 during office hours. Some Swedish buildings have special air diffusers with built-in occupancy sensors for optimal demand control. These air diffusers normally operate on an average 30% of maximum capacity on a yearly basis. None of the Swedish buildings have natural ventilation and this is representative for the Swedish building stock in general. This is probably a result of the strict guidelines for the minimum hygienic airflow which is difficult to secure without mechanical ventilation. A recent report (Boverket 2010) presents the state of building technology in existing buildings in Sweden and according to this report, 95% of the existing non-residential buildings in Sweden have a mechanical balanced ventilation system and 63% have additional heat recovery. In Germany, Austria and Switzerland, CAV systems with rather low airflows are most common. Only two buildings have VAV systems. The airflows vary from 0.26 to 1.1 l/sm^2. Some buildings have hybrid ventilation with openable windows combined with exhaust fans securing minimum hygienic airflow. There is no studied building with entirely natural ventilation.

The total SFP varies from 1.0-1.9 kW/m^3s^{-1} in Sweden and Denmark. In Norway and Finland SFP is higher, i.e. 2.0-2.9 kW/m^3s^{-1}. No information was found about the fan efficiency in Germany and the nearby countries. The current Swedish building code recommends an SFP of maximum 2.0 kW/m^3s^{-1} for mechanical balanced ventilation with heat recovery (Boverket 2011a), but guidelines recommend SFP 1.3 kW/m^3s^{-1} in low-energy non-residential buildings (BELOK 2011). As regards heat recovery, almost all buildings recover heat from the exhaust air, except the ones with hybrid ventilation. Most air handling units have rotating heat exchangers with efficiencies of 75-85% on a yearly basis. In Norway, the efficiency is generally lower (around 65%), even for rotating units.

Night ventilation for passive cooling is used in half of the studied office buildings in Germany and the nearby countries. Night ventilation is used also in buildings without heavy walls but where thermal mass is high because of the exposed concrete ceilings for heating and cooling distribution. Only some Swedish office buildings use night ventilation. In Denmark and Norway, half of the studied buildings use night ventilation. Finally, most of the buildings with night ventilation use the existing mechanical air handling unit at night, but some German offices have natural night ventilation driven by thermal buoyancy forces only.

3.3.6 Lighting, equipment and internal heat gains

Almost all of the presented office buildings have some sort of lighting control strategy in order to avoid excessive electricity use for lighting. In Sweden, the most common control strategy is to install occupancy sensors and there are only two examples with daylight control. There has been no clear focus on limiting the installed power for lighting in Sweden. Best practice is Pennfäktaren with 7.2 W/m^2 installed LPD combined with daylight control. The Swedish guideline for lighting (Ljuskultur 2010) recommends a minimum illuminance of 500 lux on the task area in office rooms. The requirement for installed LPD is 10 W/m^2 in individual office rooms, 12 W/m^2 in landscape offices and about 8 W/m^2 in other spaces. In the studied Norwegian buildings, the installed LPD lies around 6.4-10 W/m^2 and is mostly controlled by occupancy sensors. In the two Danish buildings, the control strategy is daylight control and the installed power is 8 W/m^2. In Finland, the installed LPD is high, 15 W/m^2, but in return, the control strategy is daylight dimming. In Germany and the nearby countries, there is a great variety of installed LPD, ranging from 2 W/m^2 in communication areas and up to 20 W/m^2 in office spaces. However, the high values are found in buildings constructed in the 1990s when higher values were a common praxis. Almost every building has a daylight control strategy.

The study reveals no information on installed power for electric office equipment. This is understandable for recently completed buildings since the equipment is highly user-related and not under the responsibility of the designer, unlike the general lighting design. However, the older buildings, which have been monitored for some years, do not either show much focus on equipment operation and limiting the internal heat gains.

3.3.7 Energy performance

The primary energy use, declared in some of the buildings in Germany, Austria and Switzerland, has been translated into end-use energy via primary energy conversion factors in order to be able to present all buildings together in one chart (see Figure 3.77). Note that most of the Nordic buildings are newly built and have not yet been monitored. These design values are marked with an asterisk (*). The first two bars are fictive and represent the existing office building stock in Sweden, according to the "Step by step STIL" survey (Energimyndigheten 2007), together with a typical office building just fulfilling the requirement in the Swedish building code BBR 18 (Boverket 2011a). The Swedish building code defines the specific end-use energy for heating, cooling and facility electricity and thus, all the buildings are sorted and presented in descending order according to this specific end-use energy. For buildings where information about tenant electricity is available, this is presented in white bars on the top without affecting the order in the chart. In three cases, the tenant electricity is inseparable from facility electricity and therefore the "Total electricity" is shown in a grey-to-white toned bar. These buildings (Bravida, Aibel and Wagner) are difficult to place in the chart, and should probably be moved further right if tenant electricity was presented for all buildings.

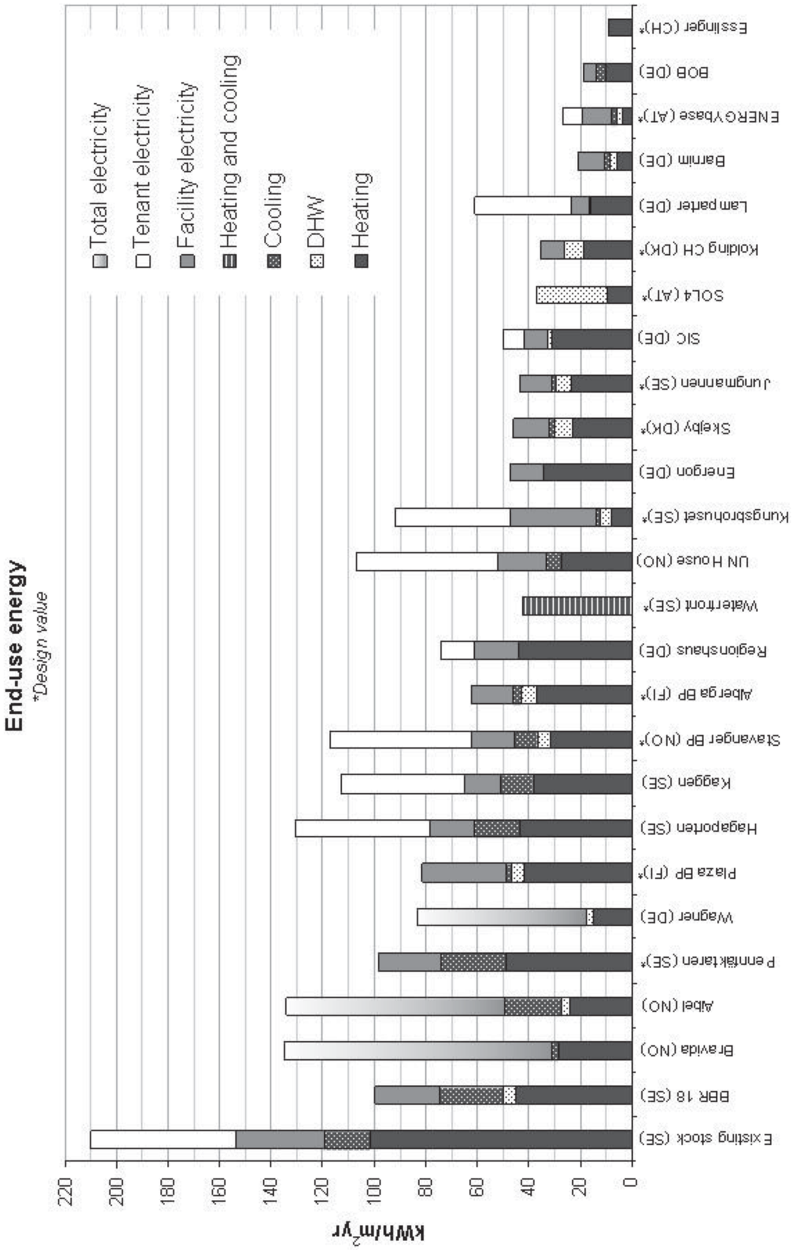

Figure 3.77 *Monitored and calculated end-use energy for the studied office buildings. The buildings are presented in descending order according to the specific end-use energy. *Design value (not monitored)*

The energy use in the Swedish buildings (SE) is well below the average of the existing office building stock in Sweden which is 210 kWh/m^{2}yr (Energimyndigheten 2007). Except for one renovation project, the Swedish buildings are at least 25% more energy-efficient compared to the regulations in BBR 18. These buildings are all certified as GreenBuildings and thus must be at least 25% better than the national requirements. The GreenBuilding label is the most frequent energy assessment in the Nordic countries. Ten out of 14 buildings are, or are about to become, certified according to GreenBuilding. Two buildings are classified (or pre-classified) according to Miljöbyggnad, two according to LEED, and three according to BREEAM. In Germany, Austria and Switzerland, three of the studied buildings are Quality Approved Passive Houses, two are classified according to GreenBuilding and one has a German Golden quality label for sustainable buildings. Generally, this region focuses more on sustainability and ecological issues than the Nordic region. Popular environmental classification systems seem to have a great impact on building design and energy performance. In the Nordic countries, where the GreenBuilding standard is rather common for office buildings, small improvements in design have been made just to fulfil the standard and meet the building code regulation with a 25% margin. The GreenBuildings in this region generally have more insulation, better airtightness, less glazing and more efficient heat recovery than other recent buildings, but apart from this and from demand controlled ventilation and lighting, the building techniques are the same as in regular buildings. In Germany and nearby countries, where the Passive House standard is used frequently, more experimental office buildings were designed in order to fulfil the rigorous standard. Some sort of new incentive could be necessary in Sweden in order to further develop the office buildings. In general, Sweden is also in need of well documented examples of low energy office buildings as demonstration projects, reliably performance-monitored and evaluated. Some of the Swedish examples in this study are promising but they have not yet been evaluated and are therefore not well documented.

As shown in Figure 3.77, Best practice in Sweden is Jungmannen in Malmö with a total end-use energy for heating, cooling and facility energy of 43 kWh/m^{2}yr (design value). Kungsbrohuset in Stockholm has a very low demand for heating and cooling but, on the other hand, large facility electricity (design value). However, these energy demands have not been verified, and the best monitored building in Sweden is Kaggen in Malmö with a total end-use energy for heating, cooling and facility energy of 65 kWh/m^{2}yr, which is less than half of the existing stock. The Norwegian buildings (NO) have moderate heating and cooling demands but in return some of them use much pump electricity. The best practice is the renovation project, the UN House in Arendal, with a total end-use energy for heating, cooling and facility energy of 52 kWh/m^{2}yr (monitored). The two similar Danish office buildings (DK) are both energy-efficient and the best practice is Kolding Company House with a total end-use energy for heating, cooling and facility energy of 36 kWh/m^{2}yr (design value). The two Finnish buildings (FI) have low cooling demand and high heating demand. The best practice is Alberga Business Park with a total end-use energy for heating, cooling and facility energy of 62 kWh/m^{2}yr (design value). There is a great variety in end-use energy in the office buildings in Germany (DE), Austria (AT) and Switzerland (CH). A large share of the energy is provided with "free" energy from solar thermal collectors, photovoltaic systems and earth-to-air heat exchangers which is not shown in the chart. Most buildings do not have to buy any cooling energy at all. The best practice is BOB in Germany, ENERGYbase in Austria and Esslinger Dreieck in Switzerland. The total end-use energy for heating, cooling and facility energy is 19 kWh/m^{2}yr for BOB (monitored), 30 kWh/m^{2}yr for ENERGYbase (design value) and only 9 kWh/m^{2}yr for Esslinger Dreieck (design value).

The state-of-the-art review indicates that Germany, Austria and Switzerland might be ahead of Sweden when it comes to designing very low-energy office buildings. Improvements should be possible in Sweden when it comes to insulation levels, airtightness, solar shading devices together with heating, cooling, ventilation and lighting strategies. In Germany and nearby countries, a number of extraordinary solutions have been applied and tested. Some of these particular solutions could be tested in a Swedish office building as well, for instance earth-to-air heat exchangers, cooling with solar energy, hybrid ventilation and more sophisticated night ventilation concepts. One barrier in Sweden could have been the large size of the Swedish office buildings which may have prevented some of these more experimental techniques because of higher costs and risks and a higher level of complexity. The study also indicates that national building guidelines and traditions can affect and make it difficult to design low-energy buildings. In Sweden for instance, generally stricter requirements for indoor air quality, hygienic airflows, control set-point temperatures and lighting intensity might result in more heating, cooling and facility energy than in countries with less demanding requirements.

Finally, the study shows no general consideration regarding the often high internal gains from office equipment and lighting. From experience, internal gains are seldom in focus in the design phase. When future very low-energy office buildings are designed, internal gains will probably have a greater focus since the benefit is multi-dimensional. Beside a reduction in installed electric power for equipment and lighting, less cooling and ventilation energy will be needed to keep the indoor temperature at acceptable levels.

4 Parametric study

This chapter presents a parametric study that has been carried out with dynamic simulations, in order to investigate the effect of various design parameters on the end-use energy in an office building in a Nordic climate. The resulting features showing large saving potential are distinguished and combined at the end into a very low energy office building, which is simulated and discussed.

4.1 Method

This method section describes in detail the dynamic simulations carried out with IDA ICE 4 on a model of a typical office building. First, a reference building was modelled as a base case, designed to correspond to the energy regulations in the Swedish building code BBR 18. Then, different design features were studied in a parametric study and the results were analysed and compared to the base case. The end-use energy was calculated for the entire building on a whole year basis. The parameters which were analysed were airtightness, insulation levels and thermal mass of the building envelope, glazing and solar control, cooling and ventilation strategies as well as control and installed power of lighting and electric equipment. These parameters were selected in consultation with the reference group of the project. The reference group is represented by architects, engineers, energy consultants, researchers, developers, project and operating managers.

The impact of climate, occupancy rate and office planning was also studied in a sensitivity analysis. Finally, the most effective design features were combined as a best case solution and simulated in order to obtain the maximum energy saving potential with commonly used technical solutions.

4.1.1 Simulation software

The simulations were carried out with IDA ICE (version 4). IDA ICE is a dynamic multi-zone simulation program for study of indoor climate of individual zones within a building, as well as whole-year energy consumption for an entire building. It is written in the neutral model format (NMF), which is program-independent and uses differential-algebraic equations for modelling dynamical systems (Kalamees 2008). This enables the user to change and write new models. However, in this study standard models were used only. IDA ICE was developed in the mid-eighties at the Royal Institute of Technology (KTH) in Stockholm and is now launched in a global market with focus in Sweden, Finland, Germany, Switzerland and the UK. The simulation tool is provided by EQUA Solutions AB and it has been validated according to CEN 13791, ASHRAE 140-2004, CEN 15255, CEN 15265, CIBSE TM33, RADTEST and Envelope BESTEST (EQUA 2012).

In the simulation process of IDA ICE, one or more zones are modelled and together they define a building. The zones can be modelled manually or imported from common 2D and 3D CAD files and to some extent even BIM (Building Information Modeling) models (EQUA 2012). The construction parts (walls, roof and floor) separate the zones from each other and the building from the ambient climate. Various heating and cooling devices, ventilation systems, lighting systems, building materials, windows, shading devices and controller set-points can be chosen from a library and attached to each zone. The climate model is an algorithmic model that, from a given weather file and location data, calculates air temperature, sky temperature, ground temperature, air humidity ratio, air pressure, CO_2 fraction, direct and diffuse horizontal solar radiation, wind direction, wind velocity, solar azimuth and altitudes. The zone model calculates the indoor climate and energy consumption in each zone output files can be provided for any data object in any system with high time resolution. IDA ICE 4 handles a number of different features and can be used for calculation of (Kalamees 2008):

- Full zone heat and moisture balance with contributions from solar radiation, occupants, equipment, lighting, ventilation, heating and cooling devices, heat transmissions, thermal mass effects, air leakage, cold bridges and furniture
- Wind and buoyancy driven airflows through leaks and openings
- Air and surface temperatures and operative temperature at any occupant location

- Temperature, CO_2 and moisture levels, which can be used for controlling the air handling system
- Solar influx through windows and the influence of local shading devices and surrounding buildings
- Daylight level at any room location
- Thermal comfort indices (PPD and PMV)
- Energy cost (based on time-dependent prices)

IDA ICE is probably the most frequently used tool for energy simulations of non-residential buildings and low-energy buildings in Sweden today. IDA ICE enables detailed modelling of the building and technical systems and performs daylight simulations, which can provide more exact solar heat gains and enable daylight controlled lighting. Thus, the program was selected for this study, even though it is rather complex and therefore not always considered optimal for multi-zone parametric studies.

