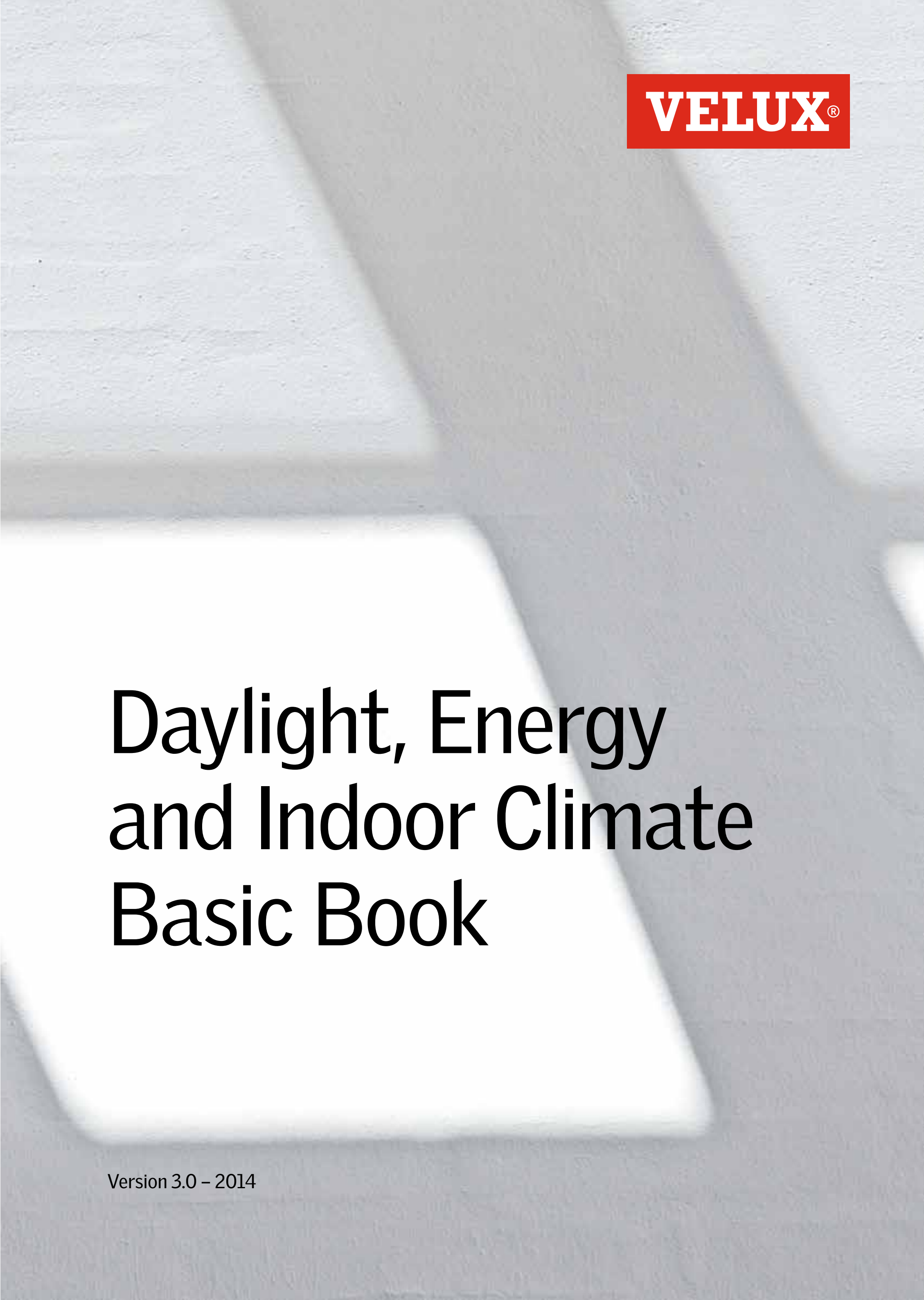


Daylight, Energy and Indoor Climate Basic Book

Version 3.0 – 2014

Content

Contents

Preface

Preface

Daylight, Energy and Indoor Climate at the heart of the VELUX brand

Daylight and fresh air have been at the core of our business since the company was founded in 1942. By bringing daylight and fresh air into people's homes, the VELUX Group has helped to create spaces of high quality and to increase the health and well-being of the occupants.

The benefits of VELUX products are more important today than ever before. Health and well-being constitute one of the most important agendas of the future, and a sharper focus on energy savings must not be allowed to overshadow the indoor climate.

A good indoor climate, with generous daylight levels and provision of fresh air from outside, is the key to making homes, offices, kindergartens and schools healthy places to live and work in. Our health and well-being are essential parameters to the quality of our lives; but we spend an excessive amount of time inside buildings – and the air that we breathe and the daylight we are exposed to have a great impact on those parameters. In recent years, much of the debate on sustainable architecture – and the public discourse on sustainability as a whole – has focused on energy, CO_2 emissions and the efficient use of material resources. These are all vitally important issues for our survival on this planet; but they are only three of a whole spectrum of issues facing us as human beings living in the built environment. Because health and well-being are paramount to all of us, the primary goal for sustainable homes and urban areas should be to preserve those precious benefits for the people who live in them.

Why this Daylight, Energy and Indoor Climate Book?

With this book, we aim to share our insight and knowledge by giving specific advice and concrete documentation on the effects and benefits of VELUX products in buildings. When creating new buildings – as well as renovating existing ones – the specific solutions need to be considered in a holistic perspective , with usage, personal needs, function, location, orientation, building geometry and window configuration playing very important roles.

Daylight, Energy and Indoor Climate Basic Book
3rd edition December 2014

Issued by
VELUX Knowledge Centre for Daylight, Energy and Indoor Climate (DEIC)

Editorial team:
Per Arnold Andersen, per.a.andersen@velux.com
Karsten Duer, karsten.duer@velux.com
Peter Foldbjerg, peter.foldbjerg@velux.com
Nicolas Roy, nicolas.roy@velux.com
Jens Christoffersen, jens.christoffersen@velux.com
Thorbjørn Færing Asmussen, thorbjorn.asmussen@velux.com
Karsten Andersen, karsten.andersen@velux.com
Christoffer Plesner, christoffer.plesner@velux.com
Marie Helms Rasmussen, marie.helmsrasmussen@velux.com
Frank Hansen, frank.hansen@velux.com

Responsible editor:

Per Arnold Andersen, per.a.andersen@velux.com

Find more information on www.velux.com

Introduction

Indoor climate in a historical perspective

Daylight and ventilation by windows are inseparably connected to indoor climate. Indoor climate encompasses all the elements: temperature, humidity, lighting, air quality, ventilation and noise levels in the habitable structure.

We spend most of our time indoors. Yet the indoor environment is discussed much less than the outdoor environment. The presumption is that we are safe indoors. Buildings provide shelter, warmth, shade and security; but they often deprive us of fresh air, natural light and ventilation.

The positive health effect of light, in this case of sunlight, was acknowledged by the Egyptians, ancient Greeks and Romans, each of whom worshipped their own sun god. Much later, at the beginning of the 1900s, sunlight as a healer was put to practical use. Sanatoria were built to administer light therapy for people suffering from skin diseases and other ailments.

The importance of the indoor environment, and of indoor air quality in particular, was recognised as early as the first century BC. However, it was not until the early decades of the twentieth century that the first relations between parameters describing heat, lighting and sound in buildings and human needs were established. In fact, the last hundred years have seen much effort put into management of the indoor environment, with the goal of creating healthy and comfortable conditions for the people living, working and recreating in them.

In the late 19th century, the environmental factor 'thermal comfort' was introduced as being part of the overall concept of indoor comfort. It was recognised that poorly ventilated rooms, besides being responsible for poor air quality, could also result in unwanted thermal effects through both temperature and humidity.

Although we spend most of our time indoors, we are still "outdoor animals" (Baker N, 2009). The forces that have selected the genes of contemporary man are found in the plains, forests and mountains, not in centrally heated bedrooms or ergonomically designed workstations. We have adapted to the indoor life, but our gene code is still defined for outdoor life. Sick building syndrome, winter depressions, asthma and allergies are symptoms linked to the quality of the indoor environment in terms of our biological needs. It is imperative that buildings and spaces where we spend much of our time are designed with those needs in mind; going back to nature, with natural ventilation and natural lighting.

How to evaluate the quality of the indoor climate?

There are no general methods that encompass everything in a formula or a single number. There are several indicators for how we can support our biological and physiological needs; ventilation rate for natural ventilation, daylight levels to be achieved, solar radiation exposure levels, comfortable temperature levels, relative humidity levels, sound levels and so on. The chapters of this book will explain the individual indicators and offer advice on specific levels that should be achieved to create a good indoor climate.

It is, however, just as important to evaluate the indoor environment with our senses; do we feel well indoors? Human factors, including physiology, perception, preferences, and behaviour make every individual a very accurate sensor. The indoor environment is more than the sum of its parts, and its assessment has to start with human beings.

Indoor climate and health

The human senses, "windows of the soul" (Bluyssen, 2010), are basically the instruments we have to report or indicate whether we feel comfortable in the indoor environment and how we feel our health is affected by it. We judge the indoor environment by its acceptability with respect to heat, cold, smell, noise, darkness, flickering light and other factors. But in terms of health effects, it is not just the human senses that are involved, but the whole body and its systems. Indoor environmental stressors that can cause discomfort and adverse health effects comprise both environmental and psychosocial factors, such as working and personal relationships. However, the greatest impact on our health from the indoor environment comes from the availability and quality of daylight and fresh air.

The prevalence of diseases like allergies and asthma is increasing rapidly. This trend is attributed to changes in the indoor environment, but there is still limited understanding of the specific causes. Presently, the only solid conclusion is that humid buildings are a cause. Sunlight is a natural anti-depressant that helps us synchronise with the natural rhythm of life, and direct sunlight and high daylight exposure levels are shown to be effective in preventing winter depressions.

Indoor climate and energy consumption

The focus on energy savings is an increasing challenge to existing building stock as well as new and future buildings, as energy consumption is believed to result in climate changes. It is, however, important to remember that all energy in buildings is used to serve people's needs, comfort and well-being. The VELUX Group considers Sustainable Living as a way of making the changes to limit the environmental impact at home, without compromising on the quality of the indoor environment.

Optimal use of daylight, natural ventilation during summertime, and intelligently controlled solar shading are all examples of technologies that – in combination with intelligent building design – can be used to reduce the energy consumption of new and existing buildings.

It is all about the sun; without solar radiation there would be no light, no wind, no heat, no life. And the solar radiation reaching the earth is far larger than the sum of energy needed. Solar energy is often viewed as a set of niche applications with a useful but limited potential. However, it is the only supply-side energy solution that is both large enough and acceptable enough to sustain the planet's long-term requirements; available solar energy exceeds the world´s annual energy consumption by a factor of 1 500 (Perez, 2009). Fossil fuels like oil and coal alone could fulfil our energy needs for another three or four generations, but would do so at a considerable environmental cost (Perez, 2009).

Environment

The production, disposal and lifetime use of VELUX products potentially impact the environment in other ways than through climate change, and materials like wood, glass and aluminium should be used with environmental impact in mind. The VELUX Group uses Life Cycle Assessment to evaluate the impact of its products on the environment.

Daylight

Daylight

Daylight has been used for centuries as the primary source of light in interiors and has been an implicit part of architecture for as long as buildings have existed. Not only does it replace electric light during daytime, reducing energy use for lighting, it also influences both heating and cooling loads, which makes it an important parameter of an energy-efficient design. Additionally, recent research has proved that daylight provides an array of health and comfort benefits that make it essential for buildings' occupants.

» There is no substitute for daylight «

1.1 Daylight

Daylight is described as the combination of all direct and indirect light originating from the sun during daytime. Of the total solar energy received on the surface of the earth, 40% is visible radiation and the rest is ultraviolet (UV) and infrared (IR) wavelengths, as shown in Figure 1.1.

Daylight availability outside varies for different locations due to different sun paths and sky conditions through the course of the day, the season and the year. Put simply, the amount of light on the ground depends on the solar elevation; the higher the sun, the greater the illuminance on the ground. Daylight levels vary significantly on horizontal and vertical surfaces by time of day and season, directly related to the local sun paths and sky conditions.

While certain electric light sources can be constructed to match a certain spectrum of daylight closely, none have been made that mimic the variation in the light spectrum that occurs with daylight at different times, in different seasons, and under different weather conditions (Boyce et al., 2003).

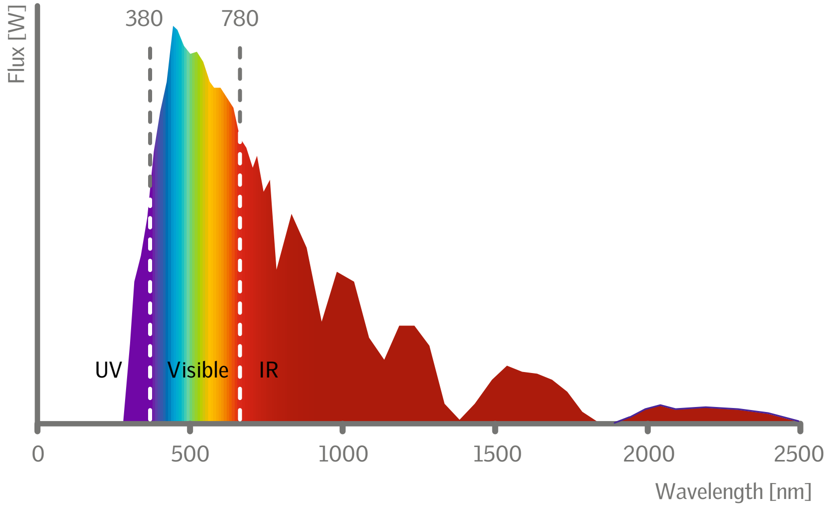


Figure 1.1 Diagram of the electromagnetic spectrum showing the location of the visible spectrum.

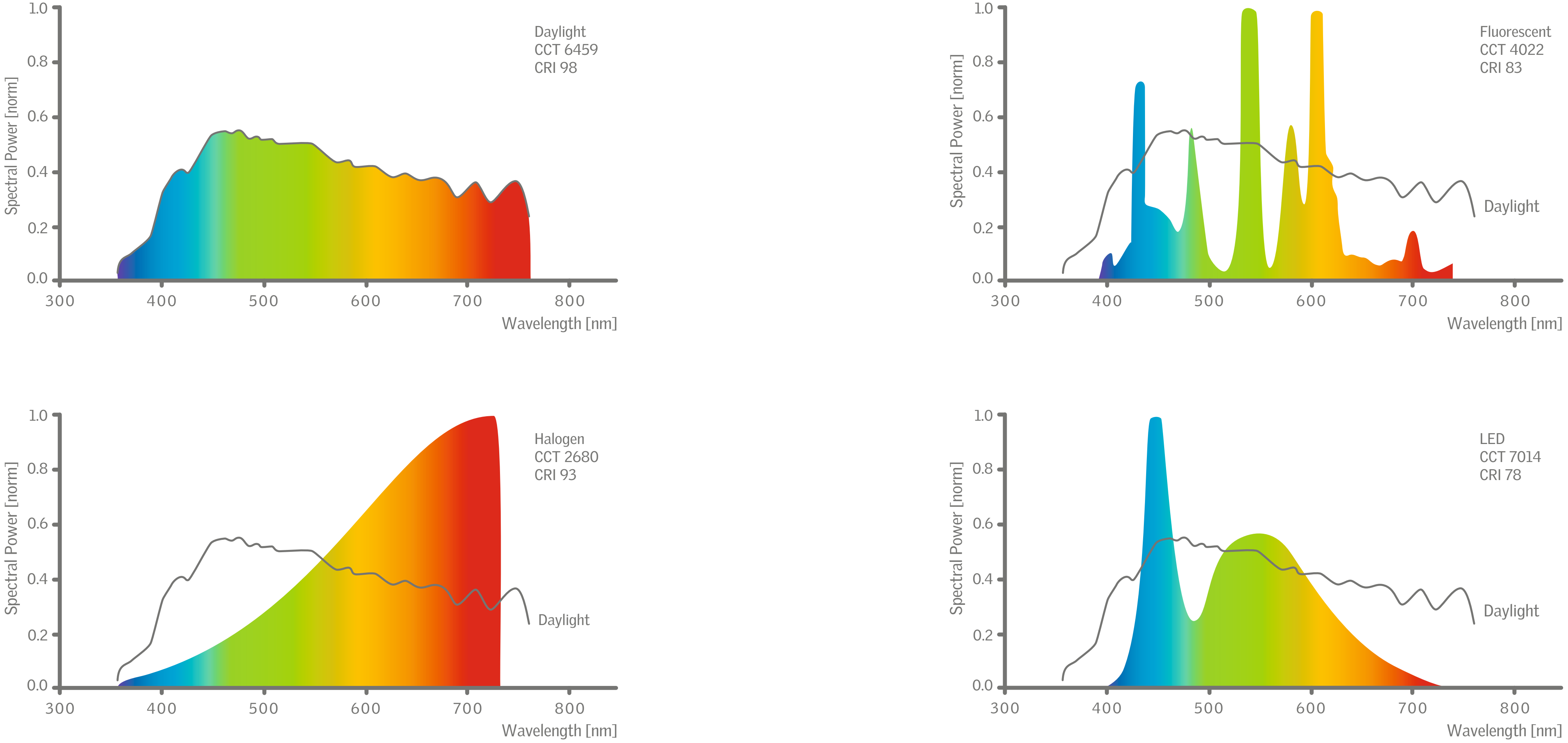


Figure 1.2 Spectral composition of four typical light sources – daylight (upper page 10), halogen (lower page 10), fluorescent (upper page 11), and LED (lower page 11). Measurements made by John Mardaljevic.

❗ Remember

Of the solar energy received on the surface of the earth, 40% is visible light and the rest is ultraviolet (UV) and infrared (IR) wavelengths.

No electric light source can mimic the qualities of daylight.

1.2 Daylighting

Daylighting describes the controlled use of natural light in and around buildings (Reinhart, 2014). It is the practice of placing windows, or other transparent media and reflective surfaces so that natural light provides effective internal illumination during the day. Successful daylighting requires design considerations at all stages of the building design process, from site planning to architectural, interior and lighting design.

Daylight in buildings is composed of a mix – direct sunlight, diffuse skylight, and light reflected from the ground and surrounding elements. Daylighting design needs to consider orientation and building site characteristics, facade and roof characteristics, size and placement of window openings, glazing and shading systems, and geometry and reflectance of interior surfaces. Good daylighting design ensures adequate light during daytime.

Some basic characteristics of daylight outdoors:

- Direct sunlight is characterised by very high intensity and constant movement. The illuminance produced on the surface of the earth may exceed 100 000 lux. The brightness of direct sunlight varies by season, time of day, location and sky conditions. In a sunny climate, thoughtful architectural design is required, with careful management of allowance, diffusing, shading and reflecting.
- Skylight is characterised by sunlight scattered by the atmosphere and clouds, resulting in soft, diffuse light. The illuminance level produced by an overcast sky may reach 10 000 lux in the winter and as high as around 30 000 lux on a bright overcast day in the summer. In a cloudy climate, the diffuse sky is often the main source of useful daylight.

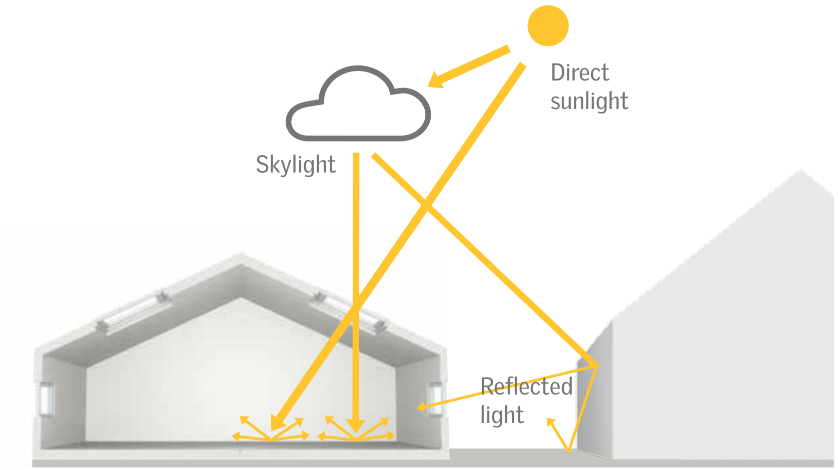


Figure 1.3 The components of daylight.

» Good quality lighting should include lighting for health, in parallel with meeting the other needs of people who will occupy the space «

- Reflected light is characterised by light (sunlight and skylight) that is reflected from the ground: terrain, trees, vegetation, neighbouring buildings etc. The surface reflectance of the surroundings will influence the total amount of reflected light reaching the building facade. In some dense building situations, the light reflected from the ground and surroundings can be a major conributory part of daylight provisions indoors.

The goals of room daylighting are to adequately illuminate visual tasks, to create an attractive visual environment, to save electrical energy and to provide the light needed for our biological needs. A good luminous environment is simultaneously comfortable, pleasant, relevant, and appropriate for its intended uses and users (Lam, 1977).

Daylighting systems can be simple: from combining window design with appropriate internal and external shading (e.g. external awning blind and internal Venetian blind) – to systems designed to redirect sunlight or skylight to areas where it is required (e.g. sun tunnels). More advanced systems can be designed to track the sun or passively control the direction of sunlight and skylight.

Daylighting is inseparably linked to the energy demand and indoor climate of a building. The size and placement of glazing should be determined together with the total energy use of the building and specific requirements for daylighting.

Remember

Daylight in buildings is composed of a mix – direct sunlight, diffuse skylight and light reflected from the ground and surrounding elements.

Light from the sun is intense and directional.

Light from the sky is soft and diffuse.

Light reflected from the ground can often account for 15% or more of the total daylight reaching a building facade.

» A daylit space is primarily lit with natural light and combines high occupant satisfaction with the visual and thermal environment, with low overall energy use for lighting, heating and cooling «

1.3 Daylighting quality

The design of well-lit environments requires an understanding of the function and capabilities of the visual system, insight into visual perception, knowledge of the basic properties of light, and other factors such as health issues (CIE, 2004a-b, LRC, 2003). These include knowledge of our visual system about adaptation (the eye's adjustments to ambient light levels), spectral (colour) characteristics, composition of diffuse and direct light, brightness contrast or luminance gradient and more. They also include knowledge of our circadian (non-visual) system about factors such as appropriate light signals during the day and darkness at night (to maintain circadian rhythms), the intensity of light and the time of day when it is applied, as well as its spectral characteristics.

1.3.1 Visual needs

We have traditionally concentrated our design work on creating lighting conditions that are suitable for the visual tasks performed in a room and that simultaneously meet individual needs. Attention needs to be given to both our central vision (illumination of an object) and our peripheral vision (illumination of the surroundings). Peripheral vision contributes to an impression of the surroundings in which we find ourselves – space dimensions and shape, ambience, materials and light distribution. In the design phases this is supported by appropriate placement and sizing of windows to achieve an intelligent balance between the intensity of light, its location and direction.

Visual comfort

The light in a room should neither restrain nor impede our ability to see, thus allowing us, at all times, easily to orientate ourselves and move freely around in the rooms and the building. If the lighting of a space is unsuitable or inadequate, and makes it difficult to see properly, it will influence our performance (the visual system), as well as affect our health (the circadian system) and personal well-being (the perceptual system). It can result in unnecessary eye strain and give rise to symptoms such as eye irritation, fatigue and headache. Lighting conditions that can cause these symptoms are poor brightness and contrast, high luminance differences and flickering.

A good daylighting design will provide large amounts of glare-free light; a poor daylighting design, on the other hand, will provide either inadequate amounts of light - so that electric lighting has to be used frequently - or large amounts of light, together with glare (Boyce et al., 2003). Furthermore, our daily life consists of changing visual tasks, with similarly changing demands on the lighting provided.

The light variation within our field of view can influence visual comfort and performance. For good visibility, some degree of uniformity of light is desirable. Poor visibility and visual discomfort, such as glare, may occur if the eye is forced to adapt too quickly to a wide range of light levels.

Too high or too low contrast can also result in tiredness, headaches and discomfort. Although there are no specific guidelines for dwellings, it is believed that luminance variations of around 10:1 are suitable for daylighting design. Generally speaking, the human eye can accept greater luminance variations when spaces are lit by daylight than when they are artificially lit.

The sensation of glare can occur when luminance variations exceed 20:1 to 40:1 (Rea, 2000). In the event of glare, the eye adapts to the high level of the glare source, which makes it hard to perceive details in the now too-dark work area. Glare from daylight may be caused by several potential sources such as the sun, bright sky and clouds, and surfaces reflecting the sun.

There are three main types of glare:

- Disability glare – the effect of scattered light in the eye whereby visibility and visual performance are reduced. This occurs when glare sources of high luminance (e.g. sun or specular reflection of the sun) are in the field of view. In daylit interiors, it is often found that discomfort glare is reported before disability glare becomes an issue.
- Discomfort glare – defined as an irritating or distracting, but not necessarily impairing, effect. So in most cases, the perceived magnitude of discomfort glare is lower than for disability glare. Discomfort glare indoors is influenced by the full visual environment, including windows, reflections (especially specular), external surroundings and/or interior surfaces. Discomfort glare may cause later side- or after effects in the form of headaches or fatigue.
- Reflections or veiling glare – reflections on display screens or other task materials (e.g. paper) reduce the contrast between background and foreground for the visual task and thus reduce readability. Reflections occur when bright light sources (e.g. windows) are in the reflected field of view of the screen.

To reduce the occurrence of glare, shading devices should be employed. Figure 1.5 below shows a situation where glare is controlled by external solar shading (awning blind). Shading devices such as Venetian blinds, awnings, vertical blinds and roller blinds are suitable for this purpose, but the specific material characteristics should be taken into consideration. A movable or retractable de-

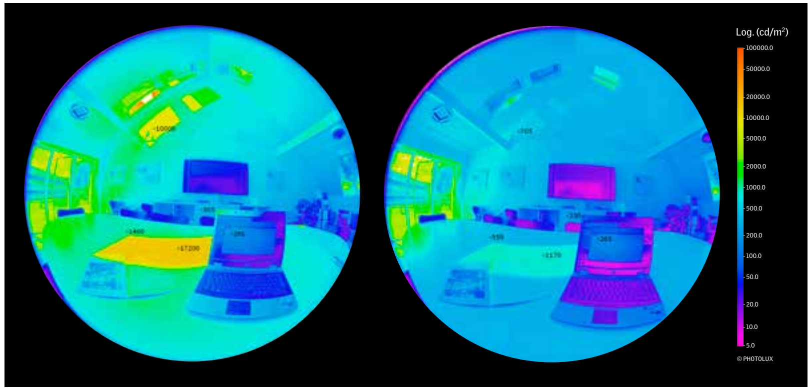


Figure 1.5 Luminance map of a task area showing sun patches causing glare.

Luminance map of task area showing glare control with external solar shading.

vice can be individually adjusted, while fixed devices may need additional shading devices to support individual requirements for glare protection. Windows located in more than one orientation, or in the roof, could adequately maintain daylight illumination for the visual tasks and provide a view to the outside, rather than being shaded to control potential glare sources.

Daylight availability

The primary target in the daylighting of buildings has generally been to provide adequate light levels in the room and on the work plane, so that daylight is the main, or only, source of light (autonomous) during daytime. Several metrics address daylight availability for a task and/or a space, and an important aspect of daylight is to understand that it is variable: it varies with the seasons of the year, the time of day, and the weather. For this reason, metrics for daylight availability calculations are often based on relative rather than absolute values. This is usually defined in terms of the relationship between the light available at different positions inside with that available outside (e.g. the daylight factor, DF).

The absolute levels of illuminance that are needed for a particular visual task will depend on the character of the task and the visual environment where it is performed. As an example, the Chartered Institution of Building Services Engineers, CIBSE (CIBSE, 2006), recommends the following light levels.

See section 1.7.1.

- 100 lux for interiors where visual tasks is movement and casual seeing without perception of detail.

» Our body uses light as it uses food and water, as a nutrient for metabolic processes «

- 300 lux for interiors where visual tasks are moderately easy.
- 500 lux for interiors where visual tasks are moderately difficult and colour judgment may be required, e.g. general offices, kitchens.
- 1 000 lux for interiors where visual tasks are very difficult, requiring small details to be perceived.

Requirements for daylighting have yet to be defined in terms of specific illuminance levels, but there is enough evidence in literature to indicate that illuminances in the range of 100 to 3 000 lux are likely to result in significant reduction of electric lighting usage (Mardaljevic, 2008).

View

Meeting the need for contact with the outside living environment is an important psychological aspect linked to daylighting (Robbins, 1986). The provision of daylight alone is not enough to satisfy user desires for views. Windows provide contact with the outside, supply information of orientation, give experience of weather changes and allow us to follow the passage of time over the day.

A view that includes layers of sky, city or landscape, and ground (Boyce et al., 2003), could counteract tiring monotony and help relieve the feeling of being closed in. The size and position of window systems need to be considered carefully in relation to the eye level of the building occupants.

1.3.2 Non-visual effects of light

Daylight has a wide range of influences on humans that go far beyond our need for vision. We often refer to this as the non-visual effects of light. When we speak about health, balance and physiological regulation, we are referring to the functions of the body's major health keepers: the nervous system and the endocrine system. These major control centres of the body are directly stimu-

Remember

Daylight should provide enough light in the room and on the work plane to be the main, or only, source of light during daytime.

Occupants can accept greater luminance variations in spaces lit by daylight than if artificially lit.

Luminance variations of around 10:1 are suitable for daylighting design.

The sensation of glare can occur when luminance variations exceed 20:1 to 40:1.

lated and regulated by light (Edwards and Torcellini, 2002) by a specific subtype of retinal ganglion cells – ipRGCs - intrinsically photosensitive retinal ganglion cells. Together with our visual system, these ganglion cells in the eye are sensitive to light.

Circadian rhythms

Many aspects of human physiology and behaviour are dominated by 24-hour rhythms that have a major impact on our health and well-being. They control sleep/wake cycles, alertness and performance patterns, core body temperature rhythms, as well as the production of the hormones melatonin and cortisol (Pechacek et al., 2008). These daily rhythms are called circadian rhythms and their regulation depends very much on the environment we live in. The dynamic variation of light, both daily and seasonally, is a critical factor in setting and maintaining our 24-hour daily rhythms – our circadian rhythms – which, in-turn, play a key role in the regulation of the sleep/wake cycle. Sleep disruption has been linked to poor cognitive function, stress, depression, poor social interaction, metabolic and cardiovascular disease, increased susceptibility to infection - and even cancer. An appropriate light signal during the day and darkness at night are therefore critical in maintaining key aspects of our overall health (Circadian House, 2013).

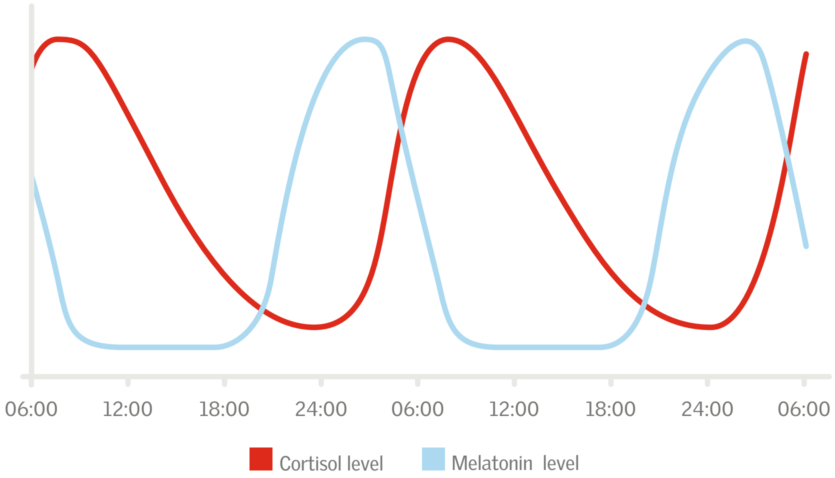


Figure 1.6 Production of the hormones melatonin and cortisol (Brainard, 2002).

For example, in order to align our body clock, morning light is the most important signal for entrainment. Light in the morning also increases our levels of alertness, allowing increased performance at the beginning of the day. Whereas reduced light levels in the evening promote sleep at night. There are other external time markers but daylight's characteristic light/dark variation, continuity and spectral composition are excellent synchronisers of our circadian rhythm. It is now evident that daylight is not just a stimulus for vision, but acts as a key element in the regulation of many areas of human health. Figure 1.6 shows the production rhythms of the hormones melatonin and cortisol.

Biological functions of light

How our biology responds to light intensity, duration, timing, and spectrum is highly complex and varies greatly between our visual and circadian systems. All these characteristics are used as a first step towards prescriptions of healthy lighting in buildings (Veitch, 2002). Inadequate light exposure can disrupt normal circadian rhythms and have a negative effect on human performance, alertness, health and safety. We know that outdoor daily light exposure allows us to regulate our sleep/wake timing and levels of alertness. But the reality is that we spend we spend 90% of our time indoors (Klepeis, 2001; Leech, 2002; Schweizer, 2007), where we are exposed to relatively low light levels of a limited spectral range, and where the patterns of light and darkness occur at irregular intervals. Preliminary evidence suggests that low light exposure is associated with diminished health and well-being and can lead to reduced sleep quality, depressed mood, lack of energy and impaired social relations.

Light intensity

Most people are able to read and work with a daily light level of 500 lux, but one hour's exposure to 500 lux may not be enough to trigger the circadian rhythm (intensity). In a study by Mardaljevic et al. (2012), a case with and without roof windows is investigated to determine the effect of light intensity. The case with only facade windows shows that the degree of light intensity is greatest for those viewpoints/directions located closest to and directed towards the window. The case with roof windows shows a greater intensity for all locations in the room, and with less of a preference for those views directed towards the window. This illustrate the importance of using daylight as a key source of light required for effective suppression of melatonin, since the magnitude needed could be of the order of 1 000 lux depending on the spectrum.

As another example, a study conducted in San Diego during a temperate and sunny period showed that, when awake,

» We need more light at the right time and the right kind «

the average person spent 4% of each 24 hours in illumination greater than 1 000 lx (on average 130 min), and more than 50% of the time in illuminance levels from 0.1 to 100 lx (Espiritu et al., 1994); the people with the shortest daily exposure time to high light levels (above 1 000 lx) reported the lowest mood.

Other light exposure investigations show a similar trend. We know daylighting can provide much higher levels of illumination than electric lighting, and can help significantly to increase the light dose received by people spending most of their time indoors. In support of this, a large Finnish epidemiological study found that health-related quality of life was higher for people reporting higher interior light levels (Grimaldi et al., 2008).

Duration and timing

The visual system reacts to and processes light impulses in a fraction of a second, whilst the biological clock needs minutes or hours (duration). This means that both the illuminance at the eye and the duration of exposure are important to the effect of light on our circadian system. The time of day at which light is registered on the retina also has a clearly different effect on the visual system and circadian rhythm (timing). Exposure to intense light in the morning can reset the biological clock to an earlier time ("get up earlier"), whilst in the evening, it sets it to a later time ("get up later"). This is, in essence, the syndrome of jetlag, caused by a conflict between the biological time of day and the geographical time of day. The visual system reacts identically whatever the time of day.

Specific requirements for different age groups also need to be taken into account. Adolescent and young adults have a somewhat delayed biological clock and need more light in the morning (bedroom, breakfast room, classroom, etc.), whereas older people have a biological clock that has shifted earlier (often resulting in falling asleep in the evening and waking up early in the morning) (Wirz-Justice and Fournier, 2010).

Spectrum

Daylight is recognised as having the highest levels of light needed for the biological functions (Hathaway et al., 1992) compared with typical electric light sources.

The light that is important to our circadian rhythm (C(λ)) is different from the light that is important to our visual system (V(λ)) because of the spectral difference in the light sensitivity of the individual photoreceptors (spectrum). The circadian system (C(λ)) is most affected by the wavelength region 446 to 488 nm, whereas the visual system (V(λ)) is most affected by the wavelength around 555 nm, as shown in figure 1.7. Figures 1.1. and 1.2 presented earlier show that the spectral composition of daylight is much richer in these regions of the electromagnetic spectrum than typical electric light sources.

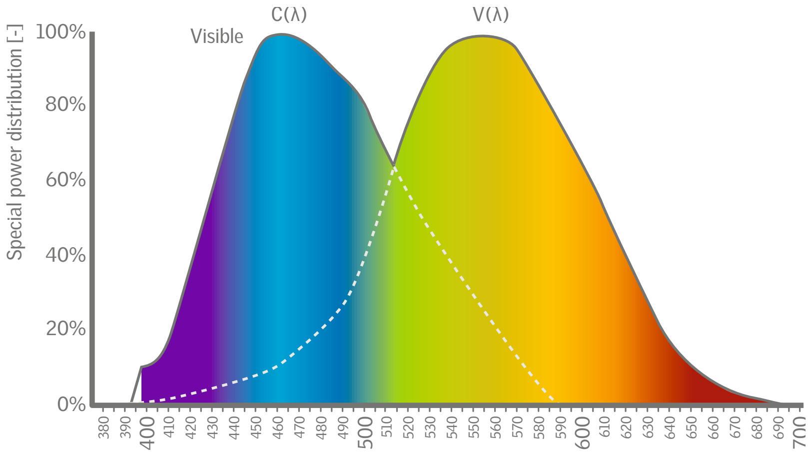


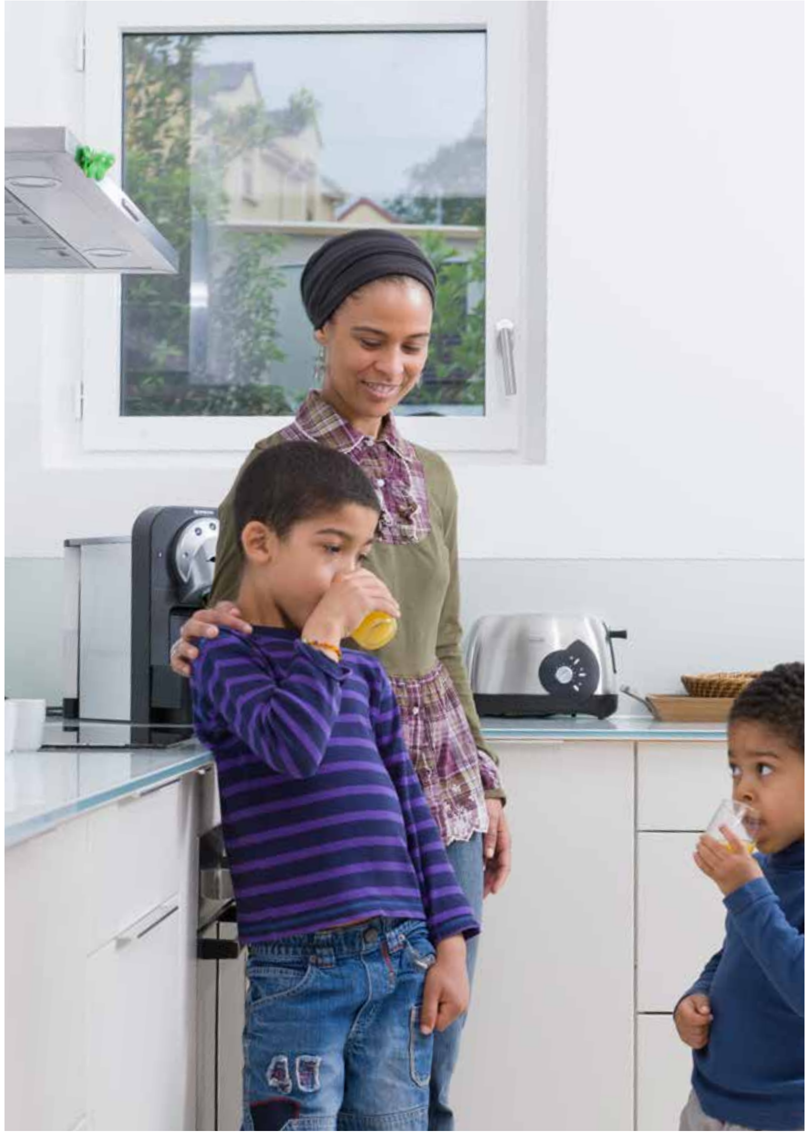
Figure 1.7 Circadian (C(λ)) and visual (V(λ)) systems' response to light (Pechacek et al., 2008).

Remember

People in modern societies do not receive enough light on a daily basis and need to be exposed to higher levels of illumination for longer durations.

We need a daily daylight exposure, because daylight is rich in the spectrum to which the non-visual system is most sensitive.

Healthy light is linked to healthy darkness.



Maison Air et Lumière, France.

» People perform better in daylight environments «

1.4 Benefits of daylight

1.4.1 Human benefits

We know that appropriate light signals during the day and darkness at night are critical in maintaining key aspects of our overall health. In order to align our body clock, morning light is the most important signal for entrainment. Light in the morning also increases our levels of alertness, allowing increased performance at the beginning of the day. From mid-morning to early evening, high levels of daylight, allow us to regulate our sleep/wake timing and levels of alertness; whereas reduced light levels in the evening and a dark room with blackout promote sleep at night. The inability to provide building occupants with a good overall lighting environment can have subsequent impact on health and place a substantial burden on the individual, society and the broader economy.

Performance and productivity

Bright lighting is generally believed to make people more alert, and well-daylit spaces are generally perceived by occupants to be "better" than dim gloomy ones (Mardaljevic et al., 2012). Daylighting has been associated with improved mood, enhanced morale, less fatigue, and reduced eyestrain (Robbins, 1986). Many studies show that the performance and productivity of workers in office, industrial, and retail environments can increase with the quality of light. Companies have recorded an increase in productivity of their employees of about 15% after moving to a new building with better daylight conditions. which resulted in considerable financial gains (Edwards and Torcellini, 2002). Another study demonstrated that greater satisfaction with lighting conditions (both daylight and electric lighting) contributed to environmental satisfaction, which, in turn, led to greater job satisfaction (Veitch et al., 2008).

Studies also show that daylit environments lead to more effective learning. It was found that students in classrooms with the most window area or daylighting produced 7% to 18% higher scores on the standardised tests than those with the least window area or daylight (Heschong, 2002).

Benefits of higher light dose

We have no evidence for "what is the necessary light dose?", but we do have clear indication that the light dose needed is higher than interior light levels prescribed by electric lighting in standards and regulations. Studies suggest that higher doses would leave people with a feeling of being more positive about life (Espiritu et al., 1994), while social interactions immediately following exposure to over 1 000 lx were more co-operative and less quarrelsome (Aan het Rot et al., 2008).

» In domestic buildings, health requirements suggest that higher levels of daylight than are currently used are desirable. This gives scope for energy savings «

CarbonLight Homes

User satisfaction

Windows are highly valued by office workers (Edwards and Torcellini, 2002). Surveys have shown that more than 60% of office workers would like direct sunlight in their offices in least one season of the year (Christoffersen, 1999) and believe that working under natural daylight is better for their health and well-being than electric lighting (Lighting Research Center, 2014). Employees working in offices highly value access to a window - indeed, they value it more than privacy in their office (Wotton, 1983). Several studies have shown that people prefer daylight to artificial lighting at work. This is often linked to daylight's dynamic variation of intensity, colour and direction and the positive effect these have on our experience and mood (Christoffersen, 1999; Veitch, 2003). Canadian studies show that there is a general perception that daylight should be the primary light source for the sake of our health and well-being (Veitch, 1993, 1996).

A few studies in dwellings show that natural light is the single most important attribute in a home, with over 60% of respondents ranking it as important (Finlay, 2012). A WHO survey involving eight cities across Europe, showed that individuals who report inadequate natural light in their homes have a greater risk of depression and falls (Brown, 2011).

Benefits of view

Building interiors should be designed in a way that permits the human need to be linked to the natural environment to be satisfied by minimising overshadowing and allowing distant views (Wirz-Justice, 2010). A natural view is preferred to a view towards man-made environment, and a wide and distant view is appreciated more than a narrow and near view. A diverse and dynamic view is more interesting than a monotonous view. The content of the view can influence rental or cost price of hotels, dwellings and office buildings (Kim and Wineman, 2005). A view to to nature may have a positive influence on people's sense of well-being (Kaplan, 2001), better subjective health (Kaplan, 1993), higher environmental satisfaction (Newsham et al., 2009), better mood (Grinde and Grindal Patil, 2009), reduced health problems (Heschong Mahone Group, 2003), job satisfaction, recovery of surgical patients (Ulrich, 1984), stressful experiences (Ulrich et al., 1991), and seating preference (Wang and Boubekri, 2010, 2011). A study by Ariës et al. (2010) shows that views in offices independently judged to be more attractive were associated with reduced discomfort and, through the discomfort effect, with better sleep quality.

» When properly selected and installed, an energy-efficient skylight can help minimise your heating, cooling and lighting costs «

Impact of daylight in hospital rooms

There is some evidence that daylight exposure can affect post-operative outcomes in patients and, consequently, that daylight should be a consideration in hospital design. Ulrich (1984) reported that hospital patients with a view of green spaces, as opposed to those with a view of a blank brick wall, recovered more quickly from surgery and required less post-operative pain medication. Beauchemin and Hays (1998) found that patients on the sunnier side of a cardiac intensive care ward showed lower mortality rates than those on the less-sunny side. Another study determined that sunlight exposure was associated with both improved subjective assessment of the patients and also reduced levels of analgesic medication routinely administered to control post-operative pain (Walch et al., 2005). The importance of the amount of daylight in a patient's room indicates an impact on patients' length of stay; coronary artery bypass graft surgery patients' length of stay in hospital was reduced by 7.3 hours per 100 lx increase of daylight (Joarder and Price, 2013).