4.1.2 The reference building

The virtual reference building, which was defined previously by Poirazis (2008) and approved by his reference group consisting of practising architects and engineers, is a typical large office building with peripheral individual office rooms and a central core with stairways, elevators and other facilities (see Figure 4.1 and 4.2). The office block is a six storey building with a narrow shape (approximately 66 m x 16 m) with the short sides oriented to east and west. The room height is 3.2 m and the floor height is 3.5 m with 0.3 m concrete slabs and a thin ceiling. Each floor is 1030 m^2 with a total heated floor area (A_{temp}) of 6180 m^2. More building data is presented in Table 4.1 in section 4.1.3.

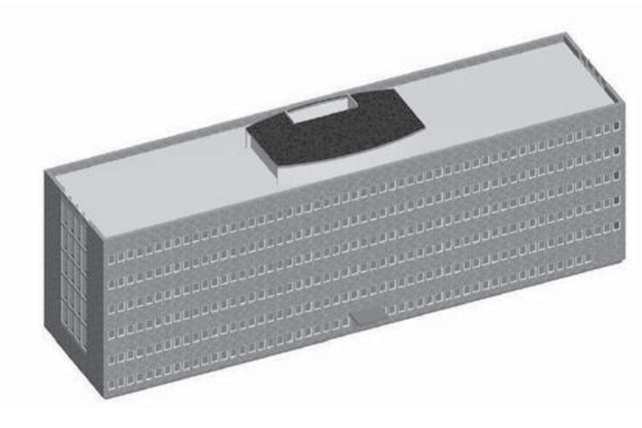

Figure 4.1 Visualization of the reference building. Christer Blomqvist, WSP.

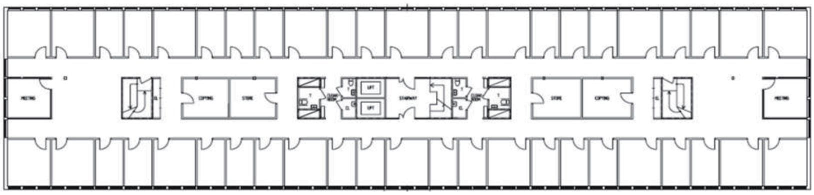

Figure 4.2 *Typical floor plan in the reference building. Christer Blomqvist, WSP.*

In IDA ICE, the building was modelled with as few thermal zones as possible in order to reduce the modelling and simulation time. Identical floors and office rooms on each floor, with the same amount and orientation of external envelope surface, were therefore modelled once and multiplied several times in the simulation (see Figure 4.2). This is current practice for speeding up the simulation and has a negligible effect on the result.

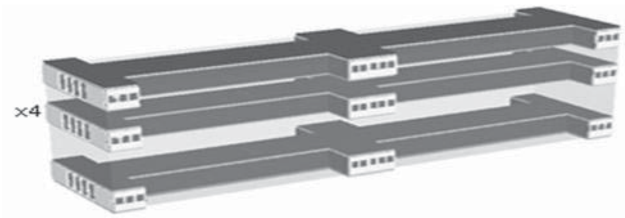

Figure 4.3 *Model in IDA ICE of ground floor, 3rd and 5th floor. The 3rd floor was muliplied four times in the simulation.*

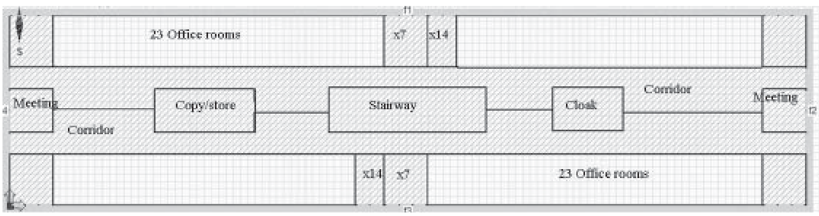

Figure 4.4 *Typical floor plan in IDA ICE. Identical zones were multiplied several times.*

Figure 4.5 shows the distribution of office space in the reference building. The individual office rooms and meeting rooms correspond to 56% of the floor space (office rooms 54%). The corridors represent 34% of total floor space and the remaining space consists of stairways and other facilities (10% in total).

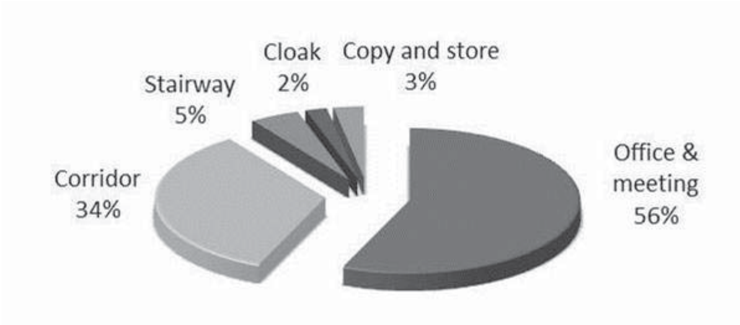

Figure 4.5 Distribution of office space in the reference building.

4.1.3 Input for parametric study

Base case

The base case input was chosen, in consultation with the reference group, to correspond to normal practice and regulations in the recent Swedish building code BBR18. In addition, the input is to a great extent in line with the standardized input parameters for energy calculations in office buildings (SVEBY 2010) provided by the SVEBY programme which stands for "Standardize and verify the energy performance of buildings" (SVEBY 2012). The SVEBY standard is the Swedish building industry's interpretation and explanation of the energy regulations in the building code BBR. The SVEBY standard was developed with the intention to agree on a common building praxis and to prevent disputes between different actors in the industry. Remaining input for the study are values experienced by members of the project and reference group. The base case input is summarised in Table 4.1 and further described in text in the following sections.

Table 4.1 Base case simulation input.

Parameter		Simulation input	Comment
Climate conditions	Location	Stockholm 59.35N, 17.95E	
	Temperature Dry-bulb min/mean/max	-18.3 / 6.5 / 26.1 °C	ASHRAE Fundamentals 2001
	Horizon angle	15°	EN ISO 13790:2008
Dimensions	Heated floor area (Atemp)	6 180 m^2	
	Air volume	19 776 m^3	
	Envelope surface	5 193 m^2	
	Surface-to-volume ratio	0.26 m^{-1}	
	Façade surface	3 133 m^2	
	Window-to-wall ratio(WWR)	35%	GWR 31%
	Window-to-floor ratio (WFR)	18%	
Building elements	External wall U-value	0.20 W/m^2 °C	170+50 mm mineral wool
	External roof U-value	0.11 W/m^2°C	300 mm mineral wool
	External floor U-value (excluding ground resistance)	0.17 W/m^2°C	200 mm EPS
	Windows U-value (including frames)	1.4 W/m^2°C	Pilkington Suncool 2-glass
	Glazing	LT 72%, SHGC 43%	Pilkington Suncool 70/40
	Internal blinds	0.83 x SHGC	SHGC multiplier
	Total UA transmission	2119 W/°C	
	Thermal bridges	445 W/°C 21% of total UA	Calculated with HEAT2
	Air leakage rate	1.5 ach at 50 Pa	EN 13829:2000
Heating/cooling efficiency	Boiler COP	0.9	Total heat supply
	Heating coil COP	0.9	In air handling unit
	Domestic hot water COP	0.9	
	Domestic hot water use	2.0 kWh/m^2yr	SVEBY standard
	Chiller COP	0.9	Total cooling supply
	Cooling coil COP	0.9	In air handling unit
Thermal climate	Set-points for mean air temperature	22-23°C	Normal target values
Ventilation	Ventilation operating hours	Weekdays 7:00-19:00	
	Constant Air Volume	1.5 $l/s,m^2$	SVEBY Standard
	Heat exchanger efficiency	70%	Yearly average
	Total Specific Fan Power, SFP	2.0 kW/m^3s^{-1}	BBR18
	Supply air temperature	17 °C	
Office operation	Office hours	Weekdays 8:00-18:00	1 hour lunch break
	Occupant space	20 m^2/person	SVEBY standard
	Activity level	1 met, 108 W	Sensible and latent heat
	Occupancy factor	0.7	SVEBY standard
Lighting	Installed power in office rooms and other spaces	10 and 6 W/m^2	
	Control	Manual switch on/off	
Computers and office equipment	Power on/standby	140/10 W/person	

Building envelope

The base case construction is typical with heavy concrete joist floors, with ceiling and floor coating, and light curtain wall elements. The U-values are given in Table 4.1 and the average U-value of the envelope is 0.5 W/ m^2°C (including thermal bridges). In the parametric study, the roof and floor components were kept constant since these constructions only have a small impact on the total transmission losses in a multi-storey building with a comparatively large façade area. External walls and windows, on the other hand, have a larger impact and the different constructions studied in the parametric study were walls with a U-value of 0.1 and windows with U-values of 0.7, 0.9 and 1.1 W/m^2°C (see Table 4.2). The wall U-value was achieved with a wooden construction with 80+195+70 mm mineral wool. The window U-values were achieved with triple glass and argon filling. Walls with U-value 0.1 and windows with U-value 0.9 W/m^2°C correspond to the former guidelines in the Swedish passive house standard (FEBY 2009).

Heavier constructions with more internal thermal inertia were simulated next. A medium heavy version with exposed concrete walls in stairway and cloak rooms, and a heavy version with additional concrete sandwich walls in the facade were studied. U-values were kept the same for these cases. In order to optimize the conditions for heat storage, larger temperature variations were allowed and simulations were performed with mean air temperature set-points of 21-24°C.

The base case air leakage rate was set to 1.5 ach (n_{50}) which corresponds to the former Swedish regulation of 1.6 l/sm^2 (q_{50}). A wind driven flow was specified in IDA ICE, based on wind and fan pressure and thermal buoyancy effects. The wind profile was based on a suburban location. Pressure coefficients depend on form factors and wind direction. The chosen pressure coefficients are a common handbook data set (from the Air Infiltration and Ventilation Centre) based on a semi-exposed building. In the parametric study, two airtight models were evaluated as well, one with an airtightness level according to the international passive house standard (0.6 ach, n_{50}) and the other according to the Swedish passive house standard (0.3 l/sm^2 envelope surface, q_{50}). Note that a value of 0.3 l/sm^2 correspond to 0.28 ach in the reference building.

The initial window-to-wall ratio (WWR) in the reference building was 35%. In the parametric study, WWR 60% was simulated which is a common ratio in modern office buildings. In this case, WWR 35% and WWR 60% are equivalent to glazing-to-wall ratios GWR 31% and GWR 54%. The base case glazing has a solar heat gain coefficient (SHGC) of 43%. Together with internal venetian blinds, SHGC is reduced to $SHGC_{tot}$

36%. The window integrated shading device is controlled by the amount of solar radiation that penetrates the glazing. As default in IDA ICE, the blinds are drawn when solar radiation level on the inside of the glass exceeds 100 W/m^2. In the parametric study, intermediate blinds ($SHGC_{tot}$ 17%) and external blinds ($SHGC_{tot}$ 6%) were analysed as well as a more efficient glazing with a SHGC of 27% together with internal blinds ($SHGC_{tot}$ 22%). In addition, all models in the study have a fixed horizontal shading of 15° (from the middle of the façade height) representing surrounding buildings and other shading objects.

Table 4.2 Studied parameter values of the building envelope.

Parameter	Studied value	Base case value
Wall	U=0.1 W/m^2°C	0.2 W/m^2°C
Window	U=1.1 W/m^2°C	1.4 W/m^2°C
Window	U=0.9 W/m^2°C	1.4 W/m^2°C
Window	U=0.7 W/m^2°C	1.4 W/m^2°C
Wall and window	U=0.1 and 0.9 W/m^2°C	0.2 and 1.4 W/m^2°C
Thermal mass	Medium heavy	Light
Thermal mass	Medium heavy with set-points 21-24°C	Light, set-points 21-24 °C
Thermal mass	Heavy	Light
Thermal mass	Heavy with set-points 21-24°C	Light, set-points 21-24 °C
Airtightness	0.6 ach (n_{50})	1.6 l/sm2 (q_{50})
Airtightness	0.3 l/sm^2 (q_{50})	1.6 l/sm2 (q_{50})
WWR	60%	35%
Solar control	SHGC 27% and internal blinds (SHGCtot 22%)	Internal blinds (SHGCtot 36%)
Solar control	Intermediate blinds (SHGCtot 17%)	Internal blinds (SHGCtot 36%)
Solar control	External blinds (SHGCtot 6%)	Internal blinds (SHGCtot 36%)

Thermal bridges for the different constructions in the parametric study were calculated with HEAT2 version 6.0. This program is a two-dimensional heat transfer software provided by Blocon (BuildingPhysics 2011). In IDA ICE, heat transmission through building elements is calculated with internal dimensions, and linear thermal bridges are added to compensate for the heat transmission through the element joints. The linear thermal transmittance Ψ (W/m°C) of all building element joints were calculated with HEAT2 and used as input in the IDA ICE model. IDA ICE calculates the length l (m) of the joints and finally the sum of all linear thermal bridges $\Sigma l\Psi$ (W/°C). For the base case, the total linear thermal bridges are 445 W/°C, which corresponds to 21% of the total transmission losses through the envelope ($\Sigma UA + \Sigma l\Psi$). The calculated thermal bridges for other constructions in the parametric study are shown in Table 4.3.

When constructions are improved and transmission losses are reduced, the total share from thermal bridges naturally increases if nothing is done to improve also the thermal bridges.

Table 4.3 The sum of linear thermal bridges for different building models in the parametric study and its share of the total heat transmission through the building envelope.

	Linear thermal bridges $\Sigma l\Psi$ (W/°C)	Share of total heat transmission
Base case	445	21%
External walls U 0.1	437	22%
Windows U 1.1	445	24%
Windows U 0.9	445	27%
Windows U 0.7	445	32%
WWR 60%	430	14%

HVAC strategies

This parametric study does not include the study of different heating and cooling production or distribution systems. Thus, only the building's actual heating and cooling demand was calculated. In the IDA ICE model, each zone is equipped with its own ideal heater (radiator) and ideal cooler (cooling beam) with unlimited heating and cooling effect. In addition, heating and cooling is distributed via heating and cooling coils in the central air handling unit, also these with unlimited effects. In order to compensate for distribution losses in pipes and ducts, the total performance of the heating and cooling system was reduced with 10% (COP 0.9) and the efficiency of the heating and cooling coils in the air handling unit was reduced with another 10% (COP 0.9). A standard air handling unit, with mechanical supply and return air and an air-to-air heat exchanger with effectiveness (eta) 70%, was applied in the base case. Set-point for supply air temperature for the whole year was 17°C (after a temperature rise in the fans by 0.5°C). The pressure rise in the fans was set to 600 Pa and electricity-to-air efficiency was set to 0.6 which gives a SFP of 1.0 kW/m^3s^{-1} per fan and a total of 2.0 kW/m^3s^{-1} for the whole system. Furthermore, the air handling unit was set to operate weekdays from 7:00 to 19:00 and otherwise shut off. The base case ventilation strategy was a CAV system with a constant airflow during operating hours of 1.5 l/sm^2.

In the base case, control set-points for indoor air temperature were 22-23°C during the whole year, which is a realistic target value for a modern office building in Sweden, in order to avoid complaints. It is also in line with the neutral (22.4 °C) and optimal (22.5 °C) temperatures measured by Schiller (1988). However, since a larger temperature range is allowed according to Swedish guidelines (Ekberg 2006), the impact of temperature set-points were studied in the parametric study. In one simulation, the mean air temperature was allowed to drop to 21°C outside working hours and in another simulation, control set-points during office hours were changed to 21-24°C (see Table 4.4). IDA ICE controls the indoor thermal conditions with strict set-points for mean air temperature and unlimited heating and cooling supply. In order to make sure that also operative temperatures are acceptable, temperatures were controlled in the most exposed rooms during the warmest summer day and the coldest winter day. Summer comfort was controlled in the corner room towards SW on the 5th floor on the warmest work day which happens to be the 24th of June. Winter comfort was controlled for a room towards N on the ground floor the 31th of January. Some of these controls are displayed in the result section.

In the parametric study, the heat exchanger's effectiveness was changed from 70% to 60% and 80% and 85%, where 60% represents a plate heat exchanger and 85% represents the best available rotating heat exchanger on the market. Furthermore, the air handling unit was studied with improved fan efficiency of SFP 1.5 kW/m^3s^{-1}.