Prevention of Seasonal Affective Disorder (SAD)

Seasonal Affective Disorder is a depression-related illness linked to the availability and change of outdoor light in the winter. Reports suggest that 0.4% to 9.7% of the world's population may suffer from SAD, with up to three times that number having signs of the affliction (called sub-syndromal SAD (or S-SAD) without being classified as a major depression (primarily in Northern America and Northern Europe) (Rosen, et al., 1990). Light therapy with exposure levels at the eye of between 2500 lux (for 2 hours) or 10 000 lux (for 30 minutes) has shown to be an effective cure against SAD (Sloane, 2008). Exposure to daylight outdoors (~ 1000 lux) can also reduce SAD symptoms (Wirz-Justice et al., 1996). So, as seasonal mood disturbance is relatively common, the amount of daylight in our homes or workplaces can be of considerable significance – though the effective value of daylight will depend on the architectural design of a room and the facade (Pechacek et al., 2008). Light therapy can also be used to treat other depression-related symptoms (e.g. non-seasonal depression, premenstrual, bulimia).

1.4.2 Energy savings for electric lighting

Another benefit of using daylighting for ambient and/or task illuminance in a space is that it can save energy by reducing the need for electric lighting. Several studies in office buildings have recorded the energy savings for electric lighting from using daylight in the range of 20-60% (Galasiu, 2007), but it depends on the lighting control system used, how well the space is daylit during occupied hours and the intended functions of the space. If no control system is installed, the occupant entering a space will often switch on the electric lights. Quite why occupants switch on or off the office lights is not always obvious, but it is even less obvious in a domestic setting, where demand for light is typically driven by human needs and wishes.

In non-domestic buildings, official recommended illumination levels are defined for the spaces they illuminate. They are dependent on the type of space to be lit and the functions within it, and are based on both the functional efficiency of anticipated tasks performed in the spaces and visual comfort (IEA, 2006). Typically guidelines and recommendations for light levels exist for communal residential buildings but not for single-family houses.

Estimation of savings potential in domestic buildings requires a user profile, and models for switching on/off the lights. In a study by Mardaljevic et al. (2012), the French RT 2005 model was used. They analysed the potential for increased daylight provision for a house with or without skylight to save electric lighting energy at eight European locations. The study shows that increased daylight is estimated to reduce the need for artificial lighting by 16-20%, depending on the location and orientation of the house. See section 1.6.6

In LichtAktiv Haus in Germany, the electric lighting used in the kitchen and living room shows a significant tendency of being affected by the interior daylight level; the lights are typically switched on before sunrise and after sunset. There is a reasonable correlation between high daylight level and switching probability, while outside weather, day of the week has less impact (e.g. family with children).

» Electricity used for artificial lighting is a significant cause of a building's CO_2 cost: in offices, it can be 30% of the total. This is why good daylighting is so important to sustainable architecture «

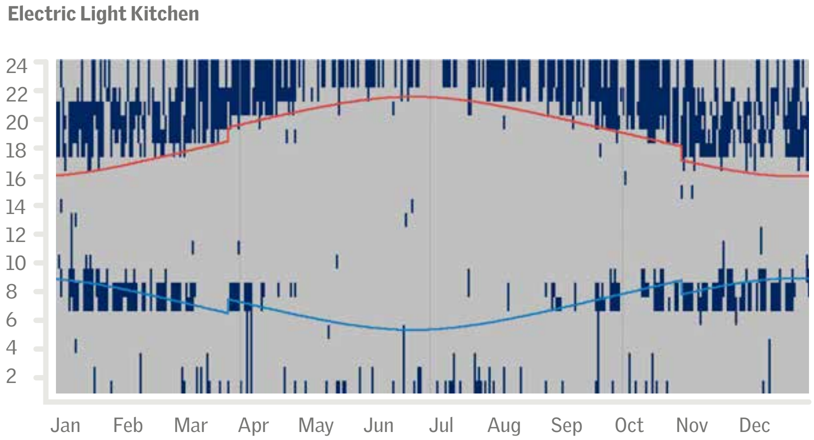


Figure 1.10 LichtAktiv Haus. Temporal map of lighting use in the kitchen (2012), showing time of sunrise (blue) and sunset (red). Lighting use and sunrise/sunset depends on local time, which accounts for Daylight Saving Time (DST).

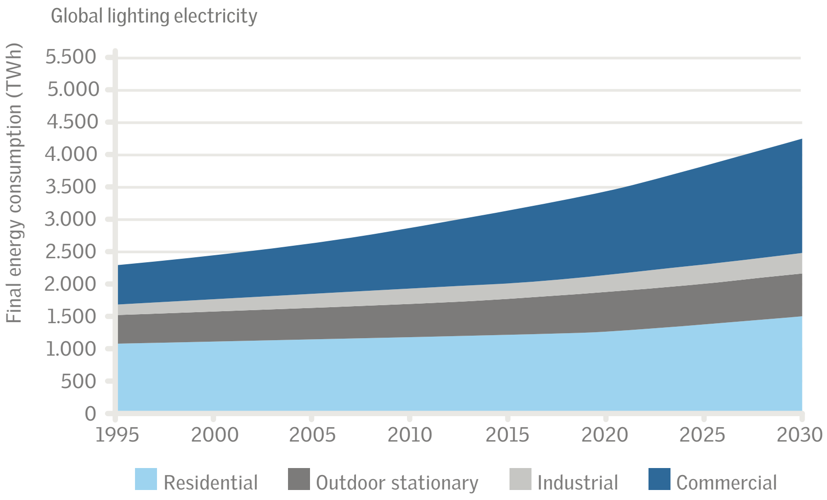


Figure 1.11 Global electricity consumption for lighting with current socio-economic trends and policies is projected to rise. The actual growth will depend on demand for artificial light and the efficiency of lighting technologies, just two of the factors influencing increased consumption (IEA, 2006).

The IEA publication Light's Labours Lost suggests that policies to encourage better use of daylight typically implement the following measures to encourage savings potential from the use of daylight:

- Implemented daylight-saving time (DST) and sometimes double DST.
- Acknowledging credit for daylight measures in building codes.
- Supported R&D and dissemination of daylighting practices and technologies.
- Labelling and certification of windows.

1.4.3 Environmental benefits

Increasing use of natural resources, such as daylight and air, in our buildings, through constructive use of windows in the facades and roofs, can influence our dependency on fossil fuels as well as reduce combustion of greenhouse gases. Lighting is one of the largest consumers of electricity and one of the biggest causes of energy-related greenhouse gas emissions. The amount of electricity consumed by lighting is almost the same as that produced from all gas-fired generation and about 15% more than that produced by either hydro or nuclear power. Indoor illumination of tertiary-sector buildings uses the largest proportion of lighting electrical energy, comprising as much as the residential and industrial sectors combined. On average, lighting accounts for 34% of tertiary-sector electricity consumption and 14% of residential consumption in OECD countries. In non-OECD countries these shares are usually higher. (IEA, 2006)

Remember

Daylit environments facilitate better performance, productivity and learning.

Light therapy with exposure levels at the eye of between 2500 lux (for 2 hours) and 10 000 lux (for 30 minutes) has shown to be an effective cure for SAD and other depression-related symptoms.

1.5 Parameters influencing daylighting performance

1.5.1 Climate

The prevailing climatic conditions of a building site define the overall preconditions for the daylighting design in terms of sunlight availability, visual comfort, thermal comfort and energy performance. Figures 1.13 to 1.15 show the effect of climatic conditions on the sky luminous distribution and intensity.

Example
The charts below show an overview of the monthly sky conditions for 3 European locations: Rome, Paris and Oslo. Within working hours (8-17), cumulative data of daylight availability show that a horizontal illuminance of 10 klx might be available for 60 to 85 % of working hours and 20 klx for around 30% of working hours. By contrast, the global illuminance (total of sunlight and skylight) varies significantly with latitude. A global horizontal illuminance of 30 klx is exceeded for 35% of working hours (8-17) in Oslo, but 65% of the time in Rome.

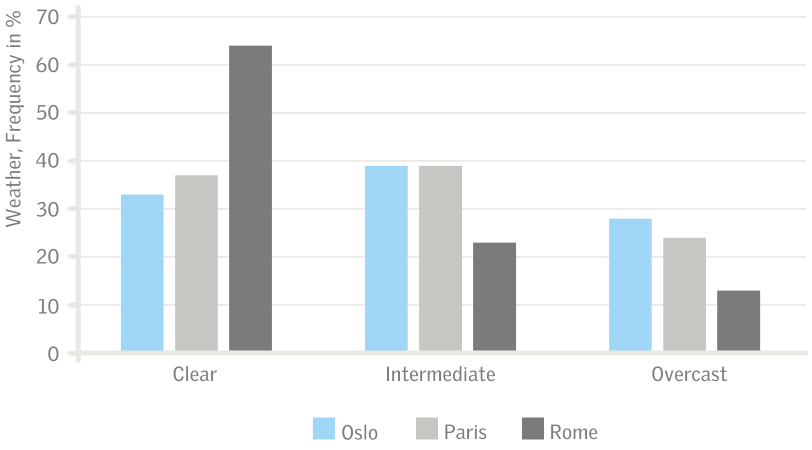
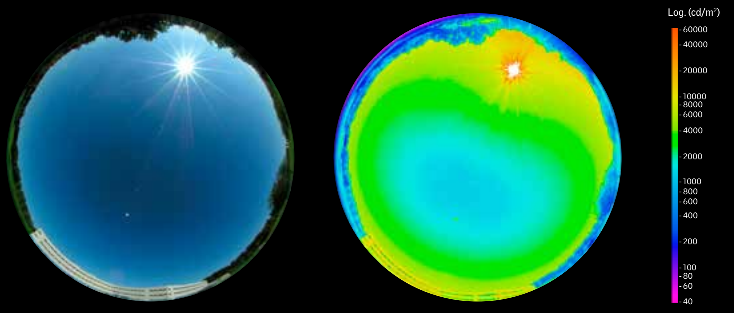
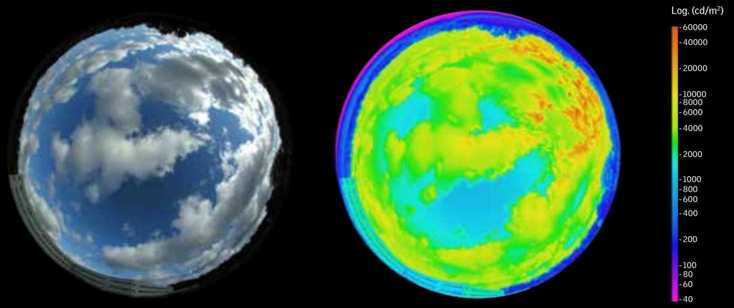


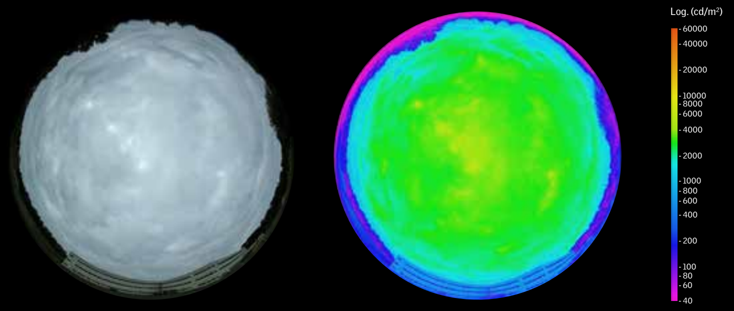
Figure 1.12 Frequency of weather in % for three different European cities.



1) Figure 1.13 Luminance map of a clear sunny sky. The image above describes a clear sky luminance distribution. Under clear sky conditions, the sky luminance is about ten times brighter at the horizon than the zenith. In addition to the sky luminance is the sun luminance. The sun acts as a dynamic light source of very high intensity.



2) Figure 1.14 Luminance map of an intermediate sky. The image above describes an intermediate sky luminance distribution. In this particular case, the sun energy has been scattered by the clouds, which results in a softer transition between the very intense luminance of the sun and the luminance of the sky. It is possible to observe that the clouds (illuminated by the sun) have higher luminance values than the sky.



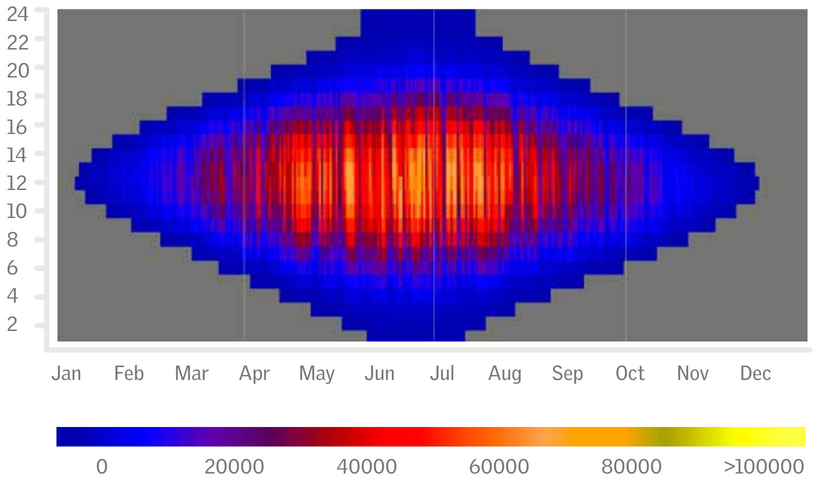
3) Figure 1.15 Luminance map of an overcast sky. The image above describes an overcast sky luminance distribution. Under perfect overcast sky conditions, the sky luminance is the same in all orientations, and the zenith is about three times brighter than the horizon.

1.5.2 Latitude

The latitude of a building site determines the solar altitude for a given time of day and year. The summer and winter solar altitude properties for a specific location are important design inputs for the control of direct solar radiation. Latitude will also determine the length of daytime and solar availability at different seasons of the year. Maximum and minim solar elevation will depend on the latitude of the site; on moving away from the equator towards north or south, the difference between summer and winter becomes greater as latitudes increase. Figure 1.16 show the difference in outdoor illuminance between northern and southern European locations.

The highest peak of global illuminance is during the summer (for the northern hemisphere), when the sun is at its highest level, and about two and a half times greater than the lowest peak during the winter, when the sun is at its lowest level.

Global Illuminance – Kiruna, Sweden (67.85°N)



Global Illuminance – Rome, Italy (41.90°N)

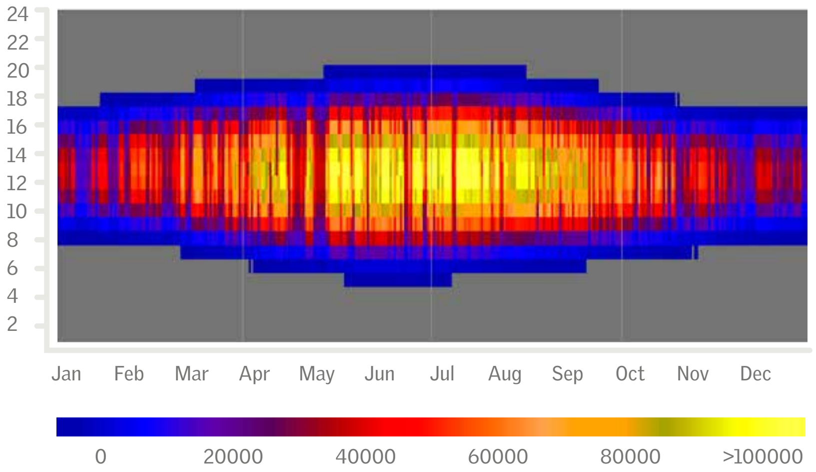


Figure 1.16 Global illuminance in northern and southern European locations.

1.5.3 Obstructions and reflections on site

External reflections and obstructions from surrounding elements on the building site (buildings, vegetation, ground surface etc.) will influence the amount of daylight reaching the interior of a building.

Roof windows and skylights are generally less affected by obstructions from sand and have more generous views to the sky than facade windows, as illustrated in Figures 1.17 and 1.18.

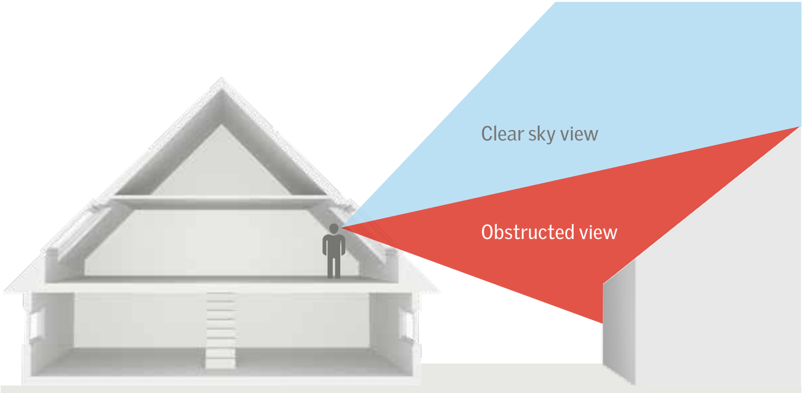


Figure 1.17 Components of view – roof window situation.

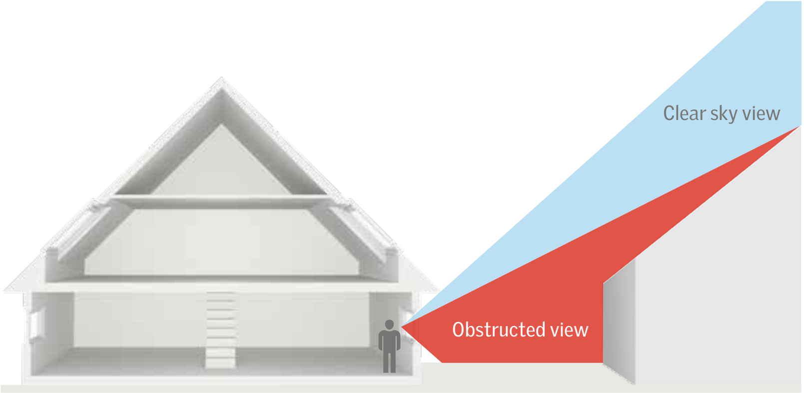
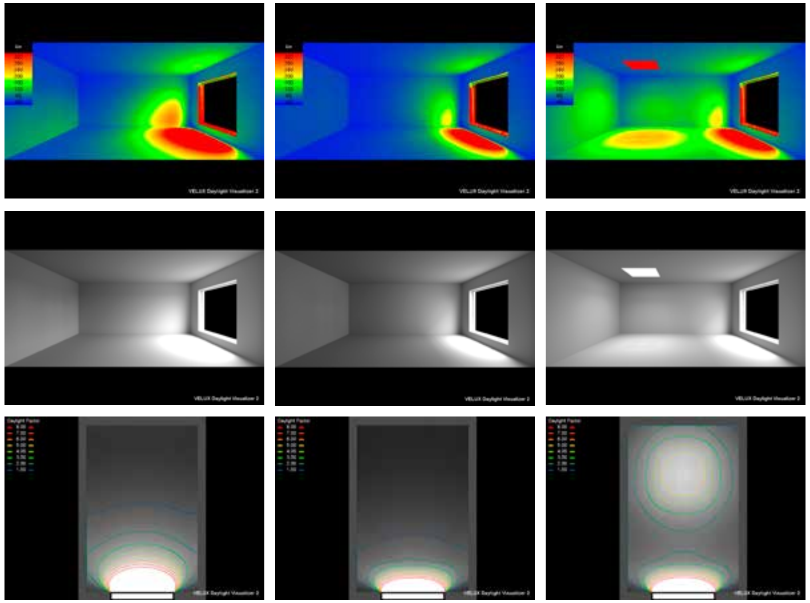


Figure 1.18 Components of view – facade window situation.

Example
The following figure show the effect of obstruction on daylight availability in a simple room with a vertical facade window, and the effect of adding a flat-roof window to deliver daylight deeper into the obstructed room. The results show that obstruction can greatly affect the amount of daylight that will reach the building interior, and how adding an unobstructed window on the roof can provide much more daylight.



DF	2.07%	Average DF	1.03%	Average DF	3.24%
Median DF	1.05%	Median DF	0.58%	Median DF	2.96%
Uniformity Dmin/Dav	0.18	Uniformity Dmin/Dav	0.22	Uniformity Dmin/Dav	0.41

Figure 1.19 Comparison of daylight levels in a room without (left) and with external obstruction (centre and right).

1.5.4 Building design

Geometry

The geometry of a building influences its capacity to deliver adequate levels of daylight to the interior. When the building is deep, daylighting solely by facade windows has its limitations. No matter how much glass there is in the facade, it will only be possible to achieve an adequate daylight distribution (DF > 2%) a few metres from the facade, as shown in Figures 1.20 and 1.21.

Measures like light shelves and reflective ceilings can improve the light distribution from the facade slightly, but these solutions are often associated with visual discomfort. The most effective way to bring daylight deeper into buildings is to use light from the roof with products like VELUX roof windows and sun tunnels.

Example: daylight in deep buildings

The simulations below demonstrate the daylight performance of a deep room with three different window configurations installed.
Room dimensions: 8m (d) x 4m (w) x 3m (h)
Pane visual transmittance (τ_v): 0.78
Surface reflectance: 0.35 (floor), 0.66 (wall), 0.90 (ceiling)

1) Situation with 10% glazing to floor area ratio (facade window only).

The results from scenario 1 show that a 10% glazing to floor area ratio will only achieve a DF of 2% a few metres from the facade and leave the back of the room with very low light levels. Even though the average DF of the room is equal to 1.9%, only a small work plane area achieves values above 2%, and only one of the three workplaces represented can be considered daylit.

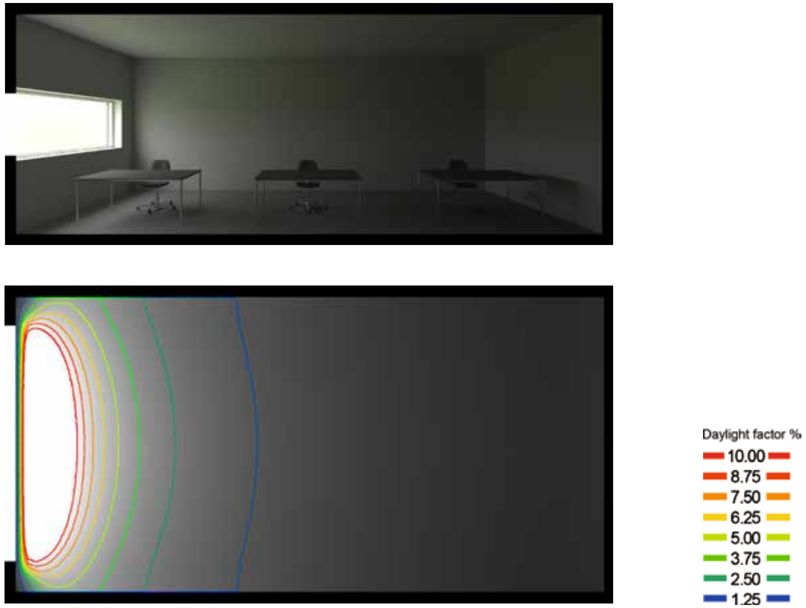


Figure 1.20 Luminance and daylight factor simulations of scenario 1.

2) Situation with 30% glazing to floor area ratio (facade window only).

The results from scenario 2 show that a 30% glazing to floor area ratio will achieve a DF facade of 2% approximately 4.5 metres from the facade. The DF average is equal to 5.1%, but it is highly non-uniform and not well distributed over the work plane area, with very high values near the window and low values at the back, a luminous environment likely to cause visual discomfort and glare. In this scenario, two of the three workplaces represented can be considered daylit.