In the next simulation setup, a VAV system with airflows of minimum 7 l/s and person and maximum 100 l/s and person was studied. These airflows correspond to 0.8 and 6.7 l/sm^2 and the actual flow is controlled by both mean air temperature (22-23°C) and CO_2 level (maximum 800 ppm). However, it is usually the temperature requirement that determines the airflows rather than the CO_2 limit in office buildings (Jardeby, Soleimani-Mohseni et al. 2009). The supply air temperature set-points were changed in order to optimise the cooling and heating efficiency. Set-points were defined as a function of outdoor temperature with a linearly variation between 15.5-19.5°C from summer to winter. When the airflow is variable, rated SFP is customary set at an estimated rated flow corresponding to an average airflow during operation. However, this estimated rated airflow differs in different guidelines. In the Swedish Ventilation Industry's guideline (Backström 2003) and in the SVEBY programme (SVEBY 2009), 65% of maximum airflow is recommended. According to the Organization for Commercial Building Owners' (BELOK) guideline, rated flow is 70% (BELOK 2011). In this simulation study, SFP was determined at 70% of maximum airflow.

Finally, the cooling potential with mechanical night ventilation was investigated. In order to make the most of the night ventilation concept, the building was designed with high internal thermal inertia and the night temperature set-point was lowered to 18°C. The night flush ventilation was activated when the following conditions were all fulfilled:

- Cooling season (May - September)
- Sunday - Thursday night, between 22:00 and 07:00
- Outdoor temperature warmer than 12°C
- Outdoor air at least 2°C colder than return air
- Return air warmer than 20°C

Night ventilation was simulated with both variable and constant flow rates. For night ventilation in combination with VAV, the same air handling unit as mentioned above in the VAV study was used with airflows varying between 0.8-6.7 l/sm^2. For night ventilation in combination with CAV, a constant night flush of 4 ach was studied assumed due to the fact that 4 ach is often considered as the minimum airflow for achieving a good cooling effect with night ventilation (Gratia, Bruyère et al. 2004; van Moeseke, Bruyère et al. 2007; Artmann, Manz et al. 2008). However, the daytime airflow was still kept constant at 1.5 l/sm^2 as in the base case. A two-speed motor was assumed in the fans, with a rated flow of 4 ach (3.6 l/sm^2) and a reduced flow of 1.5 l/sm^2 (linear relationship between fan speed and airflow). SFP was determined at the rated flow of 4 ach which make the fan electricity during normal day operation much lower than the base case. Hence, in order make the comparison reasonable, both night ventilation simulations were compared to similar models without night flush.

Table 4.4 Studied parameter values of the HVAC systems.

Parameter	Studied value	Base case value
Set-point temperature	21°C nights and weekends	22°C
Set-point temperature	21-24°C (day and night)	22-23°C (day and night)
Heat exchanger eta	60%	70%
Heat exchanger eta	80%	70%
Heat exchanger eta	85%	70%
SFP	1.5 kW/m^3s^{-1}	2.0 kW/m^3s^{-1}
Ventilation	VAV 0.8-6.7 l/sm^2	CAV 1.5 l/sm^2
Night ventilation	VAV 0.8-6.7 l/sm^2	No night ventilation
Night ventilation	CAV 4 ach	No night ventilation

User related electricity and internal gains

In the simulations, office hours were defined as weekdays 8:00-18:00 with one hour lunch break. No summer vacation or other holidays were considered. The degree of automatic schedule smoothing was set to ± 1h in IDA ICE, which means that people were assumed arriving between

7:00-9:00 and leaving between 17:00-19:00. The occupancy factor was set to 0.7 (SVEBY 2010). For a building with individual office rooms, this assumption might be a source of uncertainties of the calculated results. In reality, there are of course not 0.7 persons in each room, rather 7 out of 10 rooms are occupied which means that some rooms can be heated and some rooms cooled at the same time. However, this was not considered in the simulation study due to the complexity it would create in the model. Meeting rooms were assumed occupied 4h per day while other spaces were assumed not occupied. The office workers were assumed having an activity level of 1 met (reading, seated) with an emission of 108 W per person in sensible and latent heat. The amount of clothing was assumed 0.85 ± 0.25 clo.

User related electricity was in this study defined as office lighting and office equipment in terms of computers, printers and copy machines, projectors, chargers, adjustable desks, office kitchens, servers and more. The power input for office equipment in the base case and the parametric study (see "best practice") is presented in Table 4.5. Each office room was equipped with a computer, a charger and an adjustable desk (electric). In the "best practice" simulation, the stationary PC was exchanged for a laptop computer with an efficient LCD screen. The power to each office room was also completely shut off outside office hours, resulting in no "off mode" power.

Table 4.5 Power input for office equipment for base case and best practice. Numbers from SVEBY (2010) and EnergyStar (2012).

Tenant equipment	On (W)		Off mode (W)		Per area
	Base case	Best practice	Base case	Best practice	
Computer	125	50	5	0	Office room
Charger	10	5	1	0	Office room
Adjustable desk	4	0.5	4	0	Office room
Copy/printer	560		8.5	2.5	Floor
Fax	4	0	4	0	Floor
Projector	375	213	30	0.4	Meeting room
Pentry (20W/person)	1020		30		Floor
Server (150 kWh/person)	0.9		0.9		1 m^2
Engine warmers 1.5 kWh/m^2yr					

The base case installed LPD was set to10 W/m^2 in office rooms and 6 W/m^2 in other spaces which are realistic design values today (SVEBY 2010). In IDA ICE, all installed power is converted to heat (Johnsson 2011). Fluorescent tubes were assumed and the luminous efficacy was set to 60 lm/W. The lighting control was manual on/off switch by the door, reflecting the occupant schedule. In the parametric study, the lighting concept was improved with daylight control (photo electric dimming) with a minimum required light intensity of 500 lux at the desk (Dubois and Flodberg 2012). The installed power was reduced to 8 W/m^2 in office rooms and 4 W/m^2 in other spaces (see Table 4.6), which can be considered best practice today (BELOK 2011). However, standby losses of 2 W per room and ballast losses of 15% during office hours were added for the dimming system. Furthermore, the electric lighting was shut off completely at night, without standby losses.

The frequency of both lighting and equipment was in the base case set to 70% during office hours and to 15% otherwise due to standby losses and power left on by mistake according to SVEBY (2010). Additionally facility energy included pumps (8.9 kWh/m^{2}yr), elevators (11 MWh/yr) and entrance heaters (4 MWh/yr) but these were not studied further (Energimyndigheten 2007; SVEBY 2010).

Table 4.6 Studied parameter values of the lighting and office equipment design.

Parameter	Studied value	Base case value
Equipment	EPD 55 W/room	EPD 139 W/room
Equipment and lighting	EPD 55 W/room LPD 8 and 4 W/m^2 Daylight control	EPD 139 W/room LPD 10 and 6 W/m^2 Manual control

4.1.4 Input for best case simulation

The design features that turned out to be most effective in the parametric study were combined as a best case solution and simulated in order to obtain the maximum energy saving potential without meaningless investment costs (see Table 4.7). Besides the end-use energy, maximum heating and cooling loads were also calculated and compared to the base case. The loads were calculated in IDA ICE with synthetic design weather data for Stockholm. The winter simulation was carried out with the minimum dry bulb temperature of -18.3°C, and the summer simulation with the maximum dry bulb temperature of 26.1°C. No internal heat gains were active during the heat load calculation and all internal heat gains were active during the cooling load calculation.

Table 4.7 Design features in the best case simulation.

Parameter	Best case value	Base case value
Wall	U=0.1 W/m^2°C	0.2 W/m^2°C
Window	U=0.9 W/m^2°C	1.4 W/m^2°C
Airtightness	0.3 l/sm^2 (q_{50})	1.6 l/sm^2 (q_{50})
Solar control	External blinds (SHGCtot 6%)	Internal blinds (SHGCtot 36%)
Set-point temperature	21-24°C	22-23°C
Heat exchanger eta	80%	70%
SFP	1.5 kW/m^{3}s^{-1}	2.0 kW/m^{3}s^{-1}
Ventilation	VAV 0.8-6.7 l/sm2	CAV 1.5 l/sm2
Equipment	EPD 55 W/room	EPD 139 W/room
Lighting	LPD 8 and 4 W/m^2 Daylight control	LPD 10 and 6 W/m^2 Manual control

4.1.5 Input for sensitivity analysis

In a final sensitivity analysis, the reference building (with base case input) was studied regarding aspects which are not likely to be able to influence when designing a building but which have impact on the total energy demand, such as the actual building site and climate, and the user related operation of the building. The impact of building shape and interior planning was also analysed.

There are three different climate zones in the Swedish building code. Stockholm (base case) is situated in the north part of the south zone (zone III). Other big Swedish cities simulated in the sensitivity analysis were Malmö in the south part of the south zone (zone III), Karlstad in the middle zone (zone II), Östersund in the south part of the north zone (zone I) and finally Kiruna in the north part of the north zone (see Figure 4.6). Darmstadt in Germany was also studied, as a reference, since this is where the international passive house institute originated. However, the climate file for Frankfurt was used, which is close to Darmstadt. Climate data is presented in Table 4.8.

Figure 4.6 *Climate zones in BBR 18. Reconstruction of a figure presented by Rockwool (2012).*

Table 4.8 Location and climate. Climate files in IDA ICE.

Location	Latitude / Longitude	Temperature Dry-bulb mean °C	Temperature Dry-bulb min /max °C
Kiruna	67.82N / 20.33E	-1.1	-30.2 / 21.0
Östersund	63.18N / 14.50E	3.1	-25.8 / 23.2
Karlstad	59.37N / 13.47E	5.9	-20.6 / 25.1
Stockholm	59.35N / 17.95E	6.5	-18.3 / 26.1
Malmö	55.55N / 13.37E	8.3	-13.9 / 25.0
Darmstadt (Frankfurt)	50.05N / 8.60E	10.1	-11.0 / 30.3

The impact of occupancy attendance was investigated since this parameter is difficult to predict, and since it affects heating, cooling and electricity use. The base case occupancy factor was set to an average of 0.7 during office hours as recommended in the SVEBY programme. However, a study by Maripuu (2009) reveals that 0.7 might be too high since different monitoring studies have shown that the actual occupancy attendance is closer to 0.5 or even 0.4. Two simulations were performed, one with a low occupancy factor (0.5) and one with the highest possible occupancy factor (1.0) as reference. Note that the occupancy factor influences both the number of people and the power for computers and lighting in the simulation model.

The impact of building shape and interior planning was analysed at last. Interior planning is often optional and can be changed with time with new tenants. A square model with open landscape offices and an atrium was simulated. The building measures and interior zones were obtained from the Kaggen office in Malmö (see Table 4.9). Kaggen is a six storey building approximately 48 m x 37 m with the atrium on the south façade (see Figure 4.7 and 4.8). The atrium is solely used for daylight distribution. The room height is 3.4 m and the floor height is 3.7 m. The same input as in the reference building were used in the base case model, and the same design features were studied in a parametric study.

Table 4.9 Kaggen building data.

Heated floor area (A_{temp})	9 083 m^2
Air volume	34 911 m^3
Envelope surface	7 092 m^2
Surface-to-volume ratio	0.20^{-1}
Façade surface	3 539 m^2
WWR	43% (GWR 38%)
WFR	17%
Occupant space	20 m^2/person (incl. ground floor) 13 m^2/person (office space only)

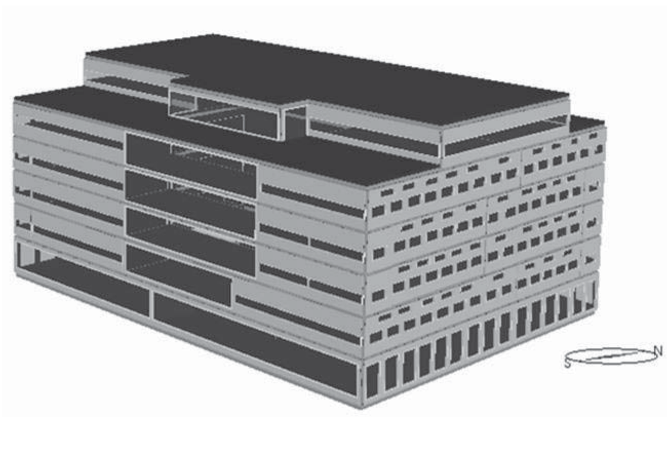

Figure 4.7 IDA ICE model of Kaggen in Malmö, south and east façades.

Figure 4.8 Kaggen interior, 2nd floor (visualisation: Metro Arkitekter).

4.2 Results

This section presents the results from the base case simulation, the parametric study, the best case simulation and the sensitivity analysis. Results for the base case and best case are displayed as annual end-use energy for heating, domestic hot water (DHW), cooling, fan electricity, additional facility electricity as well as tenant's electricity for lighting and office equipment. Results from the parametric study and the sensitivity analysis are presented as total heating, cooling and electricity deviation from the base case. The results are discussed later on, in chapter 4.3.

4.2.1 Base case

The total delivered energy for the base case is 139 kWh/m^{2}yr including user related electricity for lighting and equipment (see Figure 4.9). Excluding the user related energy, the specific end-use energy is 92 kWh/m^{2}yr. This is below the requirement in BBR 18 of 100 kWh/m^{2}yr and additional 13 kWh/m^{2}yr for large airflows (Boverket 2011a). Hence, the base case achieves the regulation with a small margin, just as anticipated. The most dominating posts are heating energy (48 kWh/m^{2}yr) and user related electricity for lighting and equipment (48 kWh/m^{2}yr). Even though internal heat gains from lights and equipment are quite large, and the cooling set-point is strict (23°C), it is clear that the heating load dominates at this high latitude. The heating demand is mainly covered by zone heating (radiators) and the contribution from the heating coils in air handling unit is small.

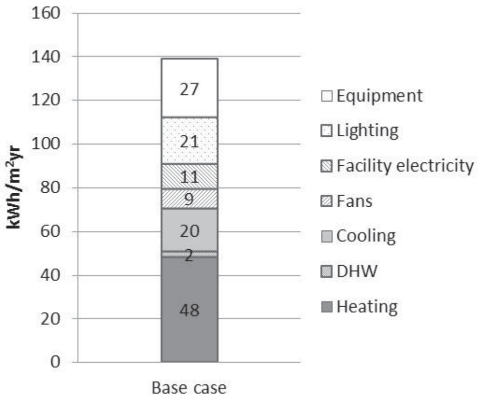

Figure 4.9 *Total end-use energy for the base case.*

Thermal conditions for the warmest and coldest days are displayed in Figures 4.10 and 4.11. In summer, the operative temperature deviates at most 1.3°C from the set-point temperature and in the winter, the operative temperature hardly deviates at all from the set-point temperature during work hours.

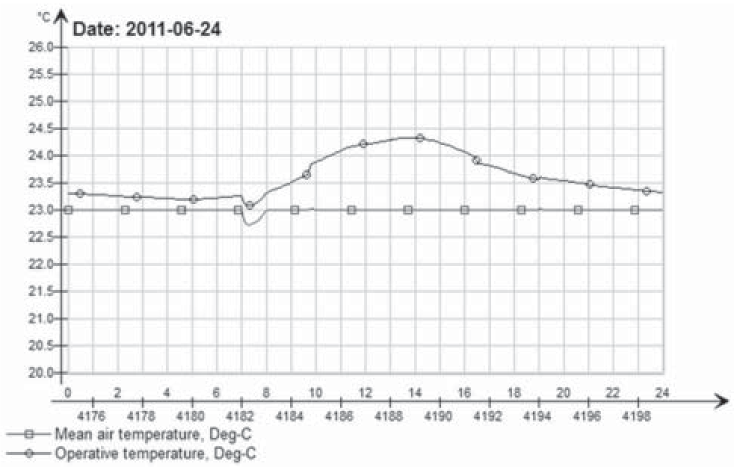

Figure 4.10 *Indoor air temperature and operative temperature for the base case. The warmest room (SW, 5th floor) the warmest day.*

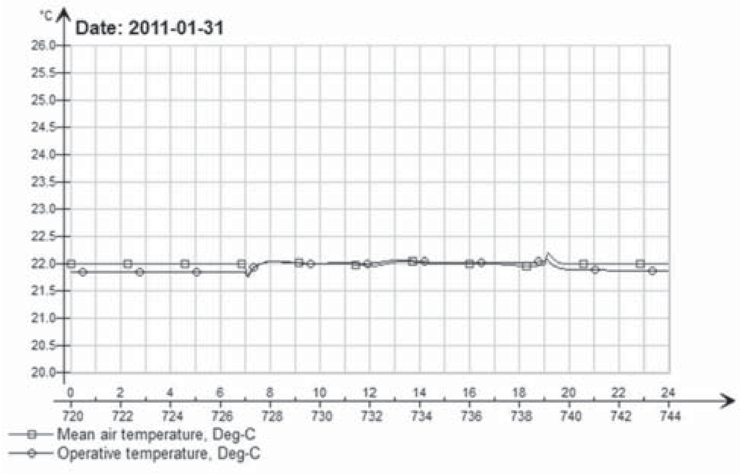

Figure 4.11 *Indoor air temperature and operative temperature for the base case. The coldest room (N, ground floor) the coldest day.*

4.2.2 Building envelope design

In the first parametric setup, the building envelope was studied. Thermal mass, insulation levels, airtightness, window-to-wall ratio, orientation and solar shades were varied. The results are presented in Figures 4.12 and 4.13, as total increase or decrease in heating, cooling and electricity, compared to the base case. It does not show in the figures, but the envelope design features affected the zone heating and cooling only, the heating and cooling energy in the air handling unit were not affected in the simulations.