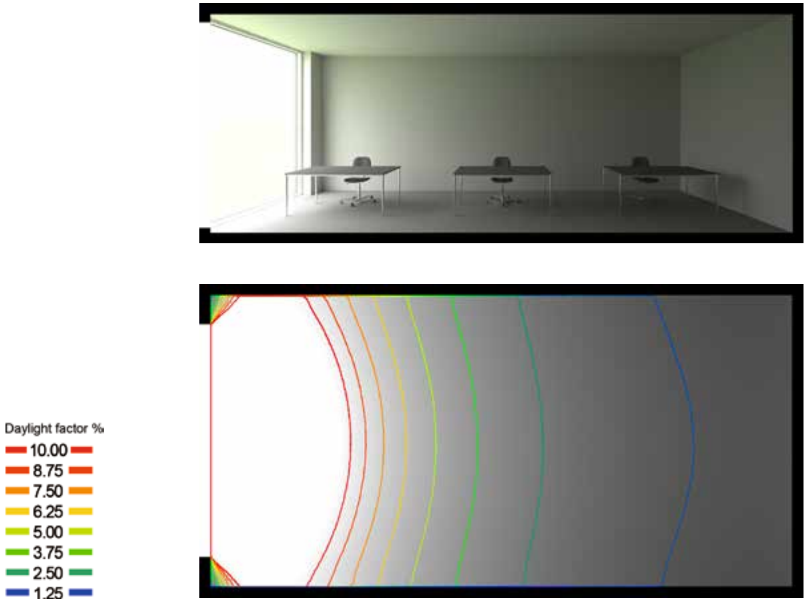


Figure 1.21 Luminance and daylight factor simulations of scenario 2.

3) Situation with 20% glazing to floor area ratio (11% facade window + 9% roof window).

The results from scenario 3 show that a combination of facade and roof windows with a 20% glazing to floor area ratio provides generous and useful DF levels over the entire work plane, with an average DF of 6.4%. The results demonstrate that the use of roof windows means better daylighting performance and a luminous environment not as likely to cause glare and visual discomfort. In this scenario, all of the three workplaces represented can be considered well daylit.

Simulations performed with the VELUX Daylight Visualizer. CVP VELUX roof windows are used in scenario 3.

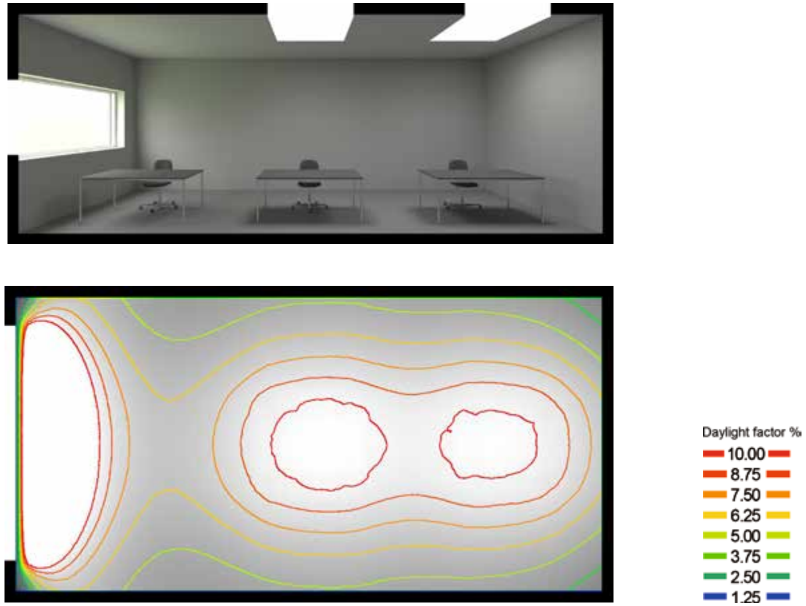
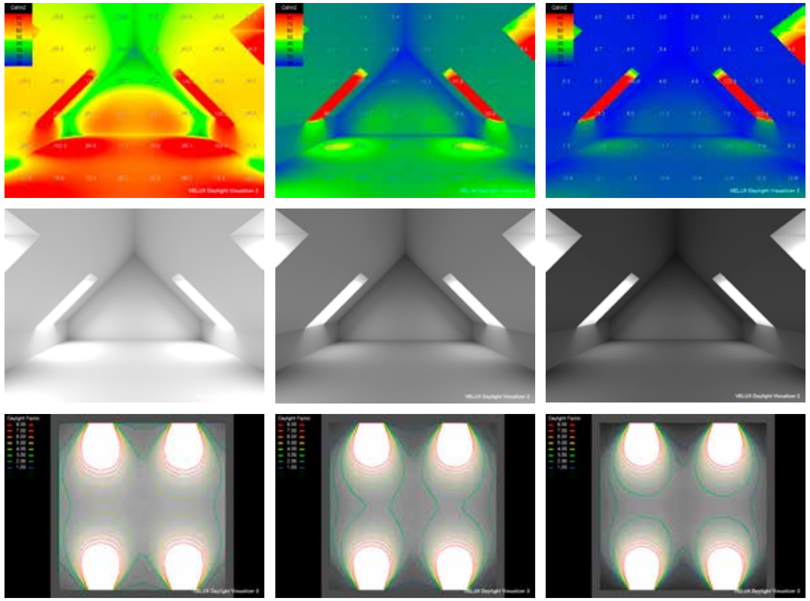


Figure 1.22 Luminance and daylight factor simulations of scenario 3.

Material properties

The colour and reflectance of room surfaces are part of the lighting system. Dark surfaces reflect less light than bright surfaces, and the result is likely to be an unsatisfactory luminous environment in which there is little indirect or reflected light. Bright vertical surfaces inside the room are generally preferred to dark ones, but shading devices used to control sunlight should use darker materials in order to limit the risk of glare (e.g. grey awning blinds).

Floor	(0.70)	Floor	(0.30)	Floor	(0.15)
Wall	(0.85)	Wall	(0.50)	Wall	(0.30)
Ceiling	(0.85)	Ceiling	(0.70)	Ceiling	(0.30)



Average DF	6.41%	Average DF	5.60%	Average DF	5.24%
Median DF	4.68%	Median DF	3.86%	Median DF	3.49%
Uniformity Dmin/Dav	0.33	Uniformity Dmin/Dav	0.21	Uniformity Dmin/Dav	0.31

Figure 1.23 Luminance simulations showing the effect of surface reflectance on daylight levels.

1.5.5 Windows and skylights

Orientation

The orientation of windows influences the availability and qualities of daylight in the interior. In the northern hemisphere, light coming from the north is mainly composed of diffuse skylight and provides the interior with a functional and comfortable light that is pretty stable throughout the day.

Light coming from south, east and west orientations will, in many cases, provide the interior with direct sunlight and light levels that vary significantly throughout the day as the sun pursues its course around Earth.

Note that roof windows and skylights installed in low-pitched roofs and flat roofs are likely to receive direct sunlight.

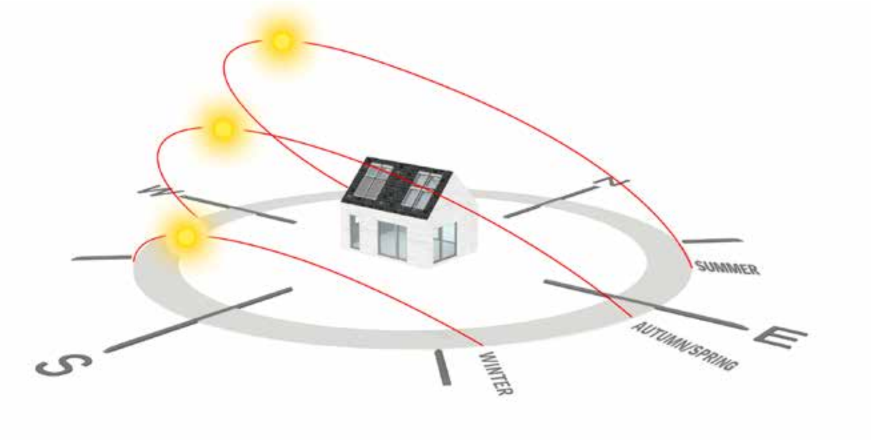


Figure 1.24 A diagram showing the sun's paths on the winter solstice (shortest day), the equinox (day and night almost equal) and the summer solstice (longest day).

Glazing dimensions

The amount of daylight entering a room is linked to the total glazing area of windows in that room.

Glazing transmittance

The amount of daylight transmitted through a window pane is reduced by the number of glass layers it has to penetrate. As a rule of thumb, double glazing (with no coating) lets in approx. 80% of the light, while triple glazing (with no coating) lets in approx. 70% of the light (compared to an open window). Coloured or coated glass can reduce the visible transmittance of a window pane to values as low as 20% and significantly modify the spectral quality of the transmitted light, as well as the perception of surface colours in the interior.

❗ Remember

As a rule of thumb, double-layer glazing transmits approx. 80% of the light and triple-layer glazing transmits approx. 70% of the light.

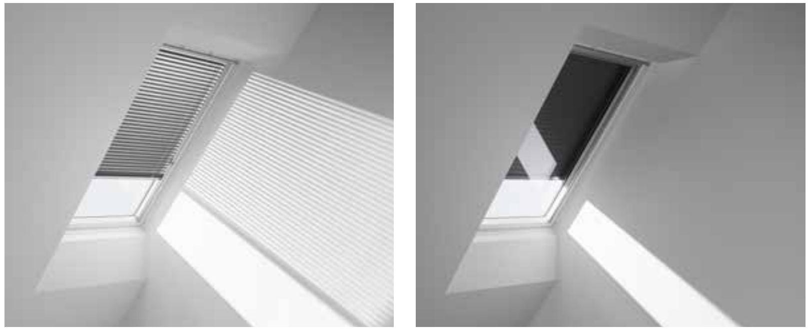
Coloured or coated glass can reduce the visible transmittance of a window pane to values as low as 20%.

> **» It is impossible to "optimise" buildings for good daylighting performance with static glazing alone, since daylight intensity varies dramatically «**

Shading

Shading and sunscreening are just as important to good daylighting performance as the window itself. Pleated blinds and Venetian blinds can be used to adjust the amount of daylight entering spaces and to reduce window luminance to control glare. The Venetian blind can also be used to redirect the light into the room.

The most efficient shading solution to prevent direct solar radiation into the building is to use external shading. Examples of external shadings are roller shutters and awning blinds. A dark grey screen (VELUX awning blind 5060) will reduce the illuminance and luminance levels significantly to a level where the risk of glare is avoided.



Interior shading, Venetian blind

Exterior shading, roller shutter

Interior shading, pleated Blind

Exterior shading, awning blind

Figure 1.25 Different shading solutions.

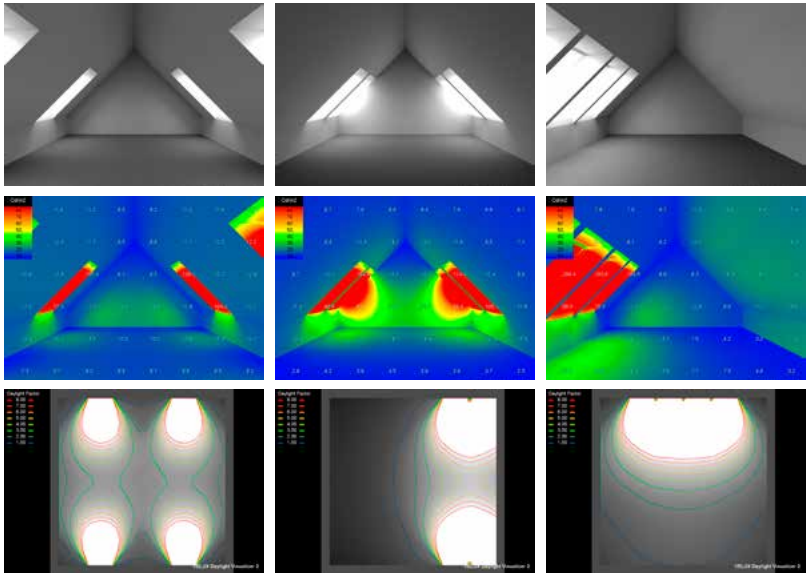
Position

The positioning of windows will influence the distribution of daylight in the room and determine the amount of 'useful' daylight. Window position should also take into account the relation between the view to the outside and the eye level of the occupants.

Linings

The geometry and depth of window linings will influence the amount of daylight entering the room and can be used to soften the luminance transition between the high luminance values of the window and the surfaces of the room.

Example
The figure below shows the effect of different window position in an attic with four roof windows. The results show that the average DF values vary in the room, but not as much as median DF values, which are a better representation of the useful amount of daylight in the room. It is also worth noting the effect of window placement on the uniformity of daylight in the room and taking it into consideration in the building design and window layout.



Average DF	5.63%	Average DF	4.45%	Average DF	5.88%
Median DF	3.88%	Median DF	1.60%	Median DF	2.94%
Uniformity Dmin/Dav	0.22	Uniformity Dmin/Dav	0.06	Uniformity Dmin/Dav	0.14

1.5.6 Sun tunnels

Orientation

Orientation is a crucial factor influencing Sun Tunnel's performance. These products are intended to transport intense sunlight - to diffuse it into useful daylight in deep areas of buildings or areas where a window is not necessary but daylight is wanted. Sun Tunnels should be oriented to maximise their exposure to direct sunlight.

Length and configuration

The length of a Sun Tunnel influences the number of inter-reflections needed for sunlight to reach the interior of a room. While shorter Sun Tunnels will deliver more light, the very high reflectiveness of the metal material used in them allow sunlight to be efficiently transported over long distances - up to 6m. Rigid Sun Tunnels will deliver more light than flexible Sun Tunnels.

Dimensions

The amount of daylight entering a room from Sun Tunnels is linked to the dimensions of the product.

Diffuser transmittance

The transmittance and optical properties of the diffuser influence both the amount and distribution of daylight from Sun Tunnels. As the name suggest, the diffuser takes the direct sunlight coming down the Sun Tunnel and diffuses it to achieve a good distribution of daylight in the room.

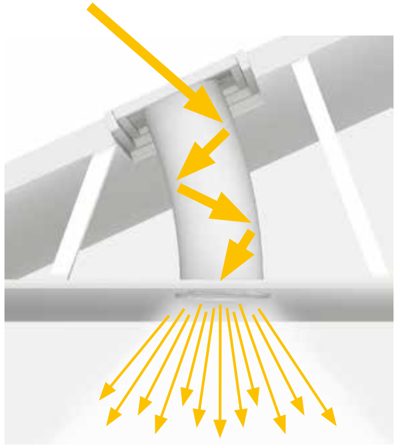


Figure 1.26 Diagram showing sunlight transport in Sun Tunnels.

> **» Roof windows and skylights deliver significantly more light than vertical and dormer windows «**

1.6 Daylight with roof windows, flat-roof windows and modular skylights

1.6.1 Impact of three window configurations on daylight conditions

Under similar conditions, roof windows are shown to provide at least twice as much light as vertical windows of the same size, and three times more light as dormers of the same size, illustrated in Figure 1.27. The roof window also provides a larger variation of light levels, which increases the visual interest of the room (Johnsen et al., 2006).

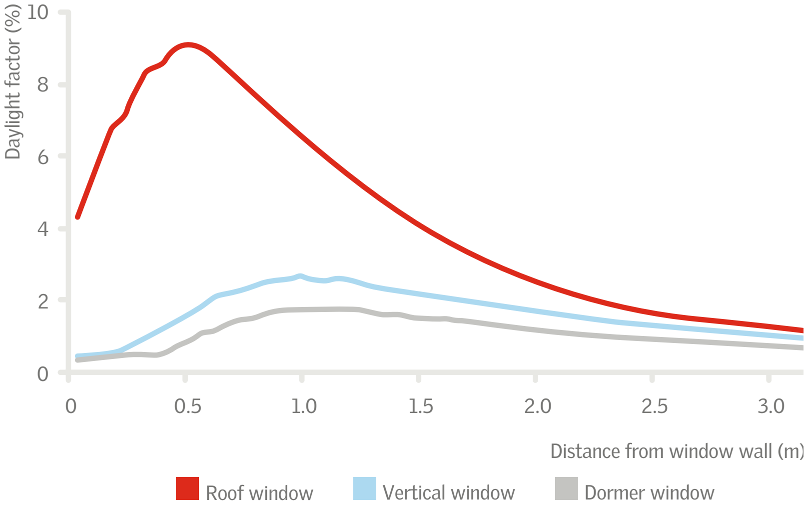


Figure 1.27 Comparison of daylight factor levels along the depth of the room.

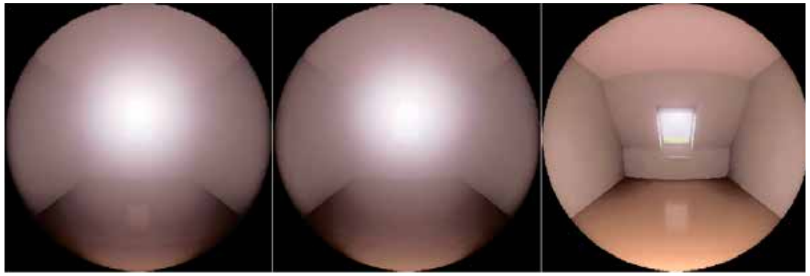


Figure 1.28 Fish-eye rendering of view toward the window wall under sunny sky conditions in December at noon. The images show that the sunlight comes directly into the field of view in all three cases. For the roof window, however, the sunlight seems to cause less glare.

In addition to providing more daylight, roof windows are also shown to give higher wall luminance than dormer and facade windows, which results in a softer transition between the high luminance of the window pane and the adjacent wall, and thus reduces the risk of glare. The figure above shows the difference between the perceived glare from a facade, dormer and roof window.

Solhuset kindergarten.

1.6.2 Effects of roof windows in Solhuset kindergarten

The architect firm Christensen & Co Architects (CCO) used daylight factor simulations to validate and optimise daylight conditions in this kindergarten project.

The daylight factor simulation of the initial design showed areas of the building where the light levels were not sufficient, such as the gymnastics room located in the central part and the dining room facing east (e.g. 5% DF instead of 2% DF). By contrast, it also showed high light levels in certain areas that could be used to optimise daylight levels throughout the building.

According to the architect, the position and design of the window linings has been optimised in the final design to achieve optimal daylight conditions in all key areas of the building, and to promote a more rational solution in terms of ceiling construction. The daylight factor simulation of the final design, shown in the figure below, shows a significant improvement on the results obtained with the initial design.

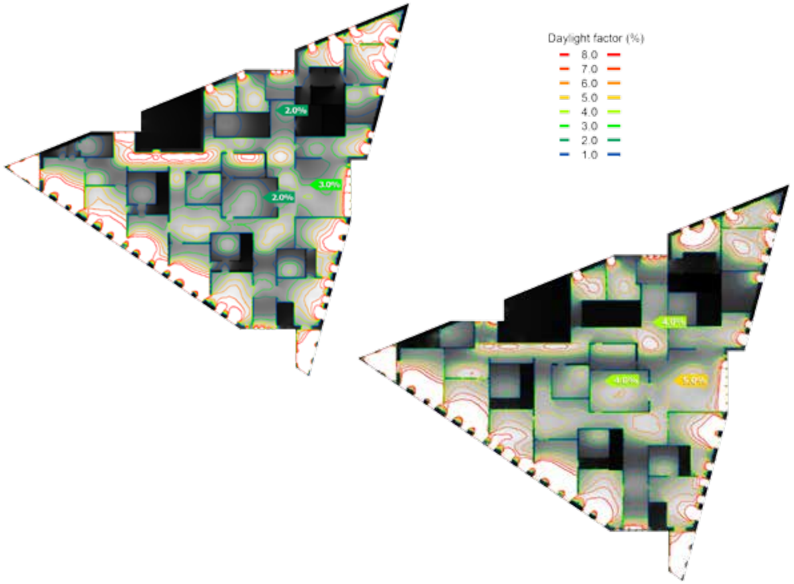


Figure 1.30 Daylight factor simulation of the initial design (left) and final design (right) of Solhuset kindergarten.

Drømmebakken kindergarten.

1.6.3 Effects of adding flat-roof windows and modular skylights to a former town hall, now a kindergarten

Daylight is the perfect material for renovation and indoor climate improvements of existing building structures. Improving daylight conditions can help significantly to revitalise the use of a space and to improve the comfort and well-being of the occupants.

This kindergarten project was a former town hall and had a flat roof with no windows or skylights before the intervention. CASA architects used VELUX Modular Skylights and flat-roof windows to add daylight in the project's key areas and provide children with bright interior spaces.

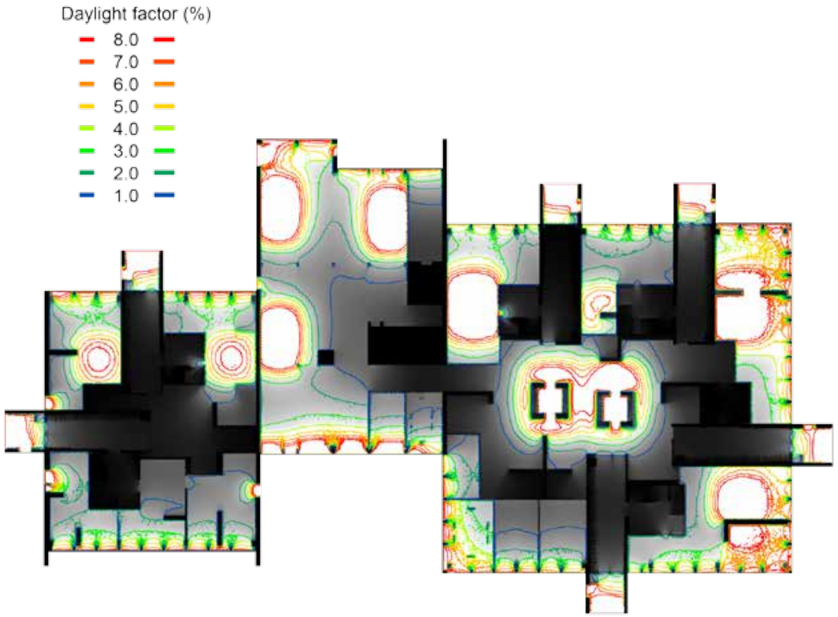


Figure 1.32 Daylight factor rendering of Drømmebakken kindergarten project in Denmark.

Green Lighthouse.

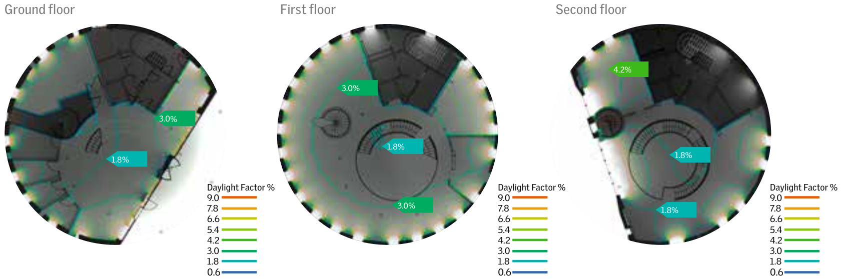
1.6.4 Effect of roof windows in Green Lighthouse

The daylight performance of Green Lighthouse, a VELUX 2020 Model Home, has been evaluated with daylight factor simulations. In order to show the effect of VELUX roof windows, a comparison of the daylight conditions with and without the use of roof windows was performed.

The results, presented in Figure 1.34, show that the roof windows deliver high levels of daylight to the second floor's lounge area, providing the occupants with a healthy, strongly daylit indoor environment, and with contact to the sky.

The results also show that the use of roof windows contributes to raising daylight levels on the lower floors substantially via the bright atrium space, and results in a better distribution of daylight on all floors by balancing the light coming from the facade windows.

Daylight performance without roof windows



Daylight performance with roof windows

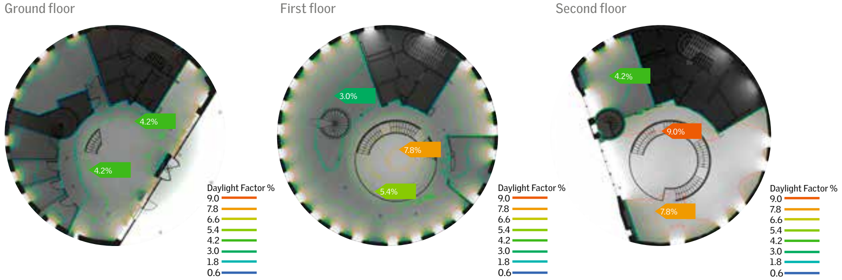


Figure 1.34 Daylight factor renderings of Green Lighthouse comparing daylight performance with and without roof windows.

1.6.5 Effect of roof windows when renovating school buildings

The effect of adding roof windows in Langebjerg School was evaluated with daylight factor simulations comparing the daylight performance before and after renovation, in which four roof windows were added to each classroom, as well as in the circulation areas. Figure 1.36 shows the daylight factor results obtained with the initial design in which the classrooms have two roof windows. The simulation results show that classrooms had average DF levels of around 3.0%-3.4%, with the exception of one room that had an average DF of 1.5%.

The daylight factor levels obtained for the new proposal of the school are shown in figure 1.37. The addition of 3 to 4 roof windows in each class room results in reach higher DF levels ranging between 4,4% and 5,3%, but most importantly they help achieve a much better distribution in the individual classrooms to ensure that each student desk receives adequate levels of daylight and reduce the contrast in the daylight levels of the room.

Langebjerg School.

» New classrooms with more, and better distributed daylight «

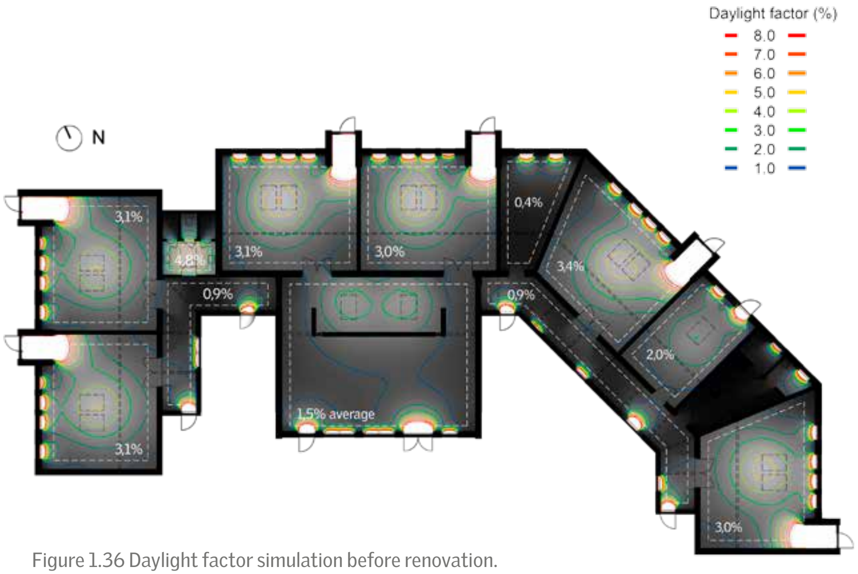


Figure 1.36 Daylight factor simulation before renovation.

Figure 1.37 Daylight factor simulation after renovation.

Sunlighthouse.

1.6.6 Effect of roof windows in MH2020 Sunlighthouse

VELUX Roof windows are used to deliver daylight both on the ground floor and first floor of Sunlighthouse, as shown in Figure 1.39. Daylight factor renderings of the ground floor and first floor show that all the main living areas of the house have generous levels of daylight above 5% DF, see figure 1.40. The analysis also show that the house and its occupants will benefit from bright circulation areas under the roof window on the first floor and around the courtyard on the ground floor.

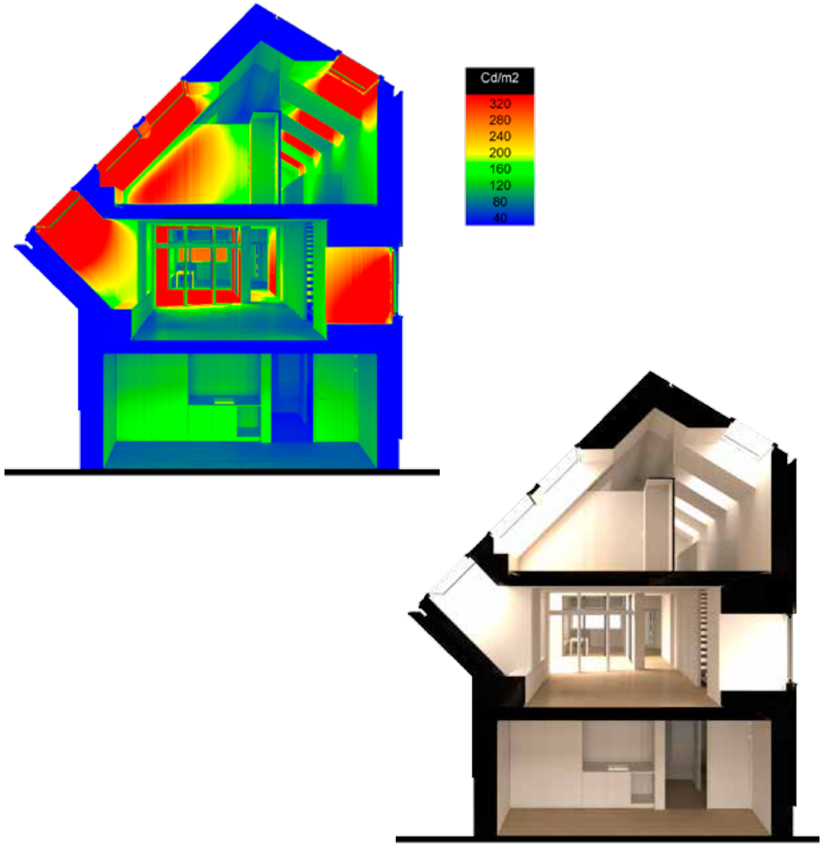


Figure 1.39 Section view of a luminance rendering showing daylight distribution in false colour (left) and photo-realistic (right).

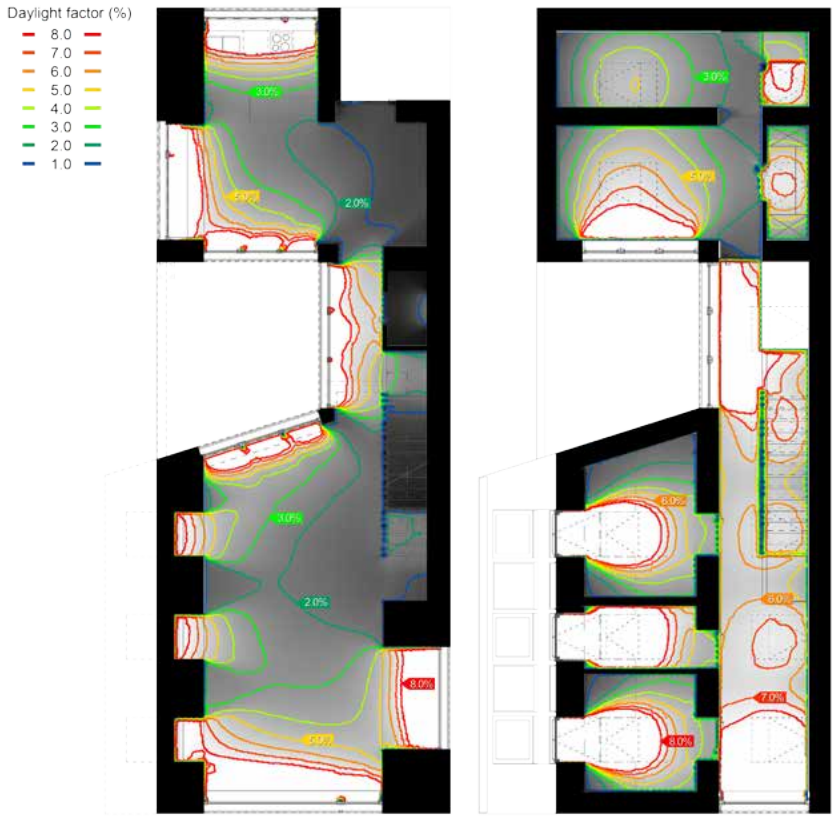


Figure 1.40 Daylight factor rendering of Sunlighthouse ground floor (left) and first floor (right).

The building monitoring report of Sunlighthouse also demonstrates the effect of the good daylight conditions, with very few hours in the year when electric lighting was used during daytime. The figure below shows electric lighting usage in the kitchen space from January to November.

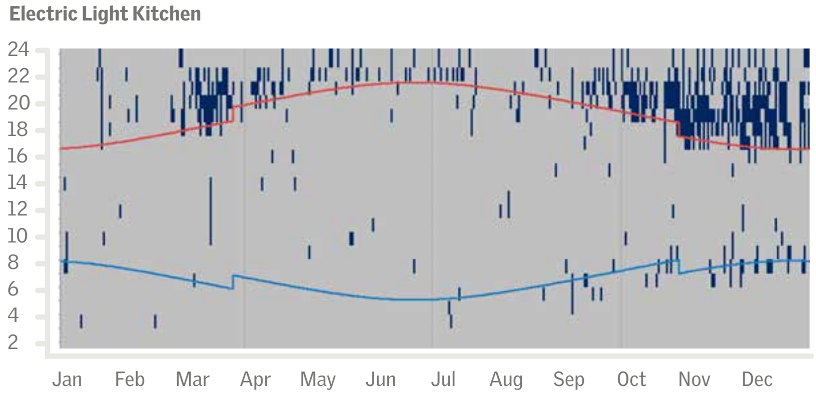

Electric Light Kitchen

Figure 1.41 Temporal map of electric lighting usage in Sunlighthouse. The blue line represents the time of sunrise, and the red line the time of sunset.

Green Lighthouse.

1.6.7 Effect of roof windows in the renovation of residential buildings

A recent study investigating the effect of adding roof windows to a single-family house has shown that roof windows and better daylight conditions can be tied to several positive outcomes, and this in all climates in Europe.

First and foremost, the addition of roof windows led to a marked increase in the amount of daylight and its occurrence in levels in the key UDI autonomous range of 300-3 000 lux. The figure below shows increases of daylight provision in the range of 40% from the addition of roof windows to the kitchen space across all climates and orientations tested (Mardaljevic et al., 2012).

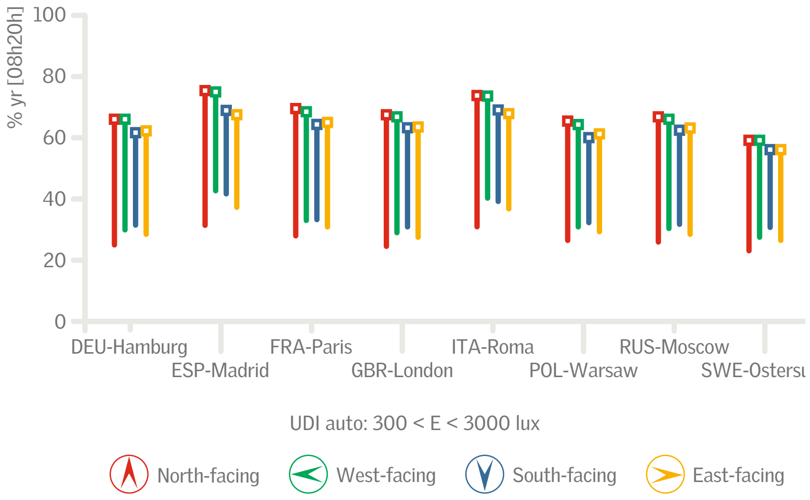


Figure 1.43 Impact of adding roof windows on the occurrence of daylight levels in the range 300-3000 lux.

The higher levels of daylight increase the number of hours when electric lighting will not be needed, which, in turn, results in significant energy savings for lighting. The figure below shows energy savings in the area of 100 KWh/yr across all climates and orientations tested (Mardaljevic et al., 2012).

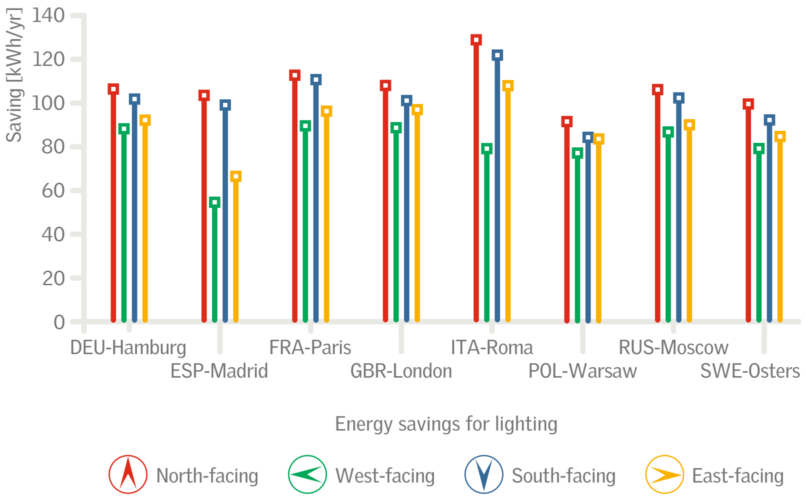
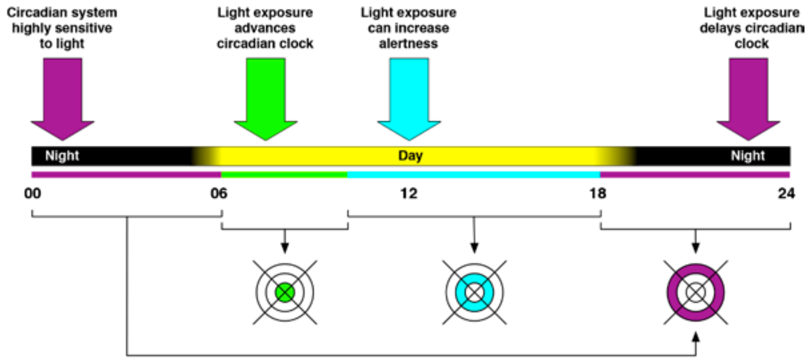
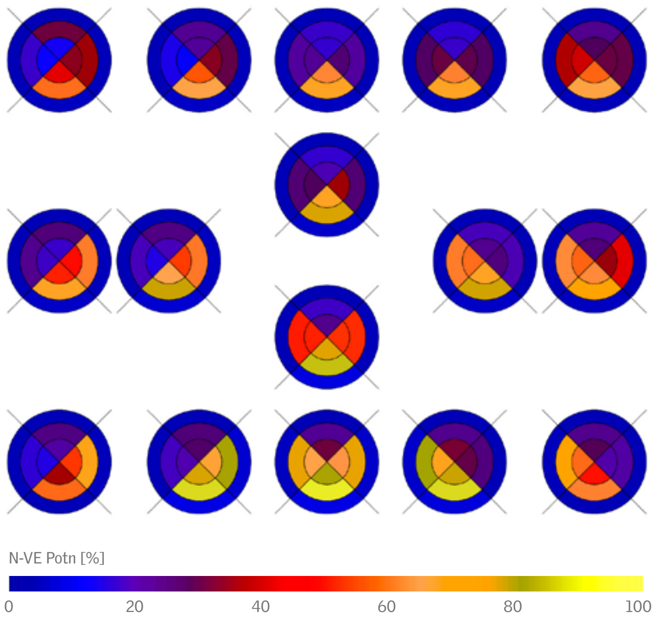


Figure 1.44 Impact of adding roof windows on energy savings for lighting.

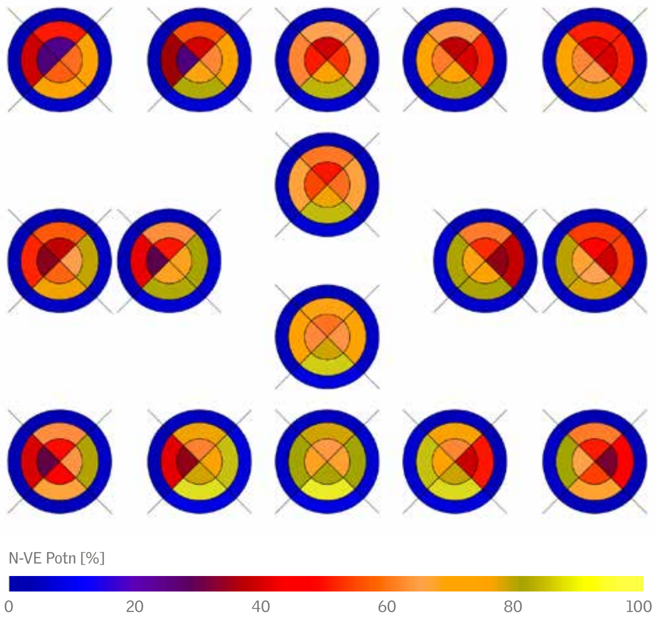
The study also investigated the impact of adding roof windows on the amount of daylight received at eye level at specific periods of the day and night in order to evaluate the non-visual of effects of light. Figure 1.45 shows the results obtained for the living room in Rome. Each circle represents a specific view position with four view directions and three time periods.

The results showed significant increases for potential non-visual effects of daylight with the addition of roof windows: a 25% increase in the morning period and a 45% increase in the afternoon period. Similar increases in performance were seen in all rooms and across all climates and orientations tested.





Period	MED	AVG	MAX	MIN
06.00-10.00	33 %	38 %	80 %	7 %
10.00-18.00	29 %	42 %	89 %	10 %
18.00-06.00	0 %	0 %	5 %	0 %



Period	MED	AVG	MAX	MIN
06.00-10.00	58 %	54 %	81 %	21 %
10.00-18.00	73 %	67 %	89 %	35 %
18.00-06.00	1 %	1 %	5 %	0 %

Figure 1.45 Impact of adding roof windows on the potential for non-visual effects of daylight for multiple positions, view directions and time of day.

1.7 Daylight calculations and measurements

1.7.1 Illuminance

Illuminance is the measure of the amount of light received on a surface. It is typically expressed in lux (lm/m²). Illuminance levels can be measured with a luxmeter, shown in Figure 1.47, or predicted through the use of computer simulations with recognised and validated software (e.g. VELUX Daylight Visualizer). Figure 1.48 shows an example of an illuminance rendering. Illuminance is the measure of light currently used by most performance indicators to determine daylight availability in the interior.

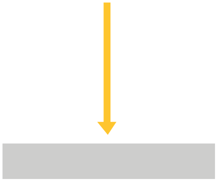


Figure 1.46. Illuminance diagram.

Figure 1.47. Luxmeter.

Typical illuminance values:	
Direct sunlight	100,000 lux
Diffuse skylight	3,000-18,000 lux
Minimum levels for tasks and activities:	
Residential rooms	200-500 lux
Classrooms (general)	300-500 lux
Workspace lighting	200-500 lux

❗ Remember

Illuminance (lux) is the measure of the amount of light received on a surface.

It is the measure of light currently used by most performance indicators to determine daylight availability in the interior.

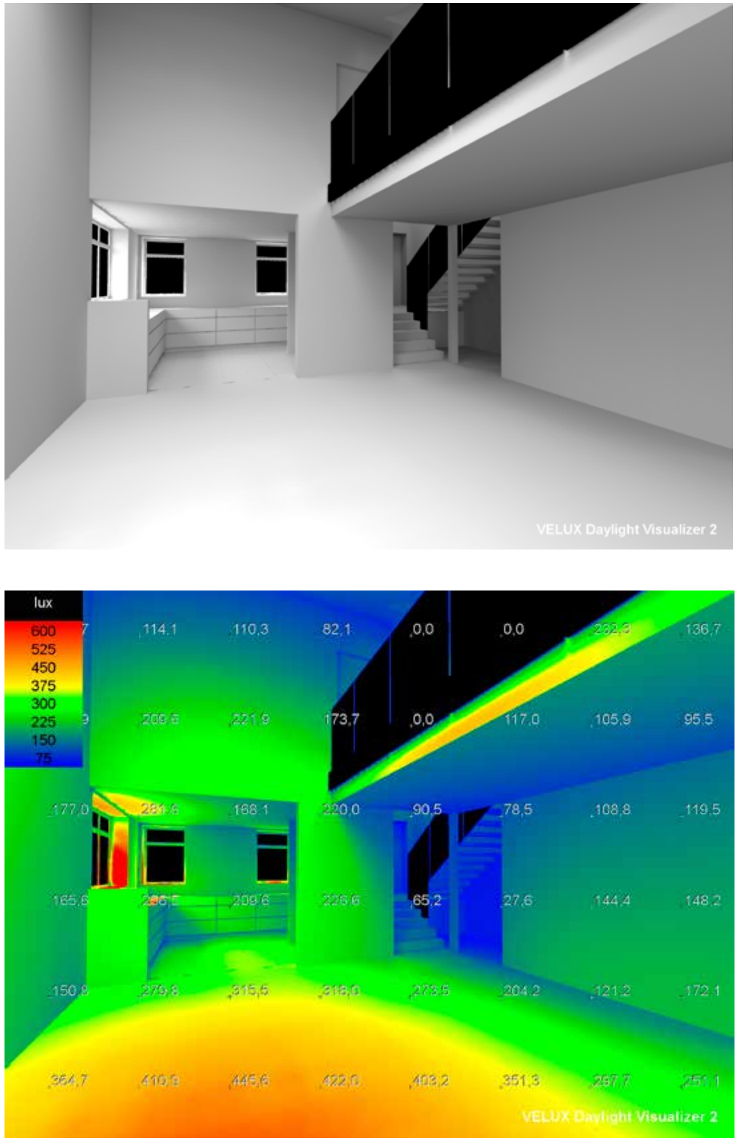


Figure 1.48 Illuminance renderings of Maison Air et Lumière.

1.7.2 Luminance

Luminance is the measure of the amount of light reflected or emitted from a surface. It is typically expressed in cd/m².

Luminance levels can be measured with a luminance meter, shown in Figure 1.51, or through the use of high dynamic range (HDR) imaging techniques together with a digital camera and luminance mapping software (e.g. Photolux), example shown in Figure 1.52. Luminance levels can be predicted through the use of computer simulations with recognised and validated software (e.g. VELUX Daylight Visualizer). Figure 1.53 shows an example of a luminance rendering. Luminance is the measure of light used to evaluate visual comfort and glare in the interior.