The results in Figure 4.12 show that thermal mass and thermal inertia have a rather small impact on the heating and cooling demand, and that the saving potential for a heavy construction can save at most 2.5 kWh/m^{2}yr compared to the base case. A larger range in indoor air temperature actually decreases the impact of thermal mass, compared to the base case with the same temperature limits. Regarding insulation levels and U-values, it is obviously more effective to choose passive house windows (U=0.9 W/m^2°C) than passive house walls (U=0.1 W/m^2°C), despite the rather modest window-to-wall ratio. However, this result depends on the base case starting points, which provided an improvement for the windows from 1.4 to 0.9 W/m^2°C, and for the wall elements only from 0.2 to 0.1 W/m^2°C. The negative aspect with improved U-values is the increased cooling demand, but this is compensated by the even larger decrease in heating demand. With a combination of passive house windows and passive house walls, the total energy saving potential is 11 kWh/m^{2}yr compared to the base case. Finally, an improved airtightness turns out to have a large impact on the building's heating demand. The result is not surprising since the base case has a particularly leaky building envelope (1.6 l/sm^2 envelope area at 50 Pa). According to the simulation results, the Swedish passive house criterion for airtightness is sharper than the international criterion, at least for the shape of the reference building.

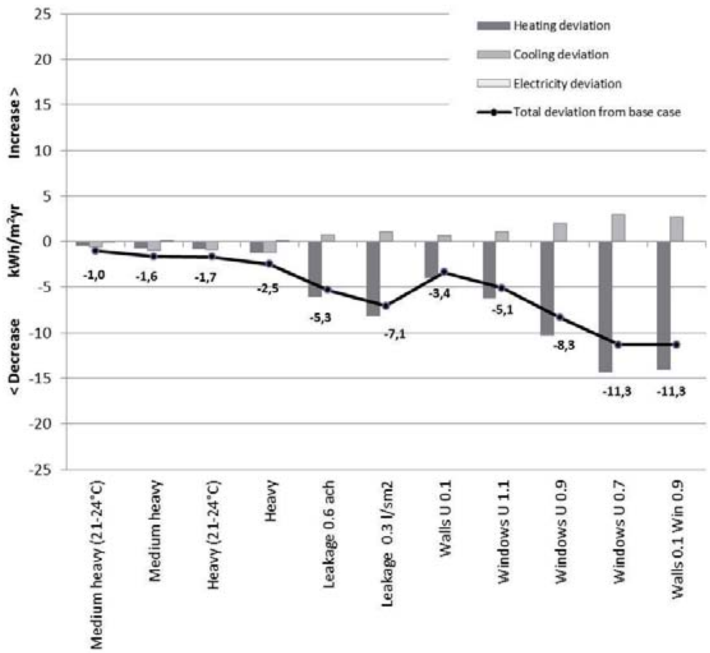

Figure 4.12 *Impact of insulation, thermal inertia and airtightness on end-use energy for total heating, cooling and electricity.*

Figure 4.13 shows the impact of a larger window area and different solar shading systems. These results indicate that a larger WWR has a significantly negative effect on energy savings, both for the heating and cooling demand. In total, an extra 25 kWh/m^{2}yr is needed for the case with WWR 60% compared to the base case with WWR 35%. The building orientation, on the other hand, does not affect the energy use according to the simulation results. Regarding solar shading devices, cooling energy is saved when the blinds are moved further out in the façade as expected. However, the heating energy increases at the same time and the difference in total energy demand between the external and intermediate blinds is negligible. The case with improved glazing (SHGC 27%) and internal blinds has the least saving potential since it increases the heating demand during winter when blinds are not used.

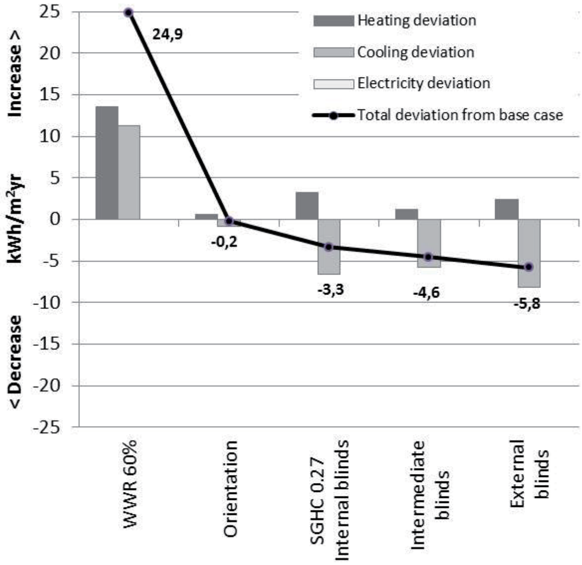

Figure 4.13. *Impact of window area and solar shading systems on end-use energy for total heating, cooling and electricity.*

4.2.3 HVAC strategies

Figures 4.14, 4.15 and 4.18 show the results from the study of temperature set-points, heat exchangers, fan power and ventilation strategies. The energy-saving potential when allowing a larger temperature range is far from negligible (see Figure 4.14). According to this study, up to 7 kWh/m^{2}yr heating energy and 5 kWh/m^{2}yr cooling energy can be saved by accepting 1°C colder and 1°C warmer.

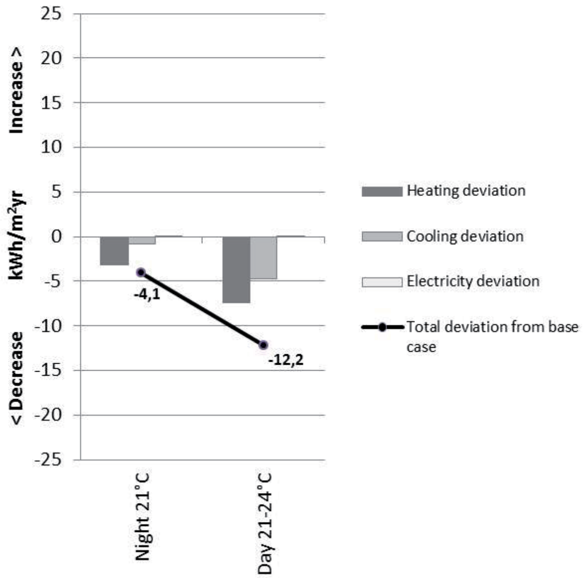

Figure 4.14 *Impact of indoor temperature on end-use energy for total heating, cooling and electricity.*

Figure 4.15 shows the results for different air handling units and strategies. The impact of the heat exchanger efficiency (compared to base case, eta 70%) is larger when the eta is reduced with 10% than when it is improved with 10%. Another 5% improvement makes no difference at all. A total saving potential of 3 kWh/m^{2}yr is possible (mainly in the heating coil in the air handling unit). The SFP was also improved in the parametric study. The base case fan efficiency, with a SFP of 2.0 kW/ m^{3}s^{-1}, was improved to 1.5 kW/m^{3}s^{-1}. However, this only decreased the electric energy with 2 kWh/m^{2}yr. The greatest saving potential occurs when changing the CAV system into a VAV system with airflows depending on indoor temperatures and CO_2 levels. For the reference building, a total of 21 kWh/m^{2}yr can be saved which is 15% of the total energy use. The airflows per hour are shown in Figures 4.16 and 4.17. The maximum total airflow in the system is 9400 l/s for the CAV case and 24 000 l/s for the VAV case, but the average airflows over the year are actually the same (3200 l/s) for both strategies.

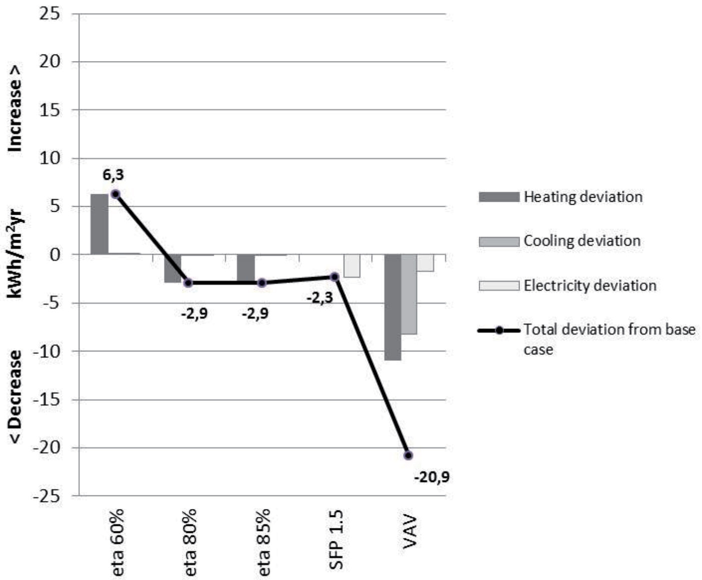

Figure 4.15 *Impact of air handling equipment on end-use energy for total heating, cooling and electricity.*

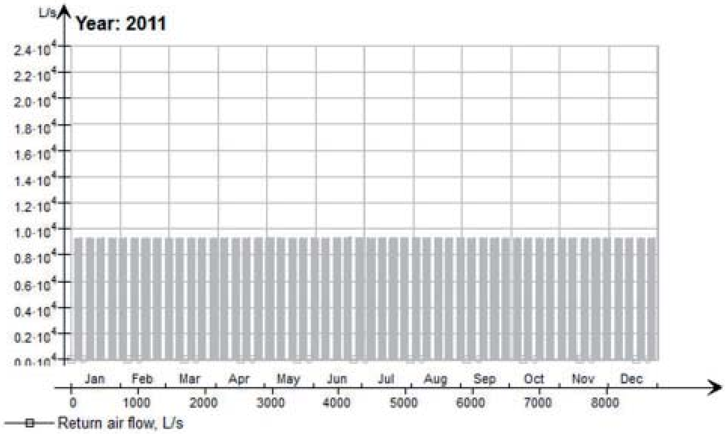

Figure 4.16 *Annual airflow per hour for the CAV system.*

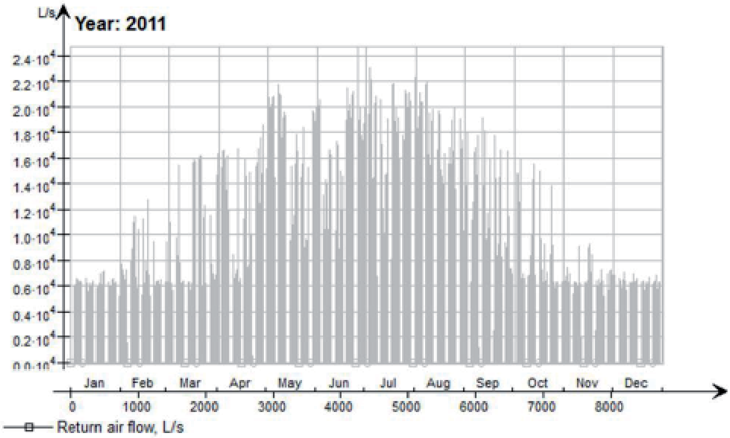

Figure 4.17 *Annual airflow per hour for the VAV system.*

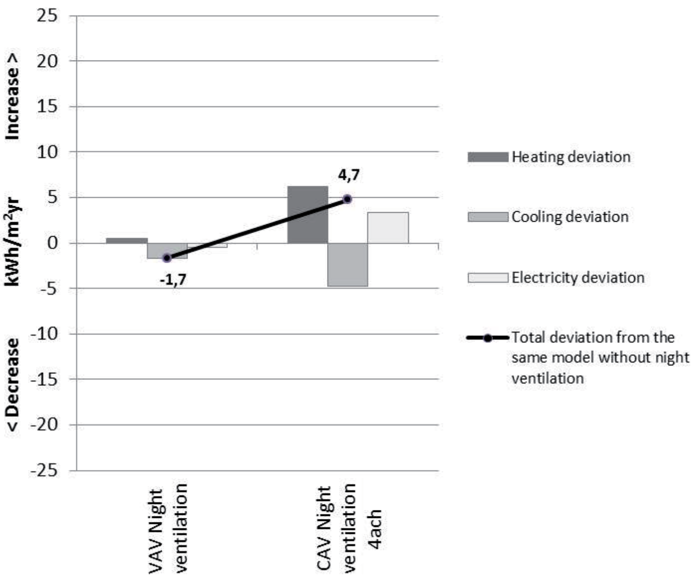

Figure 4.18. *Impact of night ventilation on delivered energy for heating, cooling and electricity.*

Figure 4.18 shows the potential cooling effect from mechanical night ventilation, with variable respectively constant airflows at night. For the VAV case, the energy saving potential is negligible (< 2 kWh/m^{2}yr) compared to a similar model without night ventilation. For the CAV case with a constant night flow of 4 ach, the savings in cooling energy implies increase in energy use for heating and fans. The total increase compared to a similar model without night ventilation is almost 5 kWh/m^{2}yr.

In a closer study of the night ventilation results, it is revealed that the improvement in thermal comfort is negligible for the two night ventilation concepts. Figure 4.19 shows the operative temperatures during the warmest day for the VAV system with ("diamond") and without ("star") night ventilation. The operative temperature peaks at 14.00 in both cases (SW orientation) and is only a few tenths of a degree cooler for the case with night ventilation. Note that set-point temperatures were 21-24°C at day and 18-24°C at night in these simulations. Nevertheless, the indoor temperature never drops below 22°C this warm night, in spite of night flush with ambient air of 15-20°C (not shown in figure). This result indicates that the cooling effect is not big enough, which can depend on too small airflows.

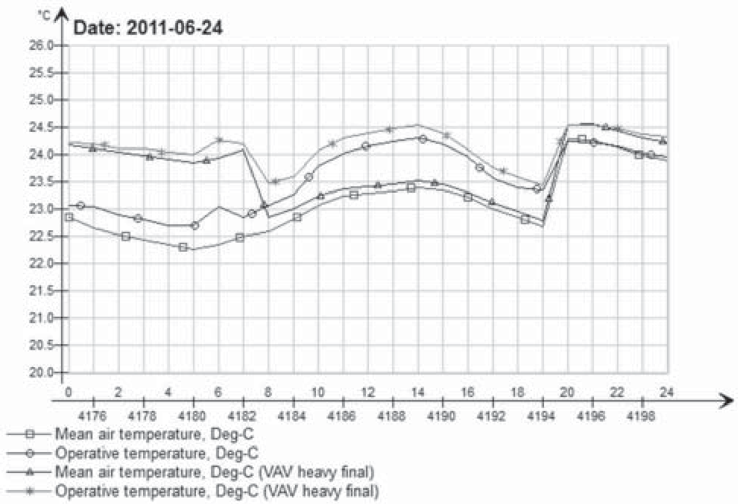

Figure 4.19 *Indoor temperature and operative temperatures for the warmest room during the warmest day. VAV with ("square" and" diamond") and without ("triangle" and "star") night ventilation.*

Figure 4.20 shows the airflows the warmest week for the VAV night ventilation system. The night-time maximum airflows in the building vary between 8000-16000 l/s this warm week, which are actually less than the maximum daytime airflows of 16000-19000 l/s. Furthermore, the maximum daytime airflows are actually less than in the case without night ventilation, for which they vary between 19000-20000 l/s this warm week. This explains why the fan electricity is not increased despite having mechanical night ventilation.

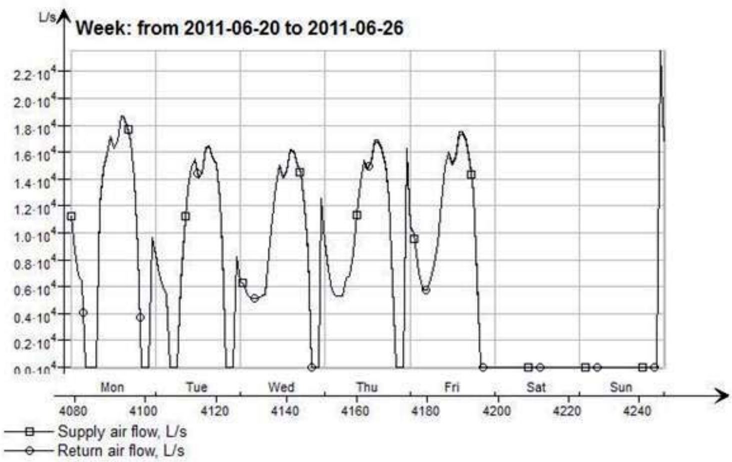

Figure 4.20 *Night time and day time airflows during the warmest week. VAV system.*

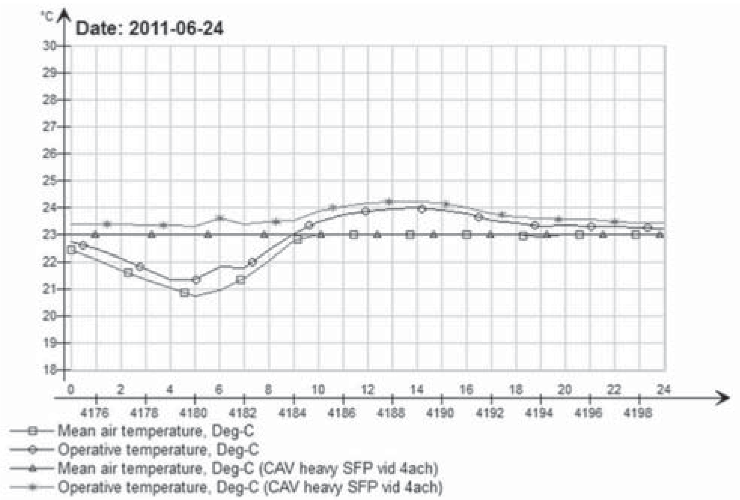

Figure 4.21 *Indoor temperatures and operative temperatures for the warmest room (SW, 5th floor) during the warmest day. CAV with ("square" and" diamond") and without ("triangle" and "star") night ventilation.*

Figure 4.21 shows the operative temperatures during the warmest day for the CAV system with ("diamond") and without ("star") night ventilation. Just as for the VAV system, the operative temperature peaks at 14.00 in both cases (SW orientation) and is only a few tenths of a degree cooler for the case with night ventilation. Note that set-point temperatures were 21-24°C and 18-24°C at night in these simulations. However, the indoor temperature only drops below 21°C at night with night ventilation, even though the night-time airflow is high. Figure 4.22 shows the airflows the warmest week for the CAV night ventilation system. The night-time airflow is 4 ach (22 000 l/s) and the daytime airflow is 1.5 l/sm^2 (9400 l/s).

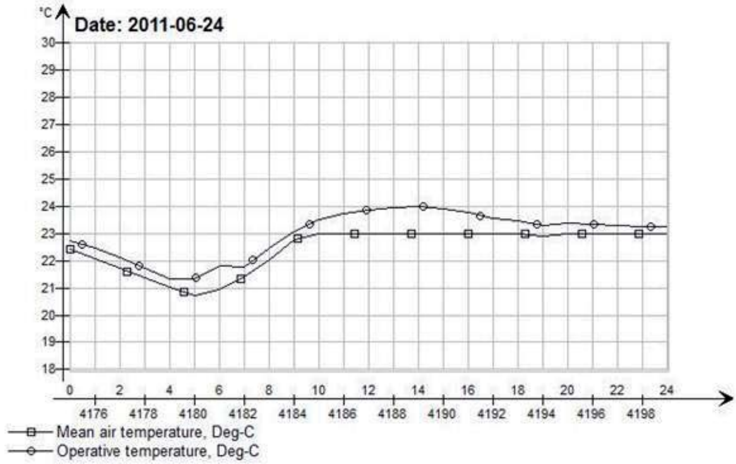

Figure 4.22 *Night time and day time airflows during the warmest week. CAV system.*

4.2.4 Lighting and electric equipment

Figure 4.23 presents the results from the parametric study when using more efficient office equipment and lighting, with reduced installed powers (EPD 55 W/room, LPD 8 and 4 W/m^2) and improved control (no standby losses at night and lighting with daylight control). Compared to the base case, approximately 10 kWh/m^{2}yr of electric energy is saved when improving the office equipment and another 10 kWh/m^{2}yr is saved when improving the lighting system. Meanwhile, the cooling energy decreases and the heating energy increases due to reduced internal heat gains. The total energy saving potential, compared to the base case, is 12 kWh/m^{2}yr when both office equipment and lighting is improved.

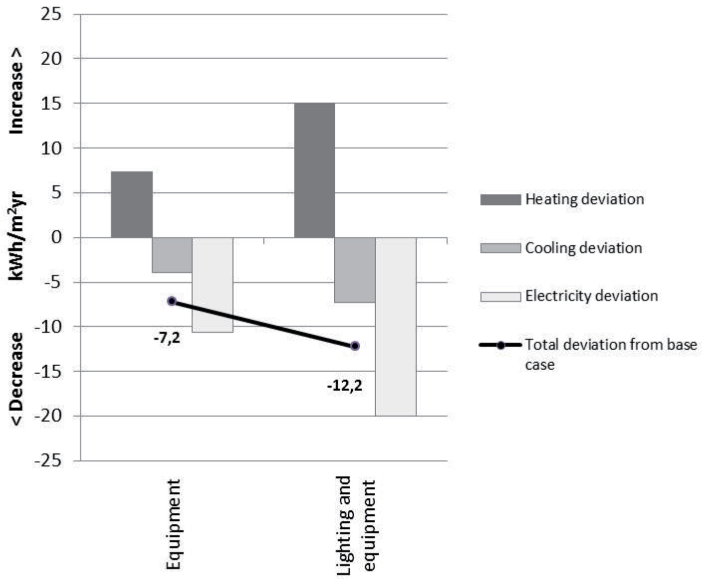

Figure 4.23 *Impact of equipment and lighting on total end-use energy for heating, cooling and electricity.*

4.2.5 The best case scenario

Figure 4.24 presents the most efficient design features from the parametric study, combined into a "best case" with the intension to reach a low-energy solution (see design features in Table 4.7). The best case solution shows a great improvement in especially heating and electricity use. The space heating energy is reduced by 26 kWh/m^{2}yr (54% heating energy saved and 19% total energy saved). The total electricity use is reduced by 25 kWh/m^{2}yr (36% electricity saved and 18% total energy saved). The reduction in cooling energy is 15 kWh/m^{2}yr (77% cooling energy saved and 11% total energy saved). The total saving potential is 66 kWh/m^{2}yr (48%). This total energy use can probably be further reduced if an effort is made to reduce the remaining facility electricity, in particular energy for pumps which in this study was set to 9 kWh/m^{2}yr and not analysed further.

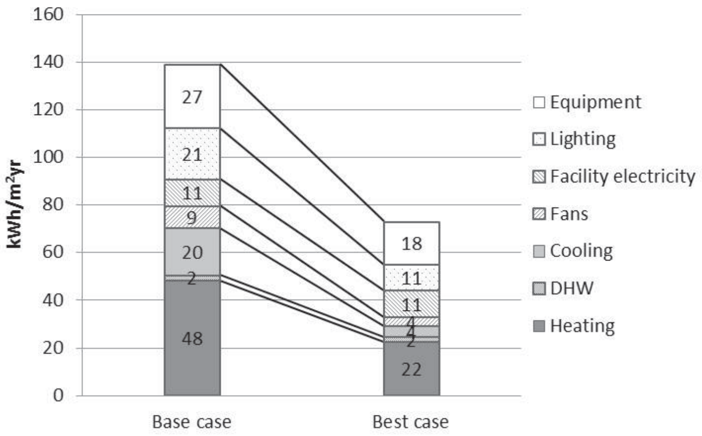

Figure 4.24 *Energy saving potential for the best case solution.*

Thermal conditions for the warmest and the coldest days in the simulation are displayed in Figures 4.25 and 4.26. The mean air temperature is allowed to swing between 21-24°C and the operative temperature stays close to the mean air temperature, between 20.9°C and 24.3°C, during office hours. The maximum operative temperature in the best case solution does not even exceed the peak in the base case, even though the cooling set-point is stricter (23°C) in the base case (see Figure 4.10).

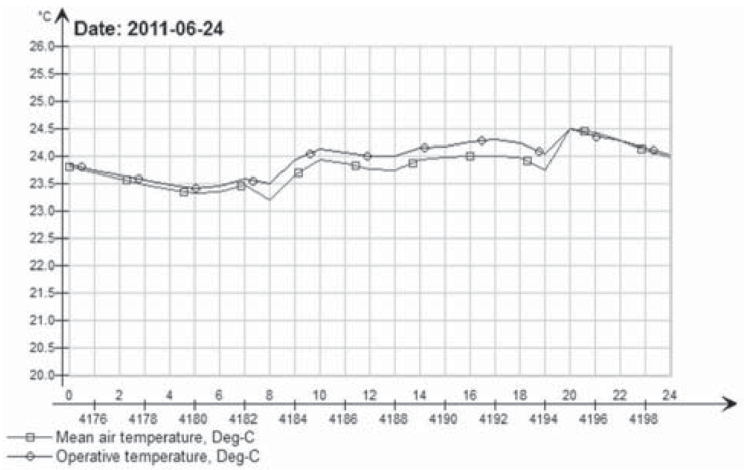

Figure 4.25 *Indoor air temperature and operative temperature for the best case. The warmest room (SW, 5th floor) the warmest day.*

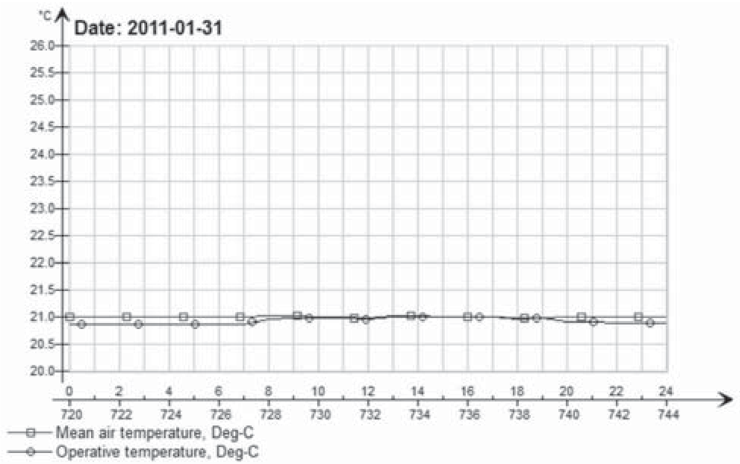

Figure 4.26 *Indoor air temperature and operative temperature for the best case. The coldest room (N, ground floor) the coldest day.*

Figures 4.27 and 4.28 show the maximum heating and cooling loads for the low energy solution compared to the base case. The total heating load is reduced with 42% to an average 30 W/m^2 and the total cooling load is reduced with 46% to an average 20 W/m^2. Note that these loads have not been calculated according to the passive house standard, and can therefore not be compared to the passive house criteria.

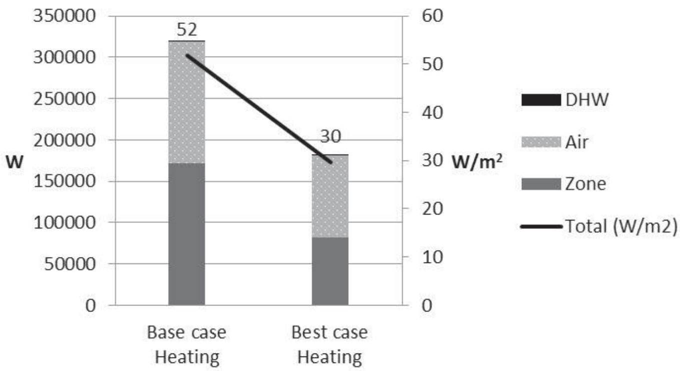

Figure 4.27 *Heat loads in the base case and the best case. Synthetic winter weather for Stockholm.*

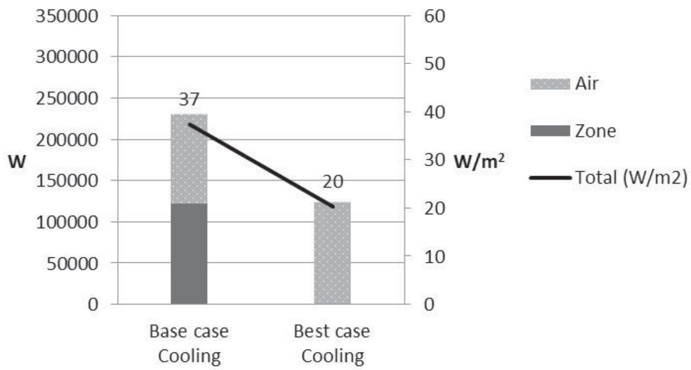

Figure 4.28 *Cooling loads in the base case and the best case. Synthetic summer weather for Stockholm.*

4.2.6 Sensitivity analysis

This section presents the results from the sensitivity analysis concerning the impact of climate, occupant attendance, building shape and interior planning.

Climate

Figure 4.29 shows the impact of climate on heating and cooling energy from the room units and air handling unit compared to Stockholm (base case). The difference in total energy demand between the coldest (Kiruna) and the warmest city (Darmstadt) is 39 kWh/m^{2}yr. Placed in Kiruna, the reference building requires 58 kWh/m^{2}yr more heating energy than in Darmstadt, but placed in Darmstadt it requires 18 kWh/m^{2}yr more cooling energy on the other hand. Furthermore, which is not apparent in this figure, the ventilation cooling battery is hardly used in Kiruna (0.5 kWh/m^{2}yr) while the ventilation heating battery is hardly used in Darmstadt (1.3 kWh/m^{2}yr). One interesting result is the fact that the difference in end-use energy between Stockholm and Karlstad is only 3 kWh/m^{2}yr for the reference building. Nevertheless, the cities represent different climatic zones, and office buildings in Karlstad are allowed to use 20 kWh/m^{2}yr more energy than in Stockholm according to the building code BBR. Likewise, Kiruna and Östersund both represent the north climatic zone, although the difference in total energy demand is 24 kWh/m^{2}yr.

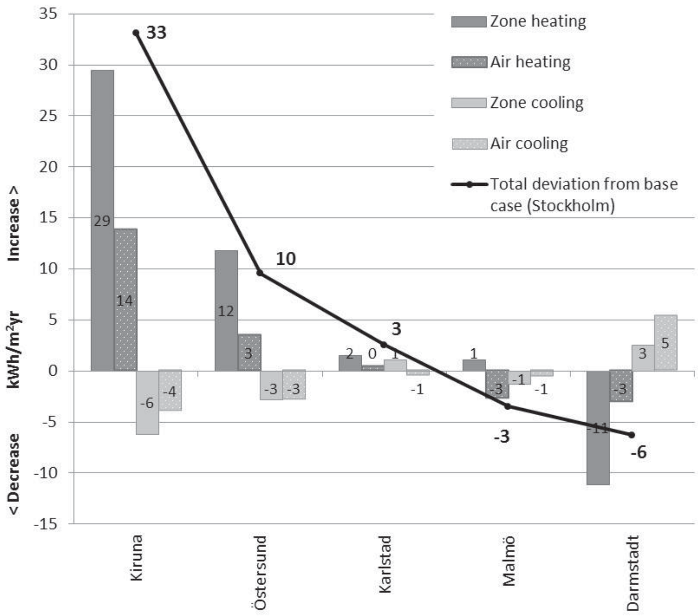

Figure 4.29 *Impact of climate on heating and cooling energy for the base case, comparsion with Stockholm. Note that the scale on the axis has been changed.*

Occupancy factor

The presence of occupants varies over the day and over the year and is difficult to predict. Figure 4.30 shows what happens with the energy use when the average occupancy factor is high and low compared to the standard occupancy factor of 0.7 (base case). The heating energy increases when the building is less occupied, but meanwhile the cooling energy decreases to some extent. As long as the equipment and lights are turned off in unoccupied rooms, the electricity decreases as well and the total energy demand is reduced. The total end-use energy is reduced by 3 kWh/m^{2}yr (3%) when the occupancy factor is reduced from 0.7 to 0.5. Hence, if the normal occupancy factor is as low as 0.5, this only has a positive effect on the end-use energy but it also means that the building is not used in a space-efficient way. The positive effect might be smaller in landscape office buildings since the lighting is often on even though the occupants are absent.