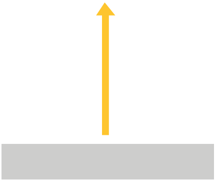


Figure 1.49. Luminance diagram.


Figure 1.50. Cool pix camera and fisheye lens used to create luminance maps.


Figure 1.51. Luminance meter.

Typical luminance values:	
Solar disk at noon	1,600,000,000 cd/m²
Solar disk at horizon	600,000 cd/m²
Frosted bulb (60 W)	120,000 cd/m²
T8 cool white fluorescent	11,000 cd/m²
Average clear sky	8,000 cd/m²
Average cloudy sky	2,000 cd/m²

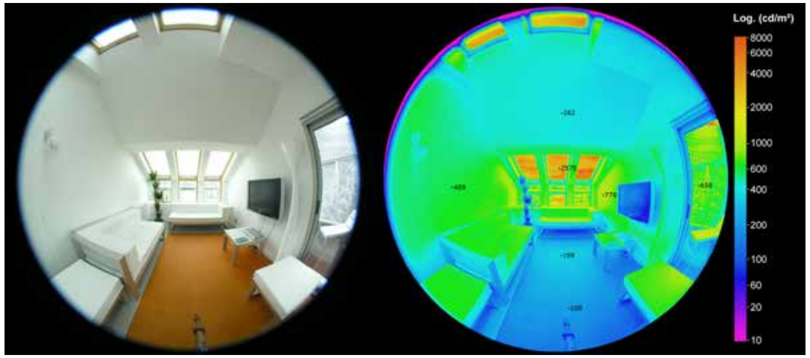


Figure 1.52 Luminance map showing the distribution of luminance values in Atika, a concept house by VELUX, under overcast sky conditions.

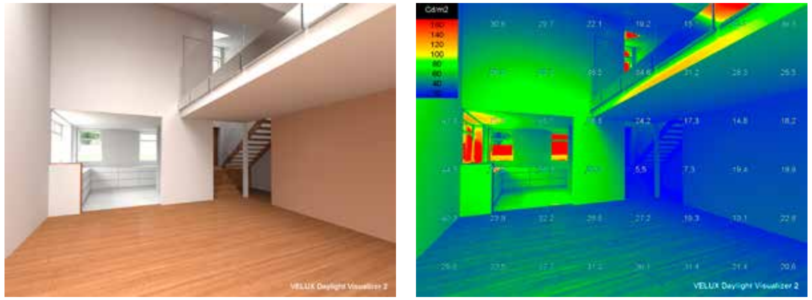


Figure 1.53 Luminance renderings of Maison Air et Lumière.

! Remember

Luminance (cd/m²) is the measure of the amount of light reflected or emitted from a surface.

It is the measure of light used to evaluate visual comfort and glare in the interior.

1.7.3 Daylight factor

Daylight factor (DF) is a daylight availability metric that expresses – as a percentage – the amount of daylight available inside a room (on a work plane) compared to the amount of unobstructed daylight available outside under overcast sky conditions (Hopkins, 1963).

The key building properties that determine the magnitude and distribution of the daylight factor in a space are (Mardaljevic, J. (2012)):

- The size, distribution, location and transmission properties of the facade and roof windows.
- The size and configuration of the space.
- The reflective properties of the internal and external surfaces.
- The degree to which external structures obscure the view of the sky.

The higher the DF, the more daylight is available in the room. Rooms with an average DF of 2% or more can be considered daylit, but electric lighting may still be needed to perform visual tasks. A room will appear strongly daylit when the average DF is 5% or more, in which case electric lighting will most likely not be used during daytime (CIBSE, 2002).

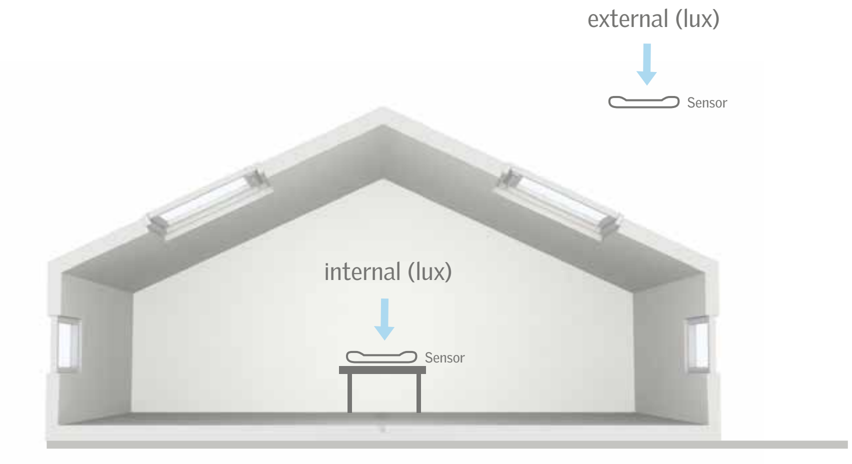
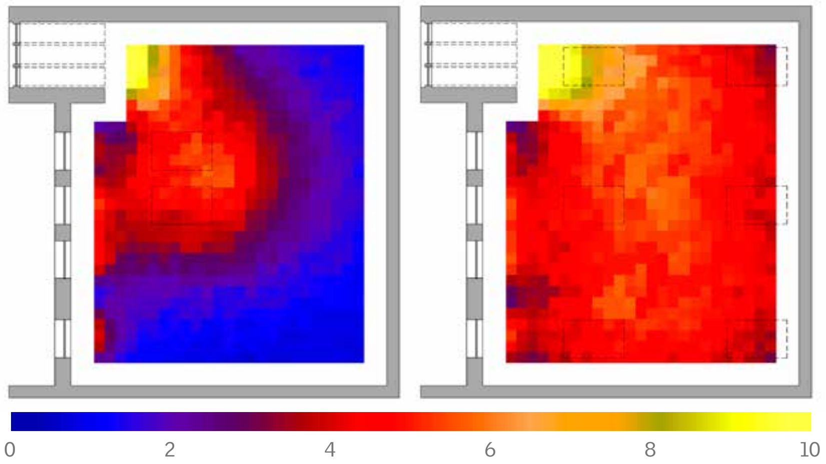


Figure 1.54 Drawing showing the values measured by the daylight factor method (simultaneous reading of the internal and external (unobstructed) horizontal illuminance levels).

Measurement grid

In most cases, daylight factor levels in rooms are measured at work plane height (e.g. 0.85m above the floor), leaving a 0.5m border from the walls around the perimeter of the work plane, as shown in Figure 1.55.



Average DF	2.75%	Average DF	5.06%
Median DF	2.30%	Median DF	4.09%
Uniformity Dmin/Dav	0.15	Uniformity Dmin/Dav	0.49

Figure 1.55 Daylight factor (DF) simulation in a classroom before (left) and after (right) renovation, including a 0.5m perimeter from the walls around the work plane.

Climate-based daylight factor

The amount of daylight in a building's interior depends on the availability of natural light outside at that location, as well as the properties of the building spaces and its surroundings. The evaluation of daylight performance should, therefore, take account of the availability of daylight on site in addition to the properties of the space (CIE, 1970). Using recorded climatic data (outdoor diffuse illuminance), we can determine what DF levels will be needed to reach the target illuminance level over a given period of the year. The example below shows how the target DF is determined from climate data to achieve daylight levels of 300 lux for 50% of the year.

$$D_T = \frac{E_{Internal}}{E_{External}} = \frac{300\text{ lux} \cdot 100\%}{15\,700\text{ lux}} = 1{,}9\%$$

City	Internal lux	External lux	D_T %
Oslo	300	12 000	2,5%
Paris	300	15 700	1,9%
Rome	300	19 200	1,6%

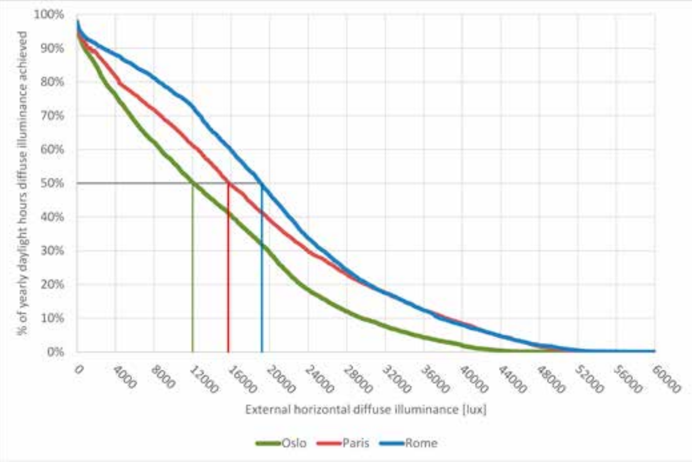
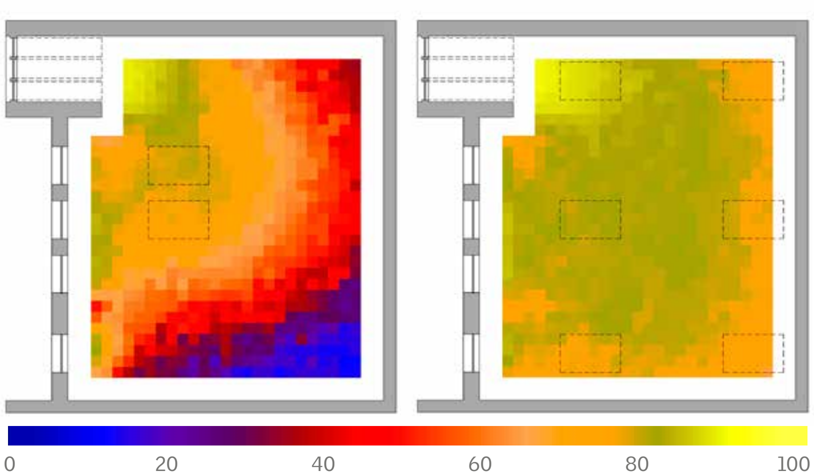


Figure 1.56 Cumulative curves of available external diffuse horizontal illuminance for Oslo (Norway), Paris (France) and Rome (Italy).

1.7.4 Daylight autonomy

Daylight autonomy (DA) is a daylight availability metric that corresponds to the percentage of the occupied time when the target illuminance at a point in a space is met by daylight (Reinhart, 2001).

A target illuminance of 300 lux and a threshold DA of 50%, meaning 50% of the time daylight levels are above the target illuminance, are values that are currently promoted in the Illuminating Engineering Society of North America (IESNA, 2013), see section 1.9.4.



Average DA_{300}	59%
Mean DA_{300}	63%
Uniformity Dmin/Dav	0.14

Average DA_{300}	82%
Mean DA_{300}	82%
Uniformity Dmin/Dav	0.83

Figure 1.57 Daylight autonomy (DA) simulation in a classroom before (left) and after (right) renovation, including a 0.5m perimeter from the walls around the work plane.

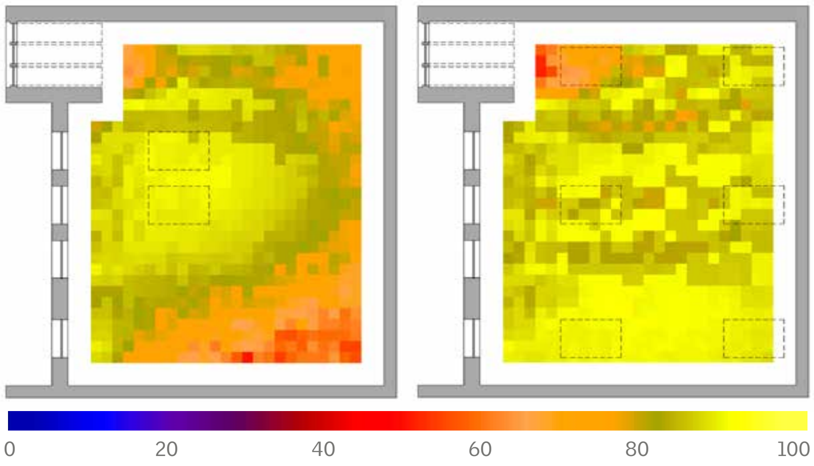
1.7.5 Useful daylight illuminance (UDI)

Useful daylight illuminance (UDI) is a daylight availability metric that corresponds to the percentage of the occupied time when a target range of illuminances at a point in a space is met by daylight.

Daylight illuminances in the range 100 to 300 lux are considered effective either as the sole source of illumination or in conjunction with artificial lighting. Daylight illuminances in the range 300 to around 3 000 lux are often perceived as desirable (Mardaljevic et al, 2012).

Recent examples in school daylighting design in the UK have led to recommendations to achieve UDI in the range 100-3 000 lux for 80% of occupancy hours.

Example



Average UDI$_{100\text{-}3000}$	83%	Average UDI$_{100\text{-}3000}$	88%
Mean UDI$_{100\text{-}3000}$	85%	Mean UDI$_{100\text{-}3000}$	90%
Uniformity Dmin/Dav	0.61	Uniformity Dmin/Dav	0.58

Figure 1.58 Useful daylight illuminance (UDI) simulation in a classroom before (left) and after (right) renovation, including a 0.5m perimeter from the walls around the work plane.

1.8 Daylight simulation tools

Daylighting simulation tools make it possible to evaluate the quantity and distribution of daylight in a room, while taking into account key influential parameters such as window placement, building geometry, external obstruction, interior divisions and material properties.

Most CAD visualisation programs used today are capable of generating images that look realistic, but they do not provide information about the quantity and quality of daylight in the rooms. Simulation tools like Daylight Visualizer enable professionals to make informed decisions about daylight performance and building design, and get an accurate impression of the appearance of daylight in the rooms. Figure 1.59 below shows a luminance rendering with photo-realistic and false colour images.

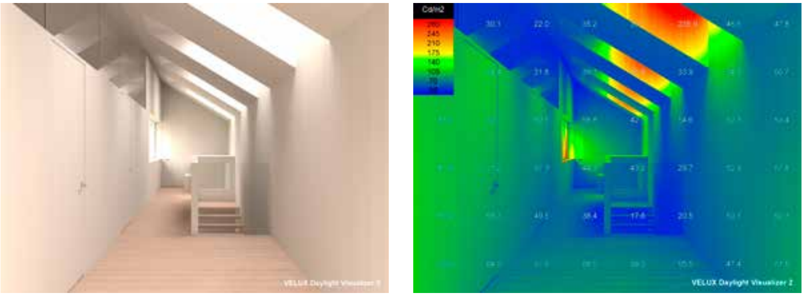


Figure 1.59 Luminance rendering of SunlightHouse shown with photo-realistic and false colour images

VELUX Daylight Visualizer

VELUX Daylight Visualizer is a professional and validated simulation tool for the analysis of daylight conditions in buildings. It is intended to promote the use of daylight in buildings and to aid professionals by predicting and documenting daylight levels and the appearance of a space prior to realisation of the building design. The program's simple user interface makes it accessible, quick and easy-to-use.

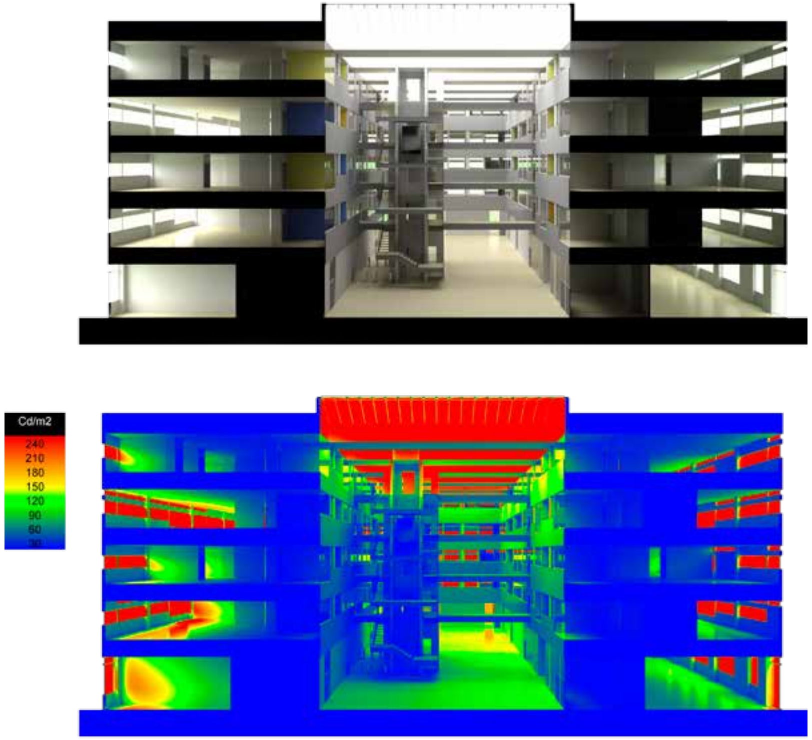
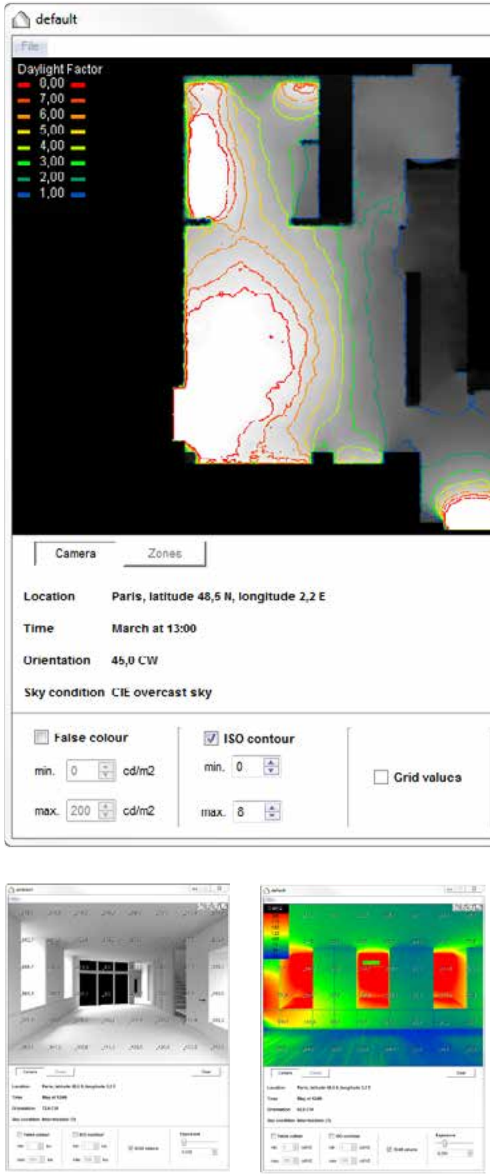


Figure 1.60 Section views of a luminance rendering showing the effects of VELUX Modular Skylights in the atrium space of an office building.



Location Paris, latitude 48,5 N, longitude 2,2 E

Time March at 13:00

Orientation 45,0 CW

Sky condition CIE overcast sky

☐ False colour min. 0 cd/m2 max. 200 cd/m2

☑ ISO contour min. 0 max. 8

☐ Grid values

Exposure 0,050

Figure 1.61 Screenshots of VELUX Daylight Visualizer output viewer showing a daylight factor rendering (top), an illuminance rendering (left) and a luminance rendering in false colour (right).

Key features

- Any project, any scale
  Daylight Visualizer can be used to evaluate daylight conditions in any type of project, including residential, commercial and industrial projects of any scale.

- Photo-realistic and false colour images
  Visualise and quantify the amount and distribution of daylight (luminance, illuminance and daylight factor) in buildings with false colour and photo-realistic images.

- Daylight factor calculations
  Daylight factor (DF) is a one-step simulation - the most commonly used performance indicator to evaluate daylight availability in buildings.

- Results report
  A report can be generated of simulation results, presenting the daylight performance by zone for each room/space in the building. Results include average, median, minimum, maximum and uniformity values for each zone.

- Create/import projects
  Use the embedded modelling tool to generate 3D models in which roof and facade windows can be freely inserted. Or simply import 3D models directly from your CAD program Autocad, Revit, SketchUp, Archicad and more) with the following supported 3D file formats DWG, DXF, SKP and OBJ.

- Fast and accurate
  Daylight Visualizer is a validated daylighting simulation tool based on state-of-the-art rendering technology capable of simulating the complex character of daylight in building interiors.

For more information about VELUX Daylight Visualizer, please visit the official website http://viz.velux.com.

1.9 Daylight requirements in building codes

There are very few (or no) daylighting requirements or recommendations in existing standards and building regulations that are enforceable by law in any country.

The VELUX Group is working to have windows recognised as sources of illumination and sun provision in buildings; we are promoting healthy indoor environments and helping to reduce the electricity used for lighting. Our goal is for daylighting to be specifically mentioned and considered in building standards and regulations, together with specific performance criteria for all main living areas and activity zones of a building. Three key points that we believe should be taken into account, when daylight requirements are implemented in national legislation:

- Daylight should be used as primary light source in buildings in daytime and fulfil both our visual and non-visual (biological) needs.

- We recommend levels of minimum 300 lux for most of the room area by meeting a target climate-based daylight factor and 500 lux for areas where productive work is performed.
  See section 1.7.3

- We recommend that national renovation strategies should address the importance of always improving daylight conditions when renovating a building.

The recommended prescriptive demands that compare window area with daylight factor as equally valid methods of achieving adequate daylight conditions have their limitations.
As an example, a study by Aarhus School of Engineering investigated the influence of window size, placement and other parameters on the distribution of daylight in a room. The window size in the 23 different models is, in all cases, in accordance with the present (10% glass area to floor area) and future Danish demands for glass area to floor area (15%). The study compared the recommended requirements for daylight in commercial buildings – a daylight factor of 2% on the work plane (present Danish building regulations), and an average daylight factor in the room of 3% (suggested requirements in the 2020 standard).

The calculations show that if shading from external surroundings or common facade design is included, then only 9 of the 23 models meet a daylight factor of more than 2%, and only 3 models meet an average daylight factor of more than 3%, corresponding to future recommended requirements in Danish building legislation.

» The EU Workplace (Health, Safety and Welfare) Regulations (1992) requires that "Every workplace shall have suitable and sufficient lighting" and that this lighting "shall, as far as is reasonably practicable, be by natural light" «

1.9.1 Building Codes

Legislation related to daylighting has historically been defined by one or more of the following criteria: window or glazing area in relation to the room area or facade area; quantity of daylight by daylight factor in a point in the room or as an average daylight factor of the room area; sunlight provision for a specific day or season; and a view to the outside environment (Boubekri, 2004):

- Requirements for windows and their glazing area in relation to room area or facade area. It is important to stress that legislation that mandates a minimum ratio of glazing area cannot be considered as daylight legislation, since it does not translate the actual daylight presence inside the room or building; it does not consider factors such as outside boundary conditions, building overhangs, permanent shading, glass configuration or transmittance.

- The quantity of indoor illumination inside a room. Levels for daylighting are generally described as preferred or recommended - either by specific illuminance (lux) levels on a workplane or by daylight factor (DF). Daylight factor is the most recognised performance indicator used to specify daylight conditions in buildings. The advantage of the DF method is that it is quick to calculate, and can be used in the early design process. It enables the validation of the quantity, uniformity and spatial distribution of diffuse daylight in rooms, giving architects and designers what they need to make informed decisions.