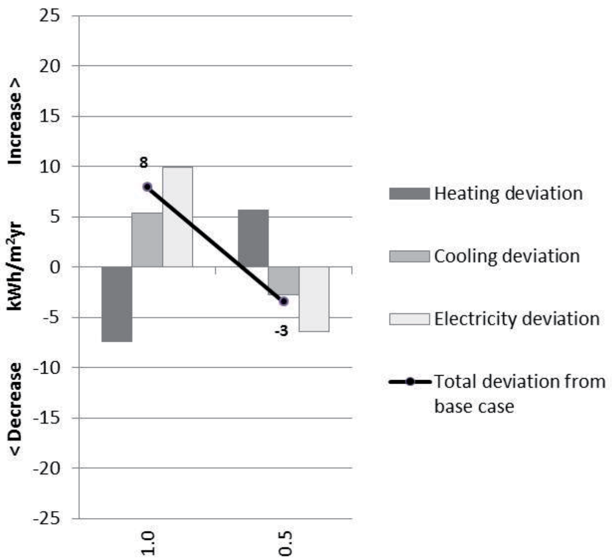

Figure 4.30 *Impact of occupancy factor on end-use energy for heating, cooling and electricity.*

Building shape and interior planning

The total end-use energy for the Kaggen building with an open landscape design, compared to the reference building with individual rooms, is presented in Figure 4.31. The result indicates that impact of building shape and interior planning is negligible. However, the two buildings are not strictly comparable since the floor heights and window-to-wall ratios are different. Kaggen yields a little bit more heating and less cooling energy. The specific energy use for lighting is a little bit larger since Kaggen has much office space and hardly any corridors with reduced installed lighting power.

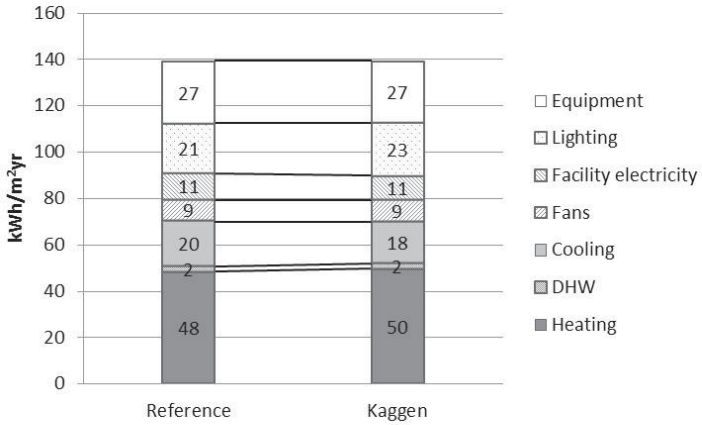

Figure 4.31 *Total end-use energy for Kaggen and the reference building. Base case input.*

It is more interesting to compare instead the impact of the different design features in the parametric study. Figure 4.32 shows the total energy deviation (%) from the base case simulation for each parameter for the two building types. The impact of thermal mass, heat exchanger efficiency, specific fan power, insulation levels, solar control and electric equipment is basically the same for the two building types. The impact of VAV system is smaller for Kaggen compared to base case but the impacts of mechanical night ventilation and of occupancy factor are larger. The most significant differences between the two building types are the effects of changing window-to-wall ratio and airtightness. The impact of increasing the WWR to 60% is smaller for Kaggen compared to the reference building. However, the initial window area was larger in Kaggen, and going from WWR 43% to 60% naturally has a smaller effect than going from 35% to 60%, as in the reference building. A more surprising result is the fact that the saving potential for improving the airtightness is greater for Kaggen compared to the reference building. Since the reference building has a larger surface-to-volume ratio and surface-to-floor ratio, the opposite effect would have been expected.

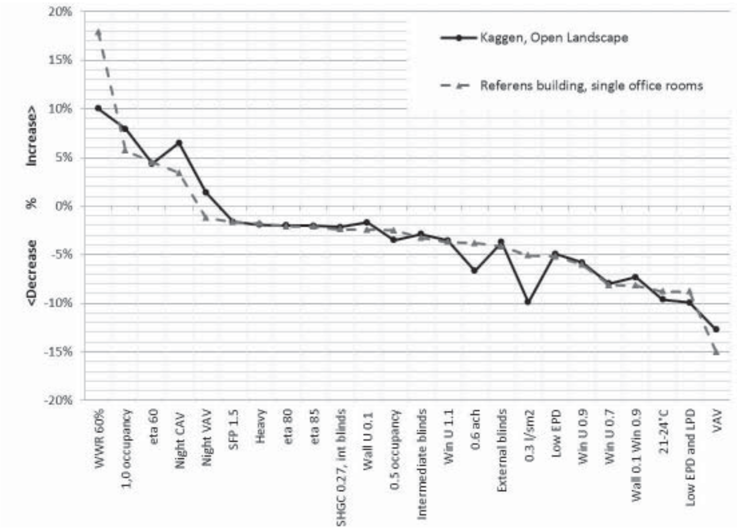

Figure 4.32 *Comparsion of impact from design features between the reference building and the open landscape building. Deviation from base case in total energy demand (%).*

4.3 Discussion

Dynamic simulations were carried out with IDA ICE on a typical narrow office building with peripheral individual office rooms in Sweden. The performance of the base case model complies with the regulations in the Swedish building code BBR18. The simulation results show a total end-use energy of 139 kWh/m²yr including tenant electricity. The most dominating post is space heating energy of 48 kWh/m^{2}yr. Cooling energy is 20 kWh/m^{2}yr, fan electricity is 9 kWh/m^{2}yr and other facility electricity (pumps and elevators) is 11 kWh/m^{2}yr. The user related electricity is 21 kWh/m^{2}yr for lighting and 27 kWh/m^{2}yr for office equipment. A parametric study was carried out in order to see how different design features affect the energy use in the base case. The results from the study show that airtightness, insulation and solar shading are important design features in order to decrease heating and cooling loads. However, the most crucial design features turned out to be glazing sizes relative to the facade and ventilation strategy. The least crucial features turned out to be building orientation, thermal inertia and cooling with mechanical night ventilation. The most interesting findings are discussed in this section.

4.3.1 Building envelope design

An increase in WWR, from 35% to 60% (GWR from 31% to 54%), generates a significantly larger energy demand, both for heating and cooling. Heating increases by 14 kWh/m²yr (29%) and cooling by 11 kWh/m²yr (55%) compared to the base case. Besides the additional energy demand, large glazing areas increase the risk of glare discomfort. According to the recent daylight study on a similar building carried out by Dubois and Flodberg (2012), the optimal GWR in Sweden for a good daylight design is 20-40%, with the lower value preferable on the south façade where the risk of glare is superior. Increasing the glazing-to-wall ratio to more than 40% has a negligible effect on available daylight inside the building, and no electric lighting will therefore be saved. Hence, the results from the energy simulations are supported by these recent daylight simulations, and it is suggested that the glazing area is kept as small as possible in order to save energy and to avoid glare, but not smaller than 20% in order to secure enough daylight and a view out.

The study of solar shading devices indicates that the further out in the façade the blinds are placed, the more cooling energy can be saved but in return more heating energy will be needed. However, the overall effect is modest. Therefore, climatic conditions and the number of heating and cooling hours must be considered when selecting solar shading strategy. It may not be profitable with external blinds if the daytime heating hours exceed the cooling hours, or if external blinds are much more expensive due to high wind exposure. One possible, but rather expensive, solution is to have both internal and external solar shades and alternate these in order to optimize the solar heat gains in different seasons. It could also be an alternative to improve the glazing performance and select a glass with low solar heat gain coefficient. However, there is a risk that the solar heat gains are reduced more than needed, creating an unnecessary heating load, and that the visual transmittance and window view are degraded.

Great savings in heating energy are achieved with improved airtightness (17%) and insulation levels (29%) in the building envelope, corresponding to recent passive house guidelines (FEBY 2009). However, the base case performance was rather poor (yet reasonable) compared to recently designed office buildings, which enabled the large saving potential.

Regarding the results from the thermal inertia study, a heavy version of the reference building with exposed concrete floors, concrete sandwich walls and various internal walls in concrete has a negligible impact on the heating and cooling demand. This result indicates that the cooling load, due to solar gains and internal heat gains, is not large enough in countries at high latitudes to take advantage of thermal inertia. Note that the reference building has a quite modest WWR (35%) compared to many modern office buildings, which implies that the solar heat gains are rather small. The result also indicates that there might already be enough thermal mass in the concrete floors alone, despite the ceilings and carpets. The reference building is large with many floors and maybe it cannot benefit from any more thermal mass, which was anticipated in the review in chapter 2.4.1. Another explanation could be the strict temperature range often used in Swedish office buildings, just allowing small variations in the indoor air temperature and hence activating heating and cooling systems too soon. However, less strict set-points (21-24°C) were tested as well and the results were not improved. Maybe thermal inertia is more crucial when having limited or no cooling supply, and when allowing the operative temperature rise to 26°C during summer.

4.3.2 HVAC strategies

Regarding ventilation, the simulations showed that having demand-controlled ventilation with combined temperature and CO_2 control is the most energy efficient feature in terms of heating, cooling and fan electricity. Compared to the base case with constant airflow, a total of 21 kWh/m²yr can be saved (heating 23%, cooling 41% and electricity 18%). This strategy is in line with recommendations from the Passive house institute, which states that comfort and a good indoor air quality shall be ensured and provided by using just the necessary air quantities (PHI 2012a). However, the average airflow over the year is actually the same for the CAV and the VAV system. The demand controlled ventilation system simply distributes the airflow during the various time periods in a more efficient way, saving both zone heating and zone cooling energy.

The improvement in heat exchanger efficiency had a rather small impact on reduction of the heating. Improving the efficiency from 70% to 80% yields a saving of 3 kWh/m²yr in heating energy (6%), and improving from 80% to 85% efficiency saves no heat at all. The explanation can be that the largest heating demand in an office occurs during night when the air handling system is off. During office hours, the building is partly heated by internal gains and solar gains and the heat exchanger is even bypassed at times. The recommendation based on this study, is to design the air handling unit with a rotating heat exchanger, but the required efficiency should be determined with a sensitivity analysis for the actual building.

Other important findings deal with a passive cooling concept with night ventilation, which is common in many German low-energy office buildings. According to this parametric study, a mechanical night ventilation strategy actually has a rather modest and even adverse effect on energy savings. For these simulations, the base case was improved with higher thermal inertia and the set-point temperatures were changed to 21-24°C and in addition a temperature drop was allowed during night ventilation. In the study with demand-controlled ventilation and variable airflows depending on temperature, the cooling energy is reduced with less than 2 kWh/m^{2}yr (9%) and the total energy savings compared to the base case are negligible (1%). The electric energy for fans actually decreases slightly with this night cooling strategy because the daytime airflows become smaller with the reduced cooling demand in the morning. For the case with a constant night flow of 4 ach, the cooling effect is improved and the saving potential is almost 5 kWh/m^{2}yr (24%). However, this saving does not compensate for the extra demands of fan and heating energy. This study indicates that cooling with mechanical night ventilation might not be profitable in a Nordic country. The cooling demand is not high enough to compensate for the cost of the increased electricity for fans and space heating. It would probably be more suitable to use the night ventilation strategy in combination with a natural ventilation strategy which does not use any fan electricity. However, a natural ventilation concept is highly dependent on the outdoor climate and the location and size of openings in the building. Furthermore, noise and air pollution from the surroundings as well as fire safety and security must be regarded.

Modern Swedish office buildings often have strict indoor temperature targets at about 22-23°C during working hours. The energy saving potential when allowing a larger mean air temperature range, for example 21-24°C, is far from negligible. According to this study, 7 kWh/m^{2}yr (15%) heating energy and 5 kWh/m^{2}yr (24%) cooling energy can be saved by accepting a larger range in indoor temperatures. To avoid thermal dissatisfaction, it is important to keep the operative temperature close to the mean air temperature by avoiding, for example, solar radiation impinging on the occupants. According the national board of health and welfare (Socialstyrelsen 2005) and the thermal comfort criteria TQ1 and TQ2 (Ekberg 2006), the operative temperatures should not fall below 20°C in the winter or exceed 26°C in the summer for longer periods. If the set-points for mean air temperature are expanded to 21-24°C or more, it could be a good idea to inform the workers of the underlying reasons for temperature variations. People tend to have a greater acceptance with the indoor climate if it is for a good cause. People already dress according to season and external temperatures, with lighter clothes in the summer, but with a greater awareness, people may also be willing to change their clothes during a workday to reflect the variations of internal temperatures (Barlow & Fiala, 2007). The results from the simulation study indicate that the saving potential in heating and cooling energy is great when allowing temperature swings, and both seasonal and daily temperature swings should therefore be considered when designing a low-energy office building.

4.3.3 User related electricity and internal heat gains

The improvement in office equipment and lighting has a large impact on electricity, heating and cooling energy. According to this study, the tenant electricity for equipment can be reduced with 10 kWh/m^{2}yr (37%), compared to a normal modern office building, by selecting office equipment with low EPD and very low "off-mode" losses. The lighting electricity use can be reduced by another 10 kWh/m^{2}yr (48%) by installing low-power lighting fixtures (8W/m^2) and by controlling the lighting system with occupancy switch-off and daylight dimming. The lighting saving result corresponds well to the saving potentials anticipated by Dubois and Blomsterberg (2011) in a literature review and by Dubois and Flodberg (2012) in a simulation study. In addition to the reduction of electricity, the cooling energy is also decreased due to reduced internal heat gains. However, the heating energy is increased instead due to the reduced gains and the total saving potential for improved lighting and equipment is 12 kWh/m^{2}yr compared to the base case. This result shows that it is desirable to reduce the internal gains even though the heating load increases. Furthermore, the heating load can be provided by renewable energy to a greater extent than the user related electricity can.

4.3.4 Best case solution

In a final best case simulation in this study, the most effective design features were combined to see the lowest reachable energy use in the reference building. The simulation result is promising and shows that 66 kWh/m^{2}yr (49%) energy can be saved compared to a new office building designed according to the recent Swedish building code BBR18. The total energy use can probably be further reduced if an effort is made to reduce remaining facility electricity, in particular energy for pumps which in this study was assumed to almost 9 kWh/m2yr (12% of the total energy use). According to Boverket's classification of energy performance, a 25% reduction compared to the energy requirement corresponds to a "low energy building" and a 50% reduction to a "very low energy building" (Boverket, 2011b). This indicates that the best case solution may be considered as a very low energy office building. By improving walls and windows, reducing window-to-wall ratios, introducing demand-controlled ventilation and lighting, allowing a larger range in temperature, and by installing more efficient equipment which is completely turned off outside office hours, the heating, cooling and electricity can decrease significantly. These design features are not very expensive solutions and nowadays they are rather well mastered. The investment cost is slightly higher compared to the base case due to more expensive walls, windows and lighting control systems. The least established of the studied features is the photoelectric dimming system, which works perfectly in theory (Dubois and Flodberg 2012) but has proved to have some practical and technical issues, revealed in a monitoring study by Gentile and Håkansson (2012). The problem can be the position and calibration of the built-in illuminance sensors, resulting in higher electric light output than required. However, these kinds of installation issues will probably diminish over time. Out of all studied design features, reducing the user related electricity is probably the greatest challenge, since there has been limited focus on this issue earlier in Sweden and since it is difficult to control the tenant's use of office equipment over time. Power strips and multiple sockets may facilitate the reduction of "off-mode" losses but in addition, some kind of incentive is required in order to influence the user behaviour. Displaying the real time electricity use is one possible aspect for raising awareness among the users.

One way to reduce the investment cost for the best case solution could be to remove the cooling system. The cooling energy was reduced with 77% in the best case simulation, which means that only 4 kWh/m^{2}yr cooling energy remains. One additional simulation of the reference building was performed in order to see the result of the indoor thermal climate when the cooling system was completely removed. Figure 4.33 shows the worst summer temperatures for the best case solution without active cooling. The operative temperature reaches 26°C a few times but does not exceed 26°C any work day in a year with normal climate. This result indicates that the risk of overheating hours is low in this best case solution of the reference building.