- The provision of sunlight and its duration. This type of legislation, usually referred to as "solar zoning legislation", attempts to guarantee building occupants access to sunlight for a predetermined period of time during the day, season and year. Considerations of sunlight access and its duration will influence the decision on orientation, the disposition of rooms and their windows, selection of solar shading devices and consideration of the surroundings. In countries such as Japan and China, solar zoning relates to public health, safety and welfare.

- A view to the outside environment provides buildings' occupants with information about orientation, and weather and times changes throughout the day. This kind of legislation calls attention to window sill-height, glazing width (or the sum of widths for all windows) as a fraction of facade area, and type of glazing material used.

1.9.2 The European Committee for Standardization, CEN

In several European Standards involving daylight, the general benefits of daylight tend to be explained as follow:

- The design illuminance levels needed to enable people to perform visual tasks efficiently and accurately shall be obtained by means of daylight, electric light or a combination of both.

- Windows are strongly favoured in buildings for the daylight they deliver, and for the visual contact they provide with the outside environment. It is important to ensure windows do not cause visual or thermal discomfort, or loss of privacy.

- Potential energy savings by using daylight

- Light is important to people's health and well-being.

In EN 12464-1:2011, the importance of daylight is taken into account and requirements for lighting are generally applicable whether it is provided by daylight, artificial lighting or a combination of both. EN 12464-1:2011 specifies requirements for most indoor work places in terms of quantity and quality of illumination. At present, only EN 15193-1 (Energy performance of buildings – Energy requirements for lighting) provides detailed considerations of the effect of daylight on the lighting energy demand (monthly and annual), and daylight availability classification as a function of the daylight factor. A new standard for daylighting of buildings that will define metrics used for the evaluation of daylighting conditions and give methods of calculation that can be applied to all spaces is under preparation.

1.9.3 The International Organization for Standardization, ISO

Several ISO working groups include daylight as an element in their work groups. At present, one standard (ISO, 2014a) applies to calculations methods for daylight in both existing buildings and the design of new and renovated buildings.

1.9.4 Design Guidelines

Several independent authorities publish guidance material and set the criteria for best practice in the profession. These are the Chartered Institution of Building Services Engineers (CIBSE), UK and the Illuminating Engineering Society of North America (IESNA), USA. As an example, CIBSE has published its Lighting Guides on Daylighting and window design, and IESNA has published a standard on approved method: IES Spatial Daylight Autonomy (SDA) and Annual Sunlight Exposure (ASE) (IESNA, 2013), which describes a new suite of metrics of daylighting performance in an existing buildings and new designs, from concept to construction documents.

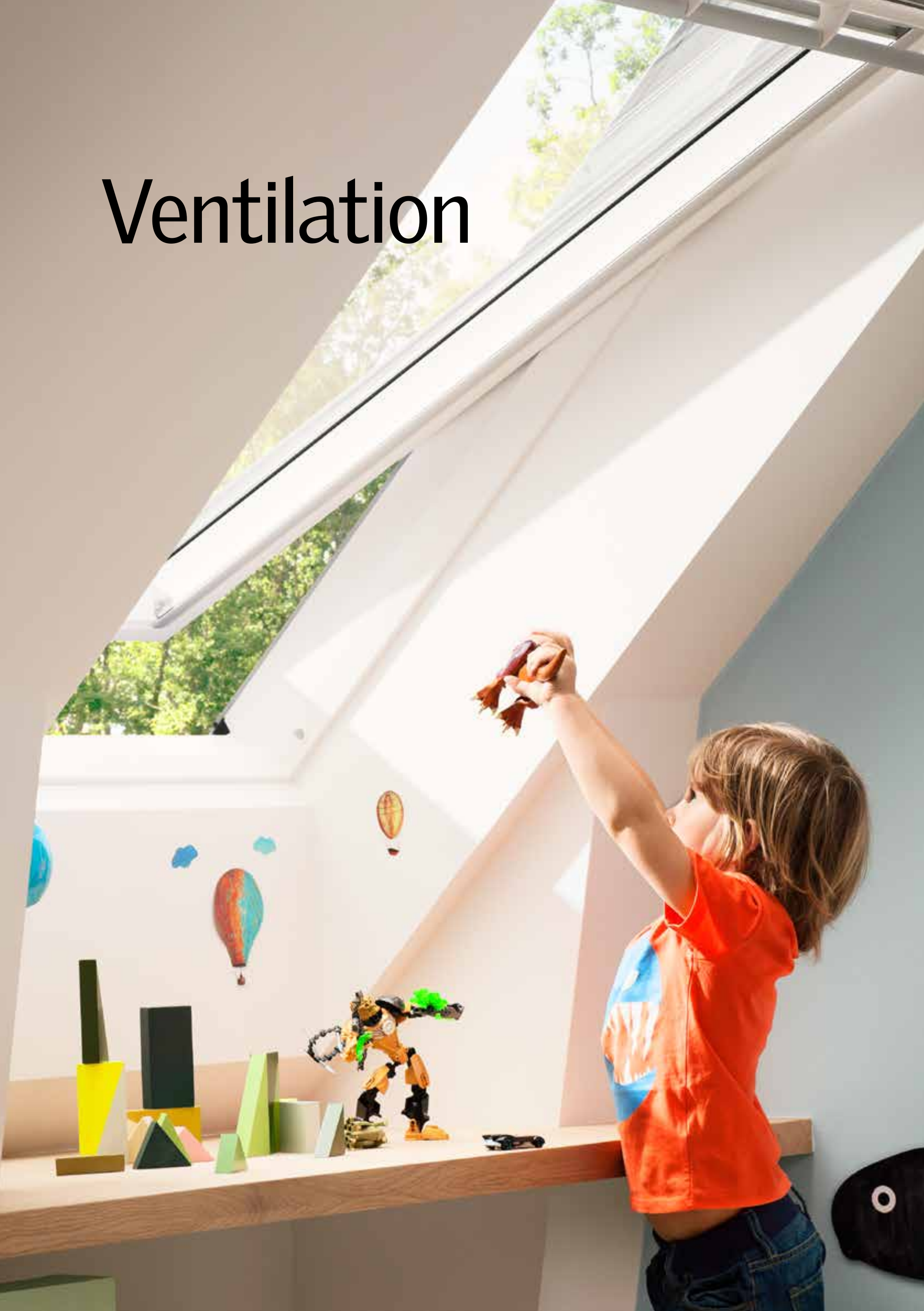
Several established and much-used methods of assessing, rating, and certifying the sustainability of buildings, such as LEED (Leadership in Energy and Environmental Design), BREEAM (Building Research Establishment Environmental Assessment Methodology), and DGNB (Deutsche Gesellschaft für nachhaltiges Bauen), make recommendations for daylight as part of their assessment schemes. Overall, daylight factor is the most common indicator in most of them, but the calculation methods and benchmarks are different. Apart from daylight factor as an indicator, a view to the outside, glare control, and illuminance levels are frequently used parameters for describing visual comfort.

- BREEAM states that "... at least 80% of floor area in occupied spaces has an average daylight factor of 2% or more". In domestic buildings, it states "... Kitchens achieve a minimum daylight factor of at least 2%; living rooms, dining rooms and studies achieve a minimum average daylight factor of at least 1.5%, and 80% of the working plane should receive direct light from the sky".

- LEED states that "... through computer simulation that the applicable spaces achieve daylight illuminance levels of a minimum of 25 foot-candles (fc) (270 lux) and a maximum of 500 fc (5400 lux) in a clear sky condition on September 21 at 9 a.m. and 3 p.m. Areas with illuminance levels below or above the range do not comply. However, designs that incorporate view-preserving automated shades for glare control may demonstrate compliance for only the minimum 25 fc (270 lux) illuminance level".

- DGNB states that "... 50% of the usable area throughout a building has a DF (> 3% very good, > 2% medium, > 1% slight, < 1% none)"; "...based on simulation, the daylight in permanently used work areas (3%≤ DF very good, 2,5%≤ DF < 3% medium, 2% ≤ DF < 2,5% slight, DF < 2% none)".

Ventilation



Ventilation

The purpose of ventilation is to freshen up the air inside buildings in order to achieve and maintain good air quality and thermal comfort. Ventilation also has important psychological aspects, which can be illustrated by the feeling of being in control, having odour management and creating a link to nature.

2.1 Indoor Air Quality

2.1.1 How to achieve good indoor air quality

As we spend 90% of our time indoors, it is crucial to understand what the quality of the indoor air we breathe is. Indoor air quality is influenced by the generation of pollutants indoors but also depends on the outdoor air around the building. Indoor air quality has a considerable impact on health and comfort. It is under pressure due to constant tightening of the building envelope, and introduction of many new materials that may emit harmful pollutants.

Indoor air quality is also about human perception. Good indoor air quality may be defined as air that is free of pollutants that cause irritation, discomfort or ill health to occupants (AIVC, 1996). Generally, rooms have different needs for ventilation; bedrooms, for example, experience more intense emission of bioeffluents/CO_2 than kitchens or living rooms. This could make demand-controlled ventilation based on room type a good way to achieve the right indoor air quality.

The quality of indoor air influences humans in several ways (Sundell, 2004a):

- Comfort: the pleasantness of the air is immediately felt when a person enters a building.
- Health: breathing poor indoor air can have negative health effects.
- Performance: high-quality indoor air can improve mental performance and general well-being.
- Other: fresh air creates a link to the outdoor environment, and fresh air through windows is a valued aspect of ventilation.

There are generally three ways of achieving good indoor air quality, (explained in more detail below (Nazaroff, 2013):

- Minimise indoor emissions (source control)
- Keep it dry (humidity management)
- Ventilate well.

Source control

Some activities lead to excessive indoor emissions, which degrades for ensuring good indoor air quality is to "minimise uncontrolled indoor emissions". Indoor air contains many different – and unwanted – compounds, which include (Bluyssen, 2009):

- Gases; e.g. formaldehyde, organic chemicals (VOC) and inorganic chemicals (NO_X, SO_X, etc.).
- Particles; e.g. house dust and combustion products.
- Radioactive gas; radon.
- Biological; e.g. mould, fungi, pollen and dust mites
- Water vapour (humidity).

Most of the pollutants come from sources indoors. They include (Bluyssen, 2009):

- Human beings and their activities; e.g. tobacco smoke, products for cleaning and personal care, consumer electronics and electrical office equipment like laser printers.
- Building materials; e.g. thermal insulation, plywood, paint, furniture and floor/wall coverings.
- Outdoor sources; e.g. pollen, traffic and industry. Radon exists naturally in the ground and enters the house through the floor construction.

Indoor air is affected by other means than the indoor generation of pollutants – outdoor air also has an influence on indoor air quality. Particles are either directly emitted into the air (primary) or formed in the atmosphere from gaseous precursors such as sulfur dioxide (SO_2), ammonia (NH_3) etc. (secondary) (WHO, 2013). Primary particles are emitted by e.g. combustion engines (diesel and petrol) - they are spread to the outside air and may eventually penetrate into buildings, thereby effecting the indoor climate. Ambient or outdoor air quality has been shown to be improving - pollution levels in cities have fallen in recent decades due to the introduction of environmental zones, filters in diesel cars and the arrival of vehicles that pollute less.

The human factors	**Achieve** thermal comfort	
	Remove chemicals, particles, smells, allergenes, moulds	
	Create link to outside	
	Avoid allergies, asthma, and other illnesses	Less illness with good air quality
	Support productivity and feeling of well-being	Higher productivity with good air quality

Figure 2.1 The main reasons for ventilation

Particles are differentiated in size (ultra-fine, fine and coarse) and the size determines how they spread within buildings and outside buildings. Particle size and their chemical composition are important factors for their health impact. Fine and coarse particles are measured by their weight in µg per m^3 while ultra-fine particles are measured in particle count (number) per cm^3.

Fine particles (also called PM2.5) can travel for thousands of kilometres across borders, while coarse particles (also called PM10) are spread over only shorter distances up to 100 km (Schmidt, 2003). Ultra-fine particles are mostly generated from diesel cars and are concentrated locally, spreading over only short distances and decreasing with height above street level, and in residential areas away from trafficked roads. There are limited studies in literature on the difference in particle levels between rural, urban background and urban street settings. For example, measurements from Denmark in 2012 show that urban background levels of fine particles (PM2.5) are 10% higher and urban street levels 40% higher than those in rural backgrounds (Ellermann et al., 2014).

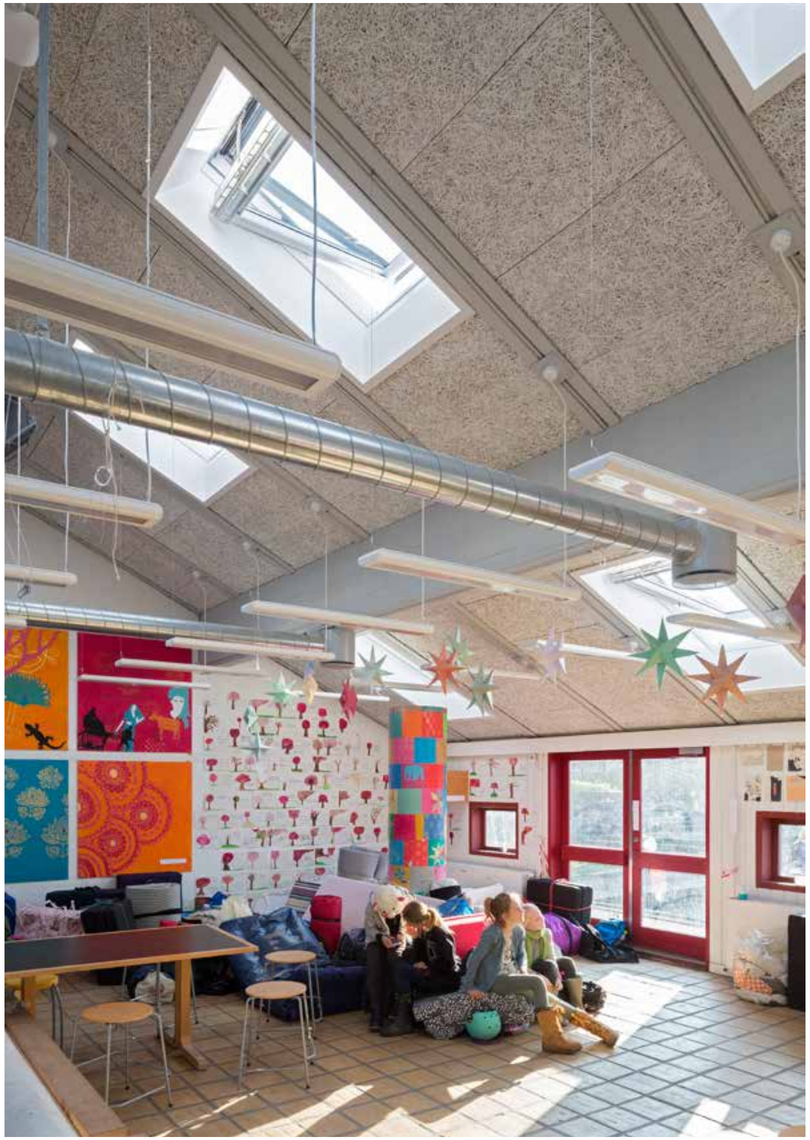
Other sources of pollution of indoor air should be included, along with ways of controlling them.

Keep it dry (humidity management)

Dampness in buildings is associated with an increased risk of adverse respiratory conditions (Bornehag et al., 2001). It is important to ensure that relative humidity indoors is kept at reasonable levels so as to limit the risk of mould and condensation in the construction - ventilation and source control can both help in this respect. Showering, cooking or an evening with guests raises humidity in the home, which needs to be removed by ventilation, ideally at source (e.g. cooking hood).

Ventilate well

Ventilation is an important means of achieving good indoor air quality in buildings, as it removes or dilutes pollution. As newer buildings have become more airtight and well insulated, there has been an increased focus on the ventilation system, either natural or mechanical, to ensure good indoor air quality. Ventilation is a compromise between energy consumption, health and costs. Too much ventilation will increase energy use in cold climates and cause draughts, while too little will cause bad indoor air quality and possible health problems.



Langebjerg school.

» Children are particularly vulnerable to poor air quality «

Airing with windows, using timers or sensors, in the morning, afternoon and before bedtime will help create good indoor air quality in the house.

2.1.2 Indoor air quality indicators

As described earlier, indoor air contains many pollutants. For many years, discussion has continued as to which indicator for indoor air quality is the most suitable. Carbon dioxide (CO_2) is probably the most commonly used indicator, measuring the CO_2 produced by human breathing and emitted by appliances such as gas cookers and boilers (CIBSE, 2011). Other indicators are humidity and volatile organic compounds (VOCs), both of which are possible indoor air quality indicators.

CO_2 as indicator of air quality

CO_2 is a good indicator of the indoor air quality in houses, where the occupants and their activities are the main source of pollution. Outdoor air contains approximately 400 ppm; breathing generates CO_2, so the indoor CO_2 concentration will always be at least 400 ppm and usually higher. An indoor CO_2 level of 1 150 ppm provides adequate air quality, 1 400 ppm will ensure good indoor air quality in most situations, and 1 600 ppm indicates poor air quality (CEN, 2007; Active house Alliance, 2013).

CO_2 is most relevant as an indicator in rooms where the need for ventilation is linked to the presence of people, e.g. in bedrooms, children's rooms, living rooms, dining rooms, classrooms and offices.

Humidity as indicator of air quality

The relative humidity indoors will vary on a yearly basis in correspondence with the humidity level outdoors. A high level of humidity in indoor air can increase the presence of house dust mites. So in climates with cold winters, the relative humidity inside should be kept below 45% during winter (Richardson et al, 2005). Generally speaking, high relative humidity levels should be avoided in order to limit the risk of mould growth, with negative health conditions such as asthma and allergies as a consequence (Liddament, 1996).

As humidity is considered to be the main pollutant in homes, it can be relevant to keep the indoor humidity level under observation. For some rooms, this can be done via the relative humidity but, in more advanced systems, the difference in humidity content between the indoor and outdoor air can be evaluated and used as an indicator.

Measuring relative humidity has been done for many years and is now a market standard. The indoor levels are generally high during summer and lower during winter. With the same ventilation rate during summer and winter, the indoor relative humidity will be very different from summer to winter. In other words, a fixed relative humidity as indicator for Indoor Air Quality has, some limitations and is most useful in wetrooms, where the objective is to avoid very high levels of humidity. Relative humidity is very relevant as indicator in bathrooms, and in kitchens.

In terms of absolute humidity, however, the difference between indoor and outdoor humidity content may be the best indicator, even though this will require indoor and outdoor sensors. In this case, a difference of 3.5 g of water vapour per m^3 of air is a reasonable level, and may be used all year to check if the humidity production in the home is balanced correctly with the ventilation rate. Measuring the difference in absolute humidity is not a market standard, so there are few products on the market.

VOC as indicator for air quality

Volatile Organic Compounds (VOCs) are substances that evaporate easily and are a mixture of many different chemicals such as benzene, formaldehyde and trichloroethylene (TCE). The effect on humans ranges from experiencing upleasant smells to severe health effects, e.g. as a cause of cancer.

There are two kinds of VOC sensors on the market: one that measures the actual VOCs in the air, registering odours, cooking and smoking fumes, and solvents; and one that correlates VOC levels with CO_2 levels coming from human activity which also generates VOCs. This fact, combined with the ability to detect smells, could make VOC sensors an alternative indicator for air quality to CO_2 as the VOC sensor is often cheaper in price.

It is generally difficult to quantify the limit levels of VOCs, which is more commonly often used in scientific circles; whereas VOC sensors correlating with CO_2 levels could be a good alternative to existing CO_2 sensors that evaluate human occupancy in buildings.

2.1.3 Health

To better understand the impact of indoor air on our health, we need to consider the amount of air we breathe per day. An average person consumes 2 kg of food and water per day – but breathes in 15 kg of air per day (12 000 litres). The health impact is thus clearly important (Nilsson, 2008).

90% of our time is spent indoors, so most of the air we breathe comes from indoor environments. And we spend a lot of time in our homes – 55% of the total intake of food, water and air during a lifetime consists of indoor air from our home, see in Figure 2.2 (Sundell, 2004b).

The individual or combined effects of the many compounds in indoor air on human health are not fully understood, but major research studies have shown that indoor air quality has an important impact on the health of humans in buildings.

Professor Jan Sundell of the International Centre for Indoor Environment and Energy at DTU (the Technical University of Denmark) says that "we do not know much about causative agents in indoor air, but there is mounting evidence that the indoor environment, especially dampness and inadequate ventilation, plays a major role from a public health perspective, and that the economic gains to society for improving indoor environments by far exceed the cost".

In Northern Europe, especially, asthma and allergy are becoming more and more common among children. This

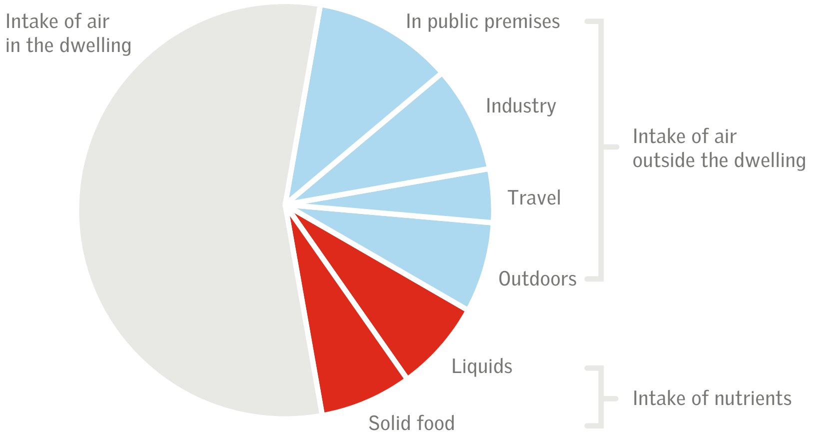


Figure 2.2 55% of the total intake of air, for a person is indoor air from our dwellings (Sundell, 2004b).

> **» Avoid high levels of humidity to ensure a healthy indoor environment «**

phenomenon has been studied by doctors and indoor environment scientists. One study investigated the prevalence of these illnesses among Swedish conscripts.

From the 1950s to the 1980s, a large increase in the number of persons with illnesses like asthma and allergy (prevalance)was recorded - see Figure 2.3. The trend has taken place too rapidly to be explained by genetic changes and must be attributed to environmental changes instead. No direct link to indoor air quality has been found, but most researchers recognise that a link exists (Bråbäck et al., 2004).

To emphasise the importance of healthy indoor air, the World Health Organisation (WHO) has adopted a set of declarations on "The right to healthy indoor air" (WHO, 2000).

Sick Building Syndrome

The term Sick Building Syndrome (SBS) is used to describe situations in which building occupants experience acute health and comfort effects that appear to be linked to time spent in a building, but where no specific illness or cause can be identified. The complaints may be localised to a particular room or zone, or be widespread throughout the building (Franchi et al., 2004).

The symptoms of these problems include headaches, eye- nose- or throat irritation, dry cough, itchy skin, fatigue and concentration difficulties. These symptoms are defined as SBS symptoms, and WHO concludes they are found in 15-50% of all buildings (Krzyanowski, 1999). A review showed that air-conditioned office buildings have a 30-200% higher prevalence of SBS than naturally ventilated buildings (Seppänen and Fisk, 2002).