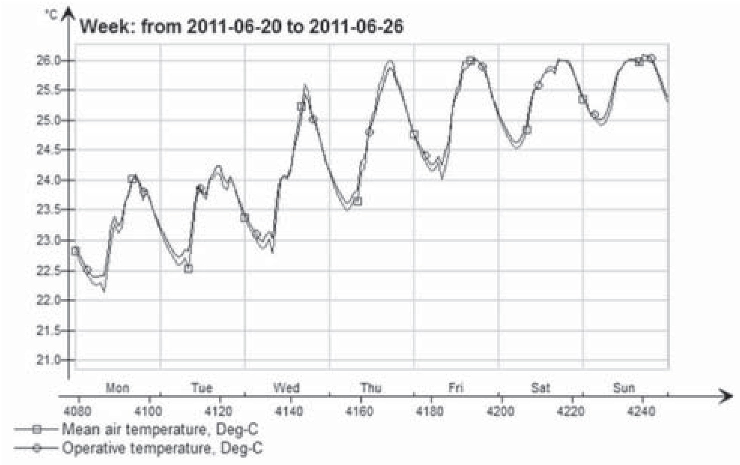

Figure 4.33 *Mean air and operative temperatures in the best case simulated without cooling. The warmest room (SW, 5th floor), the warmest week.*

4.3.5 Sensitivity analysis

In a sensitivity analysis, the impact of climate, occupant attendance and building shape and interior planning was studied. The first two of these parameters are often not possible to consider in the design phase. Different climates, from Kiruna in the north to Darmstadt in the south, were studied for the reference building and the total energy use turned out to be 39 kWh/m^{2}yr higher in Kiruna compared to Darmstadt. This indicates that even though the cooling demand is smaller in the north, it might be easier to design low-energy office buildings in warmer climates since the heating demand is still a dominating energy post. Furthermore, the climate zones in the Swedish building code may need a review since locations within the same climate zone show a great difference in heating and cooling energy. This issue becomes more important as the energy regulation gets stricter.

The occupant attendance in office buildings is of current debate. Different standards suggest that a normal daily occupancy factor is 0.7-0.8 but measurements have indicated that the occupancy factor is much lower in reality (<0.6). The occupancy estimation is used for energy calculations and for designing HVAC systems. According to the simulations, the total energy use is reduced with a modest 3 kWh/m^{2}yr if the occupancy rate is reduced from 0.7 to 0.5. When the occupancy factor is low, the heating demand increases but the cooling demand and the electricity for lighting and equipment decreases even more. The fact that the occupancy attendance vary over the day, emphasises the importance of having demand-controlled systems for lighting, ventilation and office equipment, which do not operate in a constant load mode. Another issue to consider is how to handle the estimated occupancy attendance in energy simulations. When simulating a complete model of a building it is generally accepted to simplify the occupancy attendance and assume an hourly average in each room. In open landscape offices with several people this is probably applicable, but in individual office rooms, persons are either present or absent, 0.7 persons cannot be present. The hourly average helps smoothing the internal gains but in reality some rooms have large internal gains and some rooms have small internal gains, which can lead to simultaneous heating and cooling in a building.

The simulation results of the Kaggen building with an open landscape office design are interesting and a bit surprising. The base case simulation showed that the difference between the rectangular building with individual rooms and the deep building with open landscape is negligible. The Kaggen building is deep and compact with a low surface-to-volume ratio of 0.20 m^{-1} which indicates that the transmission heat losses and the uncontrolled air leakage through the building envelope are low. However, the reference building is also reasonably compact a surface-to-volume ratio of 0.26 m^{-1}. Open landscape offices are often characterised as more space efficient with room for more people since there are few internal walls and partitions. This results in higher internal heat gains in proportion to floor area, and therefore a higher specific energy use for office equipment and cooling. On the other hand, an open planning enables a good mixture of air and distribution of solar and heat gains from one part of the building to the other, which helps reducing the heating and cooling loads.

It is possible that all the pros and cons, regarding the energy use in an open landscape office, cancel each other and therefore show negligible difference between Kaggen and the reference building. However, the two buildings are not strictly comparable since the floor heights and window-to-wall ratios differ. Therefore, the same design features as in the reference building were studied in Kaggen to investigate if the same effect of the various features could be identified. The relative saving potential when improving the building envelope and HVAC strategies are to a great extent alike for the two building types, but the comparison shows in particular one unexpected result. The relative energy saving when improving the airtightness is 5% higher for Kaggen compared to the reference building, but it should be the same. One hypothesis is that the model of Kaggen in IDA ICE is rather complex since it has an atrium which is built as one high zone with large openings to each floor. Each opening is considered as a leakage through the wall and this might disturb the airflow model.

4.3.6 The simulation model

This study is based on computer simulations only, and the results have not been verified with monitoring experiments in a real office environment. Although the attempt was to model an office building close to reality, by using real architectural drawings and realistic design parameters recommended by members of the reference group, several standardisations and assumptions had to be made. In reality, every building is unique and few office buildings are run with pure office operation as this reference building. Office buildings often contain restaurants and stores which affect the energy balance. Furthermore, occupants do not work between 08:00-18:00 every day, as assumed in this study. Occasionally people work late nights and weekends, which will affect the lighting, equipment and ventilation operation. As was discussed previously, the assumed average occupancy factor is a source of error.

IDA ICE is a powerful tool for studying the energy balance in a building. However, IDA ICE describes an ideal building operation with perfectly trimmed and maintained systems and a perfectly mixed air volume. It does not admit bad, yet common, control with simultaneous heating and cooling.

5 Conclusions

Dynamic simulations were carried out with IDA ICE 4 on a typical narrow office building with peripheral individual rooms in Sweden. Simulation input were based on design features found in literature and in a state-of-the-art review of existing low energy office buildings. The simulations resulted in a very low energy office building with a total end-use energy of 73 kWh/m²yr for heating, cooling, facility electricity and user related electricity. The result shows that 49% energy can be saved compared to a traditional modern office building, which means that the initial goal of this project was reached. The low energy building shows a specific energy use of 44 kWh/m²yr and a user related electricity of 29 kWh/m²yr. Additional simulations indicated that the specific energy use can be further reduced by cutting the remaining low cooling demand. The cooling can be cut by allowing higher indoor temperatures during hot summer days, without exceeding the recommendations of the national board of health and welfare. However, it requires that solar gains and internal heat gains are low. Another possibility might be to use free cooling in the ventilation system, with an earth-to-air heat exchanger for pre-cooling the ambient air before it reaches the air handling unit. The strategy is normal practice in German low energy office buildings and it has been applied also in some previous Swedish buildings. However, it is important to control the humidity in the underground ducts in order to avoid microbial growth and health risks.

The study showed that following design features are essential for achieving this low energy office building in Sweden:

- Reasonable WWR
- Demand controlled ventilation
- Demand controlled lighting and low-power equipment
- Wider temperature set-points
- Well insulated and airtight building envelope

These design features correspond well with the first four steps in the Kyoto pyramid (Figure 2.1). The heating demand is kept low with small transmission and ventilation heat losses. The cooling demand is reduced through low solar and internal heat gains, owing to the reduced glazing area and low electricity use. The electricity demand is reduced with efficient control and low-power lighting and office equipment. Finally, both heating and cooling energy are reduced with an efficient temperature control. These design features are not very expensive solutions and most techniques are proven and rather well mastered. The investment cost is most likely higher compared to a traditional modern office building, due to more expensive walls, windows and lighting control systems. However, with a low heating and cooling demand it might be possible to remove for instance the heating or cooling coil in the air handling unit and thus reduce the investment cost.

For low energy offices, it is crucial to decrease the user related electricity and internal heat gains. A common perception in the building industry is that low energy buildings would require additional energy when the internal gains are lowered, but this does not apply on office buildings which often include cooling systems. Not only is the user related electricity diminished, but the cooling energy is also reduced and it will be easier to maintain the desired indoor climate. The user related electricity is a challenge to reduce, and one recommendation is to include it in the building code of energy performance, or to limit it in popular environmental classification systems.

6 Future research

The main goal of this thesis work was to show that it is possible to design a very low energy office building with an investment cost of the same order of magnitude as that of a traditional modern office building. However, the exact investment cost was not calculated, it was simply considered the same order of magnitude since only common and proven technique was used in the simulations. The further research should therefore focus on calculating the cost for the different design features as well as the total investment cost for the low energy building compared to a traditional modern office building. Furthermore, it would be interesting to calculate and compare also the life cycle cost and the life cycle assessment, in order to include costs and environmental impacts associated with all the stages of the building's life, from raw material extraction through materials processing, material transports, construction, operation, maintenance, and disposal or recycling.

Since this simulation study was carried out with proven technique, the natural next step should be to carry out simulations on an office building with the best available technique on the market. These simulations should contain also the study of different renewable energy concepts in order to see if the remaining energy demand could be covered, and a net zero-energy building achieved in Sweden. Thereby, the last step of the Kyoto pyramid, about selecting energy sources, will be considered.

In the low energy simulation, the heating and cooling peak loads were reduced by 42% and 46% compared to the traditional modern office building. Peak loads were not studied further in this thesis work, but peak loads for heating, cooling and electricity are essential to study in the future, since the amount of "green" heating, cooling and electricity in Sweden is limited. In a growing number, the power companies raise the energy tariffs instantaneously when the grids are heavily loaded, and it will be important to reduce the seasonal and daily peak loads.

References

Artmann, N., Manz, H., & Heiselberg, P. (2008). Parameter study on performance of building cooling by night-time ventilation. *Renewable Energy, 33*, 2589-2598.

Aste, N., Angelotti, A., & Buzzetti, M. (2009). The influence of the external walls thermal inertia on the energy performance of well insulated buildings. *Energy and Buildings, 41*(11), 1181-1187.

Backström, C. (2003). Kalkylera med LCCenergi: Riktlinjer för val av indata. Luftbehandlingssystem. *V-skrift 2003:1*.

Balaras, C. A. (1996). The role of thermal mass on the cooling load of buildings. An overview of computational methods. *Energy and Buildings, 24*(1), 1-10.

Barlow, S., & Fiala, D. (2007). Occupant comfort in UK office: How adaptive comfort theories might influence future low energy office refurbishment strategies. *Energy and Buildings, 39*, 837-846.

BELOK. (2011). Energikrav för lokalbyggnader. Version 3. http://belok.se/docs/kravspec/Energikrav-11-09-06.pdf.

Berggren, B., Stenström, H., & Wall, M. (2011). *A parametric study of the energy and moisture performance in passive house exterior walls*. Paper presented at the The 4th Nordic Passive House Conference, Helsinki, Finland.

Berglund, T. (2010). [Visit Waterfront, 2010-09-08].

Bine. (2001). Projektinfo 8/01. http://www.bine.info/en/: Bine Informationsdienst.

Bine. (2007). Thermo-active building systems: High-comfort, energy-efficient heating and cooling of non-residential buildings. http://www.bine.info/en/: Bine Informationsdienst.

Bine. (2009a). Projektinfo 06/09. http://www.bine.info/en/: Bine Informationsdienst.

Bine. (2009b). Projektinfo 16/09. http://www.bine.info/en/: Bine Informationsdienst.

BizEE. (2011). Heating and Cooling Degree Days Retrieved 2011-06-10 from http://www.degreedays.net/

Blomsterberg, Å. (2009). *Lufttäthet i kontorsbyggnader: mätningar och beräkningar*. Malmö: WSP Environmental.

BOB. (2011). Balanced Office Building Retrieved 2012-03-04, from http://www.bob-x.de/

Bollin, E., Fernandes, J. d. C., & Feldmann, T. (2008). Energie optimiertes Bauen, Teilkonzept 3: Langzeitmonitoring des Neubauvorhabens Solar Info Center Freiburg. Offenburg, Germany: Hochschule Offenburg - Institute of Applied Research.

Boverket. (2009b). Energihushållning enligt Boverkets byggregler. http://www.boverket.se.

Boverket. (2010). Teknisk status i den svenska bebyggelsen - resultat från projektet BETSI. http://www.boverket.se.

Boverket. (2011a). Boverkets byggregler, BBR 18. BFS 2011:6. http://www.boverket.se.

Boverket. (2011b). Regelsamling för byggande, BBR 2012. BFS 2011:6 med ändringar t.o.m. BFS 2011:26. http://www.boverket.se.

Braun, D., Filleux, C., & Wehrli, S. (2009). Die sonne als einzige energiequelle. www.baslerhofmann.ch.

Breesch, H., Bossaer, A., & A., J. (2005). Passive cooling in low-energy office building. *Solar Energy, 79*, 682-696.

BuildingPhysics. (2011). HEAT2 Retrieved 2011-12-29, from http://www.buildingphysics.com

BuildUp. (2010). GreenBuilding Partner WWFF - ENERGYbase Retrieved 2011-02-23, from http://www.buildup.eu/cases/8227

CEN. (2000). EN 13829: Thermal performance of buildings - Determination of air permeability of buildings - Fan pressurization method (ISO 9972:1996, modified): CEN.

CEN. (2007a). EN 15251: Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics: CEN.

CEN. (2007b). EN 15217: Energy performance of buildings - Methods for expressing energy performance and for energy certification of buildings: CEN.

Depecker, P., Menezo, C., Virgone, J., & Lepers, S. (2001). Design of buildings shape and energetic consumption. *Building and Environment, 36*(5), 627-635.

DGNB. (2012). German Sustainable Building Council Retrieved 2012-03-18, from http://dgnb.de/_en/index.php

Di Perna, C., Stazi, F., Casalena, A. U., & D'Orazio, M. (2011). Influence of the internal inertia of the building envelope on summertime comfort in buildings with high internal heat loads. *Energy and Buildings, 43*(1), 200-206.

Dodoo, A., Gustavsson, L., & Sathre, R. (2012). Effect of thermal mass on life cycle primary energy balances of a concrete- and a wood-frame building. *Applied Energy, 92*(0), 462-472.

Dubois, M.-C., & Blomsterberg, Å. (2011). Energy saving potential and strategies for electric lighting in future North European, low energy office buildings: A literature review. *Energy and Buildings, 43*(10), 2572-2582.

Dubois, M.-C., & Du, J. (2012). *Landscape offices at high latitude: Daylight autonomy and electric lighting savings in relation to key design features*. Paper presented at the IEECB 2012 - 7th international conference on improving energy efficiency in commercial buildings, Frankfurt, Germany.

Dubois, M.-C., & Flodberg, K. (2012). Daylight utilisation in perimeter office rooms at high latitudes: Investigation by computer simulation. *Lighting Research and Technology, 0*, 1-24.

Eicker , U., Huber, M., Seeberger, P., & Vorschulze, C. (2006). Limits and potential of office building climatisation with ambient air. *Energy and Buildings, 38*, 574-581.

Eicker, U., Seeberger, P., Fischer, H., & Müller, J. (2005). Evaluierung Passiv-Bürohaus Lamparter. Stuttgart: FH Stuttgart-HFT, Stuttgart University of applied sciences.

Ekberg, L. (2006). R1 - Riktlinjer för specifikation av inneklimatkrav (2006). Kristianstad, Sweden.

En0B. (2011). Research for energy-optimised construction Retrieved 2011-02-15, from http://www.enob.info/en

Enberg. (2009). Minimikrav på luftväxling., Utgåva 8 C.F.R.

Energimyndigheten. (2007). Förbättrad energistatistik för lokaler - "Stegvis STIL" Rapport för år 1: Statens Energimyndighet.

Energimyndigheten. (2011). Energiindikatorer 2011 (Vol. ER 2011:12): Statens Energimyndighet, http://www.energimyndigheten.se.

Energon. (2011). Energon Ulm Retrieved 2012-03-04, from http://www.energon-ulm.de/

ENERGYbase. (2009). Office complex of the future Retrieved 2009-10-21, from http://www.energybase.at/eng/index.php

EnergyStar. (2012). Find Energy Star Products Retrieved 2012-03-25, from http://www.energystar.gov

EQUA. (2012). Equa Solutions Retrieved 2012-03-20, from http://www.equa-solutions.co.uk

Europa. (2012). Summaries of EU legislation: Strategy on climate change for 2020 and beyond Retrieved 2012-04-01, from http://europa.eu/legislation_summaries/environment/tackling_climate_change/l28188_en.htm

European Parliament. (2010). DIRECTIVE 2010/31/EU OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 19 May 2010 on the energy performance of buildings (recast). *Official Journal of the European Union 53* (2010).

FEBY. (2009). FEBY Kravspecifikation för Passivhus. Forum för energieffektiva byggnader. http://www.energieffektivabyggnader.se

Filleux, C. (2009, 2009-10-16). [09-09-22 fachbeitrag GHC].

Gentile, N., Håkansson, H., & Dubois, M.-C. (2012). Lighting control systems in individual offices at high latitude: measurements of lighting conditions and electricity savings. Paper presented at the IEECB 2012 - 7th international conference on improving energy efficiency in commercial buildings, Frankfurt, Germany.

Geving, S., & Holme, J. (2010). *Increased insulation thickness and moisture*. Paper presented at the 3rd Nordic Passive House Conference, Aalborg, Denmark.

Goethals, K., Breesch, H., & Janssens, A. (2011). Sensitivity analysis of predicted night cooling performance to internal convective heat transfer modelling. *Energy and Buildings, 43*, 2429-2441.

Google. (2011). Google Maps Retrieved 2011-04-13, from http://maps.google.se/

Gratia, E., Bruyère, I., & De Herde, A. (2004). How to use ventilation to cool narrow office building *Building and Environment, 39*, 1158-1170.

Gratia, E., & De Herde, A. (2003). Design low energy office buildings. *Energy and Buildings, 35*, 473-491.

Greenbuilding. (2011). Best practise example Retrieved 2011-02-24, from http://www.eu-greenbuilding.org

Grini, C., Mathisen, H.-M., Sartori, I., Haase, M., Sörensen, H. W. J., Petersen, A., . . . Wigenstad, T. (2009). LECO - Energibruk i fem kontorbygg i Norge: Befaring og rapportering: SINTEF Byggforsk, Prosjektrapport 48.

Gräslund, J. (2010). [Information about Hagaporten].

Haase, M., Buvik, K., Dokka, T. H., & Andresen, I. (2010). Project report no 56 - Guidelines for energy efficiency concepts in office buildings in Norway. Oslo: SINTEF Building and Infrastructure.

Haugland, L., & Haugstad, K. (2010). [Information about Stavanger BP].

Haves, P., Linden, P. F., & Da Graça G., C. (2007). Use simulation in the design of a large, naturally ventilated office building. *Building Services Engineering Research and Technology, 28*, 223-235.

Henze, G. P., Felsmann, C., Kalz, D. E., & Herkel, S. (2008). Primary energy and comfort performance of ventilation assisted thermo-active building systems in continental climates. *Energy and Buildings, 40*(2), 99-111.

Hernandez, P., & Kenny, P. (2010). From net energy to zero energy buildings: Defining life cycle zero energy buildings (LC-ZEB). *Energy and Buildings, 42*(6), 815-821.

Herneheim, B. (2011). [Design values Jungmannen 3].

Hummelgaard, J., Juhl, P., Saebjörnsson, K. O., Clausen, G., Toftum, J., & G., L. (2007). Indoor air quality and occupant satisfaction in five mechanically and four naturally ventilated open-plan office buildings. *Building and Environment, 42*, 4051-4058.

Humphreys, M. A., & Hancock, M. (2007). Do people like to feel 'neutral'?: Exploring the variation of the desired thermal sensation on the ASHRAE scale. *Energy and Buildings, 39*(7), 867-874.

Høseggen, R., Mathisen, H. M., & Hanssen, S. O. (2009). The effect of suspended ceilings on energy performance and thermal comfort. *Energy and Buildings, 41*(2), 234-245.

Isfält, E., & Bröms, G. (1992). Effekt- och energibesparing genom förenklad styrning och drift av installationssystem i byggnader. Stockholm: Institutionen för Installationsteknik, KTH.

Jaboyedoff, P., Roulet, C.-A., RDorer, V., Weber, A., & Pfeiffer, A. (2004). Energy in air-handling units: results of the AIRLESS European Project. *Energy and Buildings, 36*, 391-399.

Jagemar, L., & Olsson, D. (2004). Användarprofiler för hyresgästel i kontorsbyggnader - mätningar från tre moderna kontorshus: CIT Energy Management AB.

Jansson, U. (2010). *Passive houses in Sweden: From design to evaluation of four demonstration projects*. Doctoral Thesis, Lund University, EBD-T--10/12, Lund University. (EBD-T--10/12)

Jardeby, Å., Soleimani-Mohseni, M., & Axell, M. (2009). Distribution av kyla och värme i bostäder och lokaler: SP Rapport 2009:31.

Jensen, F. S. (2011). [Information about Skejby CH].

Johansson, P., Nylander, A., & Johnsson, F. (2007). Primary energy use for heating in the Swedish building sector—Current trends and proposed target. *Energy Policy, 35*(2), 1386-1404.

Johnsson, H. (2011, 2011-05-06). [IDA ICE Support].

Kalamees, T. (2008). IDA ICE: the simulation tool for making the whole building energy and HAM analysis. *MOIST-ENG, Annex 41*, 1-6.

Kalema, T., Jóhannesson, G., Pylsy, P., & Hagengran, P. (2008). Accuracy of Energy Analysis of Buildings: A Comparsion of a Monthly Energy Balance Method and Simulation Methods in Calculating the Energy Consumption and the Effect of Thermal Mass. *Journal of Building Physics, 32*(2).

Kalz, D. E., Herkel, S., & Wagner, A. (2009). The impact of auxiliary energy on the efficiency of the heating and cooling system: Monitoring of low-energy buildings. *Energy and Buildings, 41*(10), 1019-1030.

Kiessler, K., Stockinger, J., & Stausberg, L. (2005). SOL4 Business and training center Eichkogel. http://www.sol4.info/English-Presentation.pdf: SOL4 Info.

Knissel, J. (2002). *Energieeffiziente Bürogebäude mit reduzierten internen Wärmequellen und Wärmeschutz auf Passivhausniveau.* Doctoral thesis, Berlin University of technology, Berlin University of technology.

Kolokotroni, M., & Aronis, A. (1999). Cooling-energy reduction in air-conditioned offices by using night ventilation. *Applied Energy, 63*, 241-253.

Kornadt, O., & Wallasch, K. (2008). Building Assessment Report for Office and Seminar Building SOL4 in Mödling, Austria. http://www.lensebuildings.com/downloads/projects/11_AT_KO_LEnSE_Building_Report.pdf: LEnSE Test Pilots.

Källman, O., Hindersson, P., & Nord, B. (2004). Effektivare distribution av fjärrkyla: Svensk Fjärrvärme FOU 2004:11.

Ladekjaer, B. (2011). [Information about Kolding CH].

Larsson, L. (2010). [Information about Kungsbrohuset HVAC].

Layberry, R. (2008). Degree days for building energy management - presentation of a new data set. *Building Services Engineering Research and Technology, 29*(3), 273-282.

Leroux, M. (2010, 2010-09-13). [Information about review search terms and electronic data bases].

Leslie, R., Raghavan, R., Howlett, O., & Eaton, C. (2005). The potential of simplified concepts for daylight harvesting. *Lighting Research and Technology, 37*(1), 21-40.

Levin, P. (2010). Energieffektiva byggnader - Kretsloppsrådets översikt: CERBOF. http://www.kretsloppsradet.com

Ljuskultur. (2010). Ljus & rum Planeringsguide för belysning inomhus. Stockholm: Ljuskultur.

Maripuu, M.-L. (2009). *Demand controlled ventilation (DCV) systems in commercial buildings: functional requirements on systems and components.* Dissertation Thesis, Chalmers University of Technology, Göteborg, Göteborg, Sweden. (ISBN 9173852562)

Marszal, A. J., Heiselberg, P., Bourrelle, J. S., Musall, E., Voss, K., Sartori, I., & Napolitano, A. (2011). Zero Energy Building – A review of definitions and calculation methodologies. *Energy and Buildings, 43*(4), 971-979.

MINERGIE. (2010). The MINERGIE - Standard for buildings: Information for architects. Bern, Switzerland.

Mitchell, J. W., & Beckman, W. A. (1989). Theoretical limits for storage of energy in buildings. *Solar Energy, 42*(2), 113-120.

Morgan, S., & Krarti, M. (2007). Impact of electricity rate structures on energy cost savings of pre-cooling controls for office buildings. *Building and Environment, 42*(8), 2810-2818.

NCC. (2011a). Commercial Space Retrieved 2012-03-04, from http://www.ncc.dk/en/Commercial-Space/Offices/

NCC. (2011b). Commercial Premises Retrieved 2012-03-04, from http://www.ncc.fi/en/commercial_premises/offices

Nì Riain, C., Kolokotroni, M., Davies, M., Fisher, J., White, M., & Littler, J. (1999). Cooling Effectiveness of South Façade Passive Stacks in a Naturally Ventilated Office Building: Case Study. *Indoor and Built Environment, 8*, 309-321.

Nilsson, P.-E. (2001). Komfortkyla. Centrum för effektiv energianvändning: www.effektiv.org

OSRAM. (2012). OSRAM Retrieved 2012-03-07, from http://www.osram.se/osram_se

Ourghi, R., Al-Anzi, A., & Krarti, M. (2007). A simplified analysis method to predict the impact of shape on annual energy use for office buildings. *Energy Conversion and Management, 48*(1), 300-305.

Persson, A., Rydstrand, C., & Hedenskog, P. (2005). Allt eller inget - Systemgränser för byggnaders uppvärmning. Stockholm: ÅF Energi & miljö AB.

Persson, J., & Arvidsson, H. (2010). [Visit Hagaporten, 2010-09-08].

Pessenlehner, W., & Mahdavi, A. (2003). *Building morphology, transparence, and energy performance*. Paper presented at the Eighth International IBPSA Conference, Eindhoven, Netherlands.

Pfafferott, J., Herkel , S., & Jäschke, M. (2003). Design of passive cooling by night ventilation: evaluation of a parametric model and building simulation with measurements. *Energy and Buildings, 35*, 1129-1143.

Pfafferott, J., Herkel , S., & WambsganB, M. (2004). Design, monitoring and evaluation of a low energy office building with passive cooling by night ventilation. *Energy and Buildings, 36*, 455-465.

Pfafferott, J., Herkel, S., & Wapler, J. (2005). Thermal building behaviour in summer: long-term data evaluation using simplified models. *Energy and Buildings, 37*(8), 844-852.

Pfafferott, J., Herkel, Ü., Kalz, S., Doreen, E., & Zeuschner, A. (2007). Comparison of low-energy office buildings in summer using different thermal comfort criteria. *Energy and Buildings, 39*, 750-757.

PHI. (2012a). Passive House Checklist Retrieved 2012-02-27, from http://www.passiv.de/

PHI. (2012b). Passive House Institute Retrieved 2012-03-04, from http://passiv.de/07_eng/index_e.html

Poirazis, H. (2008). *Single and double skin glazed office buildings: analyses of energy and indoor climate*. PhD, Lund Institute of Technology, Lund.

Poirazis, H., Blomsterberg, Å., & Wall, M. (2008). Energy simulations for glazed office buildings in Sweden. *Energy and Buildings, 40*, 1161-1170.

Pos. (2011). ENERGYbase - Passive house office building, Vienna Retrieved 2011-02-23, from http://www.pos-architecture.com

Rauhs, G., Schneider, U., & Preisler, A. (2008). Sunny Energy Building: ENERGYbase - Bürohaus der Zukunft. Vienna: Haus der Zukunft.

Rockwool. (2012). Tre klimatzoner Retrieved 2012-05-21, from http://www.rockwool.se/

Rogers, Z., & Goldman, D. (2006). Daylighting Metric Development Using Daylight Autonomy Calculations in the Sensor Placement Optimization Tool (A. E. Corporation, Trans.). Architectural Energy Corporation. Boulder, Colorado.

Samuelsson, I. (2008). Ökar risken för fuktskador i passivhus? *Bygg & Teknik 5/08*, 12-15.

Sartori, I., & Hestnes, A. G. (2007). Energy use in the life cycle of conventional and low-energy buildings: A review article. *Energy and Buildings, 39*(3), 249-257.

Schiller, G. (1988). A comparsion of measured and predicted comfort in office buildings. *ASHRAE Transactions, 94*, 609-622.

Schimschar, S., Blok, K., Boermans, T., & Hermelink, A. (2011). Germany's path towards nearly zero-energy buildings—Enabling the greenhouse gas mitigation potential in the building stock. *Energy Policy, 39*(6), 3346-3360.

Schneiders, J., & Feist, W. (2002). Passiv-Verwaltungsgebäude Wagner & Co. in Cölbe. Darmstadt, Germany: Passivhaus Institut.

SCNH. (2012). Kravspecifikation för nollenergihus, passivhus och minienergihus - Lokaler FEBY 12: Sveriges centrum för nollergihus. http://www.nollhus.se

SGBC. (2012). Certifieringssystem Retrieved 2012-03-19, from http://www.sgbc.se/index.php/certifieringssystem

Sjöqvist, R. (2010). [Visit Jungmannen 3, 2010-03-24].

Skanska. (2008a). Case Study 32: Hagaporten 3, Sweden. http://www.skanska-sustainability-case-studies.com.

Skanska. (2008b). Case Study 48: UN House, Norway. http://www.skanska-sustainability-case-studies.com.

Socialstyrelsen. (2005). SOSFS 2005:15 Allmänna råd: Temperatur iomhus.

Sundholm, K. (2010). [Information about Kungsbrohuset].

SVEBY. (2009). Särskilda mätföreskrifter för energikrav 2009. SVEBY http://www.sveby.org/.

SVEBY. (2010). Brukarindata för energiberäkningar i kontor - vägledning. Stockholm, Sweden: SVEBY http://www.sveby.org/.

SVEBY. (2012). Branschstandard för energi i byggnader Retrieved 2012-03-23, from http://www.sveby.org/

Södergren, D., Isfält, E., & Vinberg, H. (1992). Energibehov och inneklimat i byggnader med olika värmekapacitet. Byggforskningsrådet, Stockholm.

Söderling, H. (2010). [Energiberäkning och uppmätta värden för Kaggen].

UNFCCC. (2012). United Nations Framework Convention on Climate Change Retrieved 2012-04-01, from http://unfccc.int/2860.php

Utriainen, I. (2011). [Information about Alberga BP and Plaza Pilke].

Uvslökk, S., Skogstad, H. B., & Grynning, S. (2010). *How to prevent natural convection causing extra heat loss and moisture problems in thick insulation layers*. Paper presented at the 3rd Nordic Passive House Conference, Aalborg, Denmark.

Wagner, A., Gossauer, E., Moosmann, C., Gropp, T., & Leonhart, R. (2007). Thermal comfort and workplace occupant satisfaction: Results of field studies in German low energy office buildings. *Energy and Buildings, 39*, 758-769.

Van Moeseke, G., Bruyère, I., & De Herde, A. (2007). Impact of control rules on the efficiency of shading devices and free cooling for office buildings. *Building and Environment, 42*(2), 784-793.

Waterfront. (2009). Energilösning i världsklass. http://www.waterfront-building.se/pdf/stockholmwaterfront.pdf.

Wille, A., John, R., & Vajen, K. (2004). Passiv-Verwaltungsgebäude Cölbe: Messtechnische Begleitung und systemtechnische Untersuchungen. Kassel, Germany: Institut für Thermische Energietechnik, Universität Kassel.

Voss, K., Herkel, S., Pfafferott, J., Löhnrt, G., & Wagner, A. (2007). Energy efficiency office buildings with passive cooling: Results and experiences from a research and demonstration program. *Solar Energy, 81*, 424-434.

Zettergren, T. (2010). [Visit Pennfäktaren 2010-09-08].

Appendix A

Energy Efficient Office Building

Office name: **Location:**

	General description	**Details**	
Activity	*Other activities than office premises?* *Rooms/open plan?*	Finishing year	
		Floor area	
		Number of people	
		Office hours	
		Indoor temperature	
Building envelope	*Shape of the building* *Heaviness, materials* *Elements of construction* *Window amount (%)* *Window shading device (placement, control)*	Walls (insulation thickness, U-value)	
		Roof	
		Windows (U, SHGC)	
		Floor (insulation thickness)	
		U-value average	
		Infiltration/air leakage	
HVAC	*Heating system* *Distribution/room units* *Cooling system* *Distribution/room units* *Night ventilation?* *Air handling system.* *VAV/CAV* *Temperature- CO2 control* *Supply air, return air?* *Heat exchanger*	Heating source	
		Cooling source	
		Air flow (min,max)	
		Efficiency heat exchanger	
		Supply air temperature	
		SFP	
		Operating hours	
Lighting/ Internal heat gain	*Type, control* *daylight*	Installed power (W/m²)	
Other	*Other energy saving systems* *Sun collectors, PVCs etc*		
Environmental assessment	*Method, assessment system*	Grade	
Energy use	*Delivered energy* *(calculated or measured?)*	Heating	
		Domestic hot water	
		Cooling	
		Electricity (facility)	
		Electricity (tenant)	
		Total (kWh/m²,year)	

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