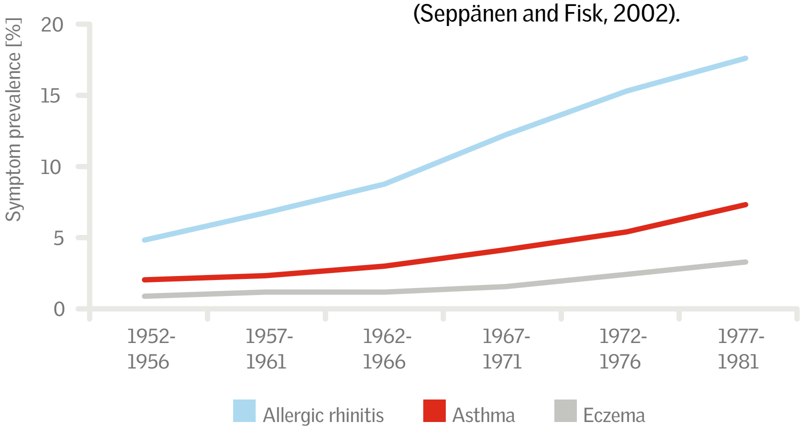


Figure 2.3 The prevalence of allergy, asthma and eczema among Swedish conscripts (young men who join the armed forces) (Bråbäck et al, 2004)

The symptoms are believed to be caused by poor indoor environments and can be helped by improving the air quality.

2.1.4 Increased airtightness requires occupant action

50-100 years ago, the houses in most of Europe were often leaky, which meant that their ventilation rate was often in the range of one air change per hour (ACH) without open windows. This led to high heating demands and the building codes have been focusing on reducing leakages since the 1960s. Measurements show that infiltration has been reduced, as illustrated by Figure 2.4.

Infiltration is the uncontrolled ventilation through leakages in a building, a measure of the airtightness of a building. Increased airtightness provides better energy performance, but buildings in Northern Europe today are generally so airtight that infiltration alone is far from sufficient to provide reasonable ventilation and good air quality. Consequently, building occupants need to actively ventilate their homes to achieve good air quality and a healthy indoor environment. It is important that the VELUX ventilation flap is used to ensure a reasonable background ventilation rate, and particularly that airings are performed several times a day. Children are particularly vulnerable to poor air quality, as was seen in section 2.1.3.

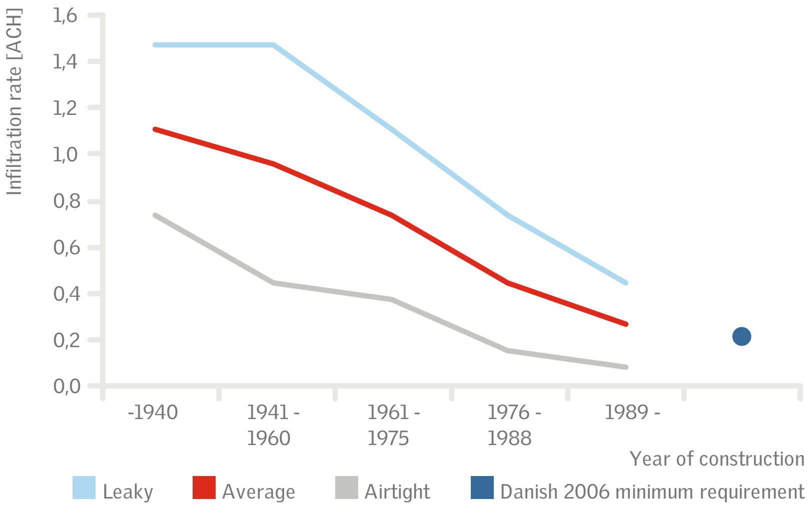


Figure 2.4 The prevalence of allergy, asthma and eczema among Swedish conscripts (young men that join the armed forces)

» Use VELUX INTEGRA® roof windows for automatic ventilation to ensure a healthy indoor environment «

Humidity in buildings can cause illnesses

Living or working in damp buildings are among the indoor air quality factors that are most likely to cause illnesses. Investigations thousands of houses have shown that damp buildings can cause illnesses such as coughs, wheezing, allergies and asthma. A damp building is a building with an increased humidity level (the exact risk level of humidity is not known). Figure 2.5. is an example of the effects of damp buildings – it shows how dampness increases the risk of allergy (Sundell, 1999; Wargocki et al., 2001).

Human activities such as cleaning, cooking and bathing add moisture to indoor air, resulting in the air indoors containing more moisture than the air outdoors. The activities of a family of four typically add ten litres of water to the indoor air – per day (British Standard, 2002).

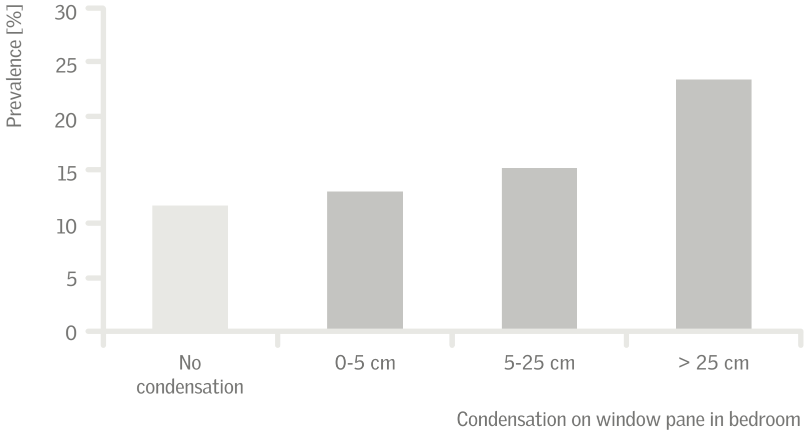


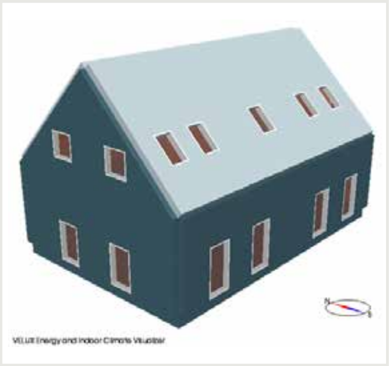
Figure 2.5 Shows the amount of condensation seen on the inside of bedroom windows and how this affects the prevalence of allergic rhinitis among children living in the houses (Bakó-Biró and Olesen, 2005). It is important to notice that condensation is an indicator of dampness in the room; condensation on the window pane is, by itself, not problematic for health (Wargocki, 2011).

❗ Remember

The moisture production from a typical family is 8-10 litres per day – this corresponds to emptying a large bucket of water on the floor every day. It should be removed with adequate ventilation to reduce the risk of illnesses.

There is no clear scientific explanation of exactly how dampness has an impact on health. It is well-known, however, that house dust mites thrive in humid indoor environments. House dust mites are a well-known cause of allergy, and to reduce this risk, the relative humidity should be kept below 45% for several months a year (Sundell et al., 1995).

The ventilation rate is a compromise between energy demand and a healthy indoor environment. In figure 2.7 we saw that high ventilation rates could improve human health. But high ventilation rates also increase the heating demand in climates with cold winters, as shown below.



Example: effect of ventilation rate on heating demand.

A house in Stockholm, Sweden, is investigated with VELUX Energy and Indoor Climate Visualizer. The heating demand is determined for a ventilation rate of 0.5 and 0.7 ACH. The heating demand rises by 21% when the air change rate is increased from 0.5 to 0.7 ACH.

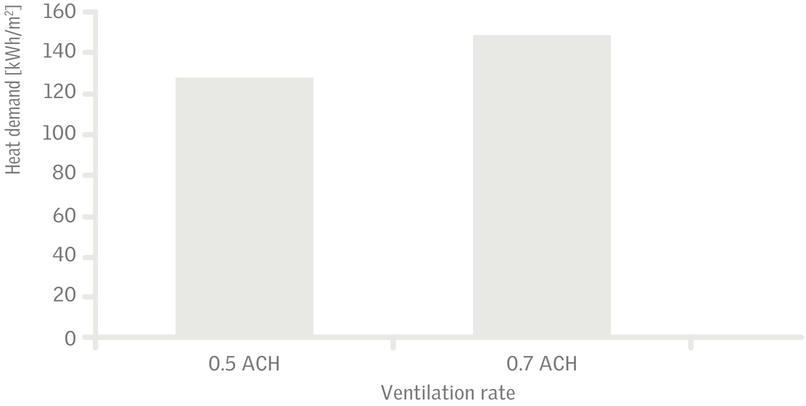


Figure 2.6 Heat demand at 0.5 and 0.7 ACH in a house in Stockholm

Low ventilation rates can cause illnesses

The ventilation rate is an indicator of how frequently the indoor air is changed in a house. If the ventilation rate is below 0.5 ACH, as typically required in the North European building legislations (Mathisen et al., 2008), there is an increased risk of becoming ill with dampness-related illnesses sich as asthma and allergies, as seen in Figure 2.7.

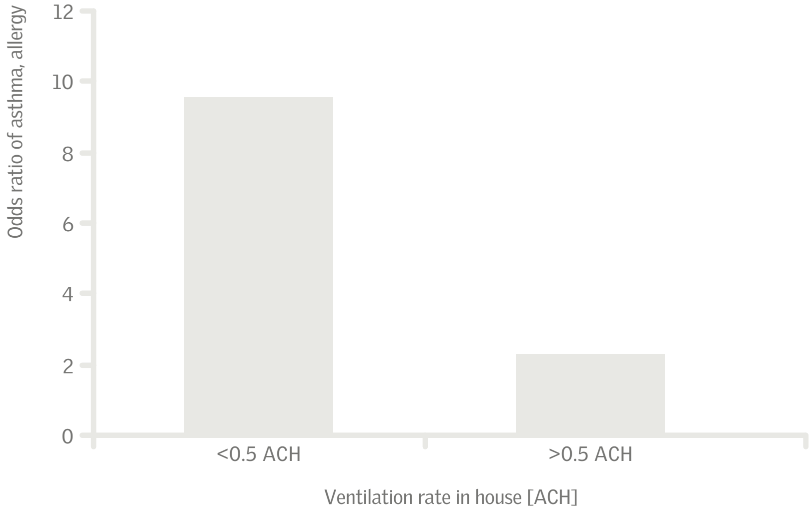


Figure 2.7 The odds ratio is an expression of probability. The figure shows the risk of becoming ill with asthma. Allergy increases in houses with a ventilation rate below 0.5 ACH (Öie, et al. 1999).

! Remember

Good indoor air quality is a precondition for preventing important illnesses like asthma and allergy, especially among children.

2.1.5 Mental performance and indoor air quality

Investigations on the mental performance of occupants in office buildings and schools have shown that poor air quality reduces mental performance, while good air quality improves it (Seppanen and Fisk, 2006; Seppanen et al., 2009) – see Figure 2.8.

It can be assumed that if the indoor environment was productive to work in, it would also support our ability to concentrate and stay focused elsewhere. At home, we engage in activities that require concentration – like reading, playing games and listening to music – that can be expected to benefit from an indoor environment that supports productivity.

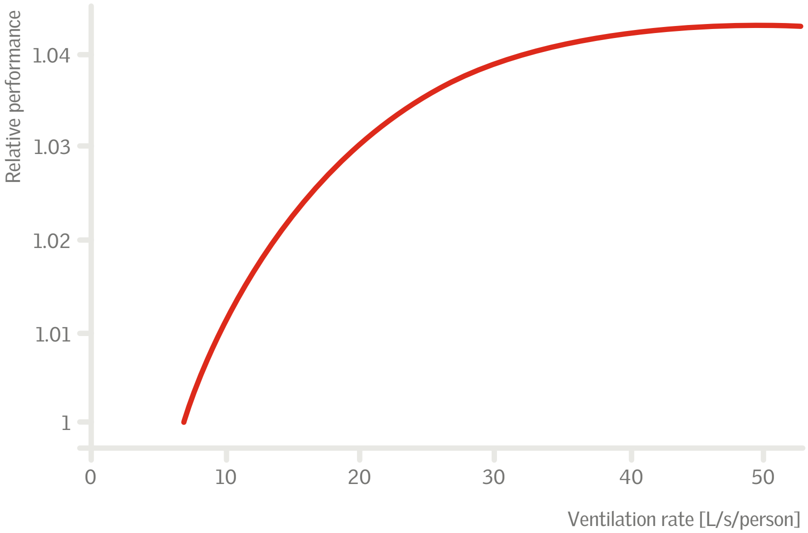


Figure 2.8 The performance of students in schools improves when the air quality is improved by increasing the ventilation rate (Seppanen et al, 2009).

2.2 Ventilation and ventilation systems

There are several ways to bring fresh air into our homes. Ventilation systems can be natural, mechanical or hybrid (a combination of the two).

There are two ways to ventilate or cool buildings: actively or passively. Active ventilation/cooling refers to systems where mechanical components or other energy-consuming components (such as air-conditioning systems) are used. Passive ventilation/cooling is a technology or design feature used to ventilate/cool buildings with no energy consumption (e.g. natural ventilation by openable windows).

Passive cooling is a measure that uses no energy to cool buildings. It involves at least three concepts:

- Solar shading
- Thermal mass
- Ventilative cooling

Passive cooling techniques are described further in chapter 3 Thermal Comfort.

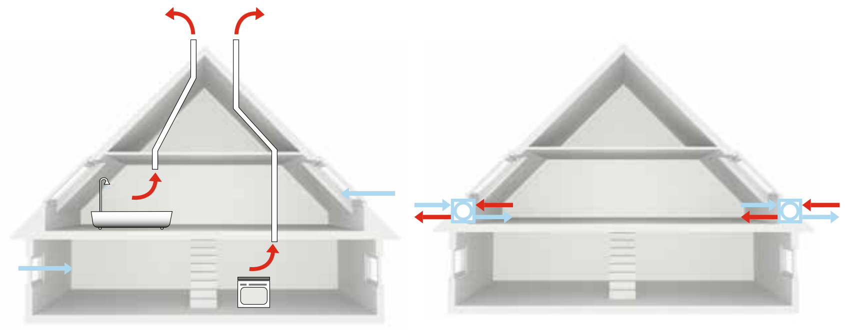
2.2.1 Natural ventilation

Natural ventilation uses natural forces to exchange the air in a building. The driving forces are wind and temperature differences, as explained further **in section 2.4.1.**

In residential buildings, air is often supplied through the facade and extract air is removed from selected rooms (often kitchen and bathrooms) through ducts, as illustrated in Figure 2.7.

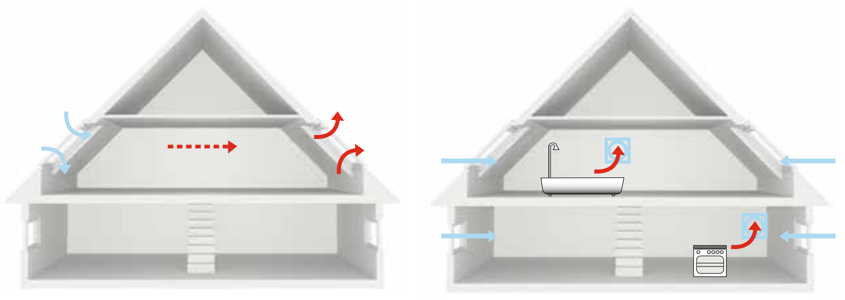
The air supply can be through fresh air grilles in the facade or through the ventilation flaps of VELUX roof windows. It can also enter through leakages in the facade.

It is important to ensure an efficient air flow path through the building, see section 2.5.1.



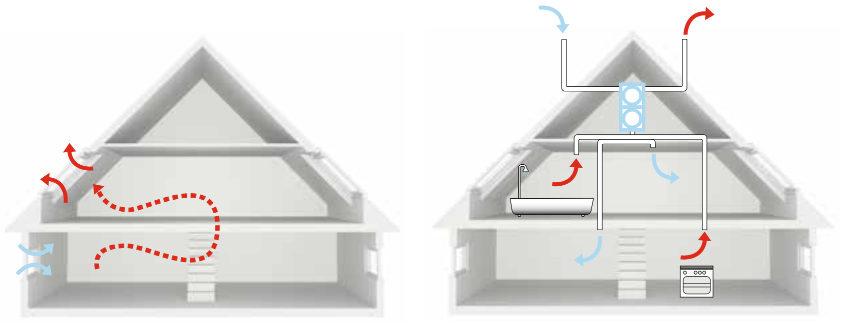
Natural ventilation:
Background ventilation with stack ducts

Mechanical ventilation:
Balanced decentral supply and extract



Natural ventilation:
Cross-ventilation with open windows

Mechanical ventilation:
Decentral extract



Natural ventilation:
Stack effect with open windows

Mechanical ventilation:
Balanced central supply and extract

Figure 2.9 Common natural and mechanical ventilation systems

» Hybrid ventilation combines the best of natural and mechanical ventilation in newbuilt houses «

2.2.2 Mechanical ventilation

Mechanical ventilation systems use electric fans to direct the airflow in the building. Mechanical ventilation can provide a constant air change rate independently of external weather conditions, but it uses electricity and usually cannot change the ventilation rate as the need changes over the day and year.

Several variations exist, as illustrated in Figure 2.9. Systems with both supply and extract can be combined with a heat recovery unit, which recovers (reuses) the heat of the extract air that would otherwise be lost. Up to 90% of the energy can be 'reused'.

It is becoming a standard solution in many North European countries for newbuilt houses to be provided with mechanical heat recovery ventilation in order to meet current energy requirements. This is a very energy efficient solution for the heating (winter) season. However, in the summer season, electricity for running of fans can be saved by using natural ventilation. Systems shifting between natural ventilation and mechanical ventilation are called hybrid ventilation systems.

Mechanical ventilation requires filters to be changed regularly. Dirty filters are a source of pollution of the indoor air and reduce indoor air quality, which, in turn, reduces the performance of the occupants of the building and increases the prevalence of SBS symptoms (Wargocki et al., 2002; Bekö, 2009).

It has been found that SBS symptoms occur more frequently in buildings with air conditioning than in naturally ventilated buildings (Wargocki et al., 2002). If a mechanical ventilation system with heat recovery is to perform energy efficiently, the building must be perfectly airtight. If it is not, a substantial part of the ventilation will come from infiltration, which bypasses the heat exchanger. So mechanical ventilation with heat recovery is often not an energy-correct solution for existing buildings – unless they are made more airtight.

Mechanical ventilation systems can be central or decentral. Central systems have one central unit, with supply and extract fans; if the system has heat recovery, the heat recovery unit is included in the central unit. Ventilation ducts are installed from the unit to most rooms of the house. Decentral ventilation does not use ducts; instead, small units, which can include heat recovery, are installed in individual rooms of a house. Such a system has the advantage of not requiring space for ducts.

2.2.3 Hybrid ventilation

Hybrid ventilation is is a system that combines natural and mechanical ventilation. Hybrid ventilation is a relevant solution for new residential buildings, especially if roof windows are available to facilitate stack effect. Several variations of hybrid ventilation systems exist.

Combined natural and mechanical ventilation

Mechanical ventilation is used in the heating period and natural ventilation in the rest of the year. This principle provides a good energy performance for newbuilt houses and works well in combination with VELUX roof windows.

Fan-assisted natural ventilation

This principle is mainly used in larger commercial buildings where the natural driving forces are inadequate in some periods. A fan is therefore used for assistance.

Stack- and wind-assisted mechanical ventilation

This principle is also used mainly in larger commercial buildings, where the ventilation system is designed with ducts to transport the air, and natural driving forces provide most of the airflow – with fans used for assistance.

Hybrid ventilation is used to optimise the indoor environment while reducing energy costs. As mentioned, mechanical ventilation with heat recovery is used in new houses to reduce the heating demand and to allow the house to meet energy requirements for heating. But during the warm part of the year, it is more energy efficient to use natural ventilation to reduce the electricity demand for the electric fans.

Furthermore, open windows are appreciated by most users in the warm part of the year.

Hybrid ventilation combines the best of both worlds: good winter energy performance with mechanical heat recovery ventilation, and good summer performance with natural ventilation.

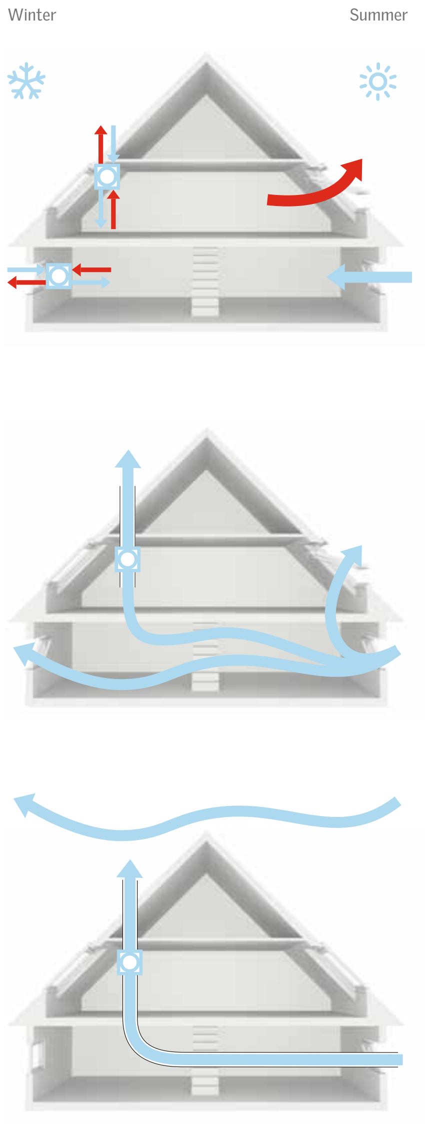


Figure 2.10 Three principles of hybrid ventilation systems [(Heiselberg, 2002).

Example: using hybrid ventilation to save energy

An example of how much energy can be saved with hybrid ventilation compared to mechanical heat recovery ventilation.

Typical houses in Istanbul, Paris and Copenhagen are being investigated. Natural ventilation is used whenever it is warm enough to make heat recovery ventilation unnecessary (Foldbjerg et al., 2010).

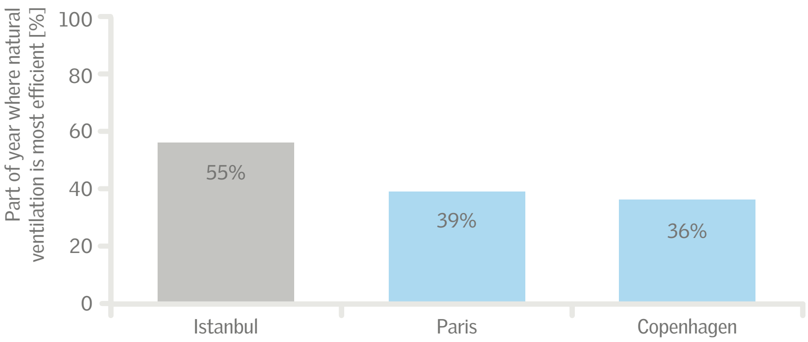


Figure 2.10 In Paris and Copenhagen, natural ventilation is more energy efficient than heat recovery ventilation for 36%-39% of the year; in Istanbul, that figure is 55% of the year.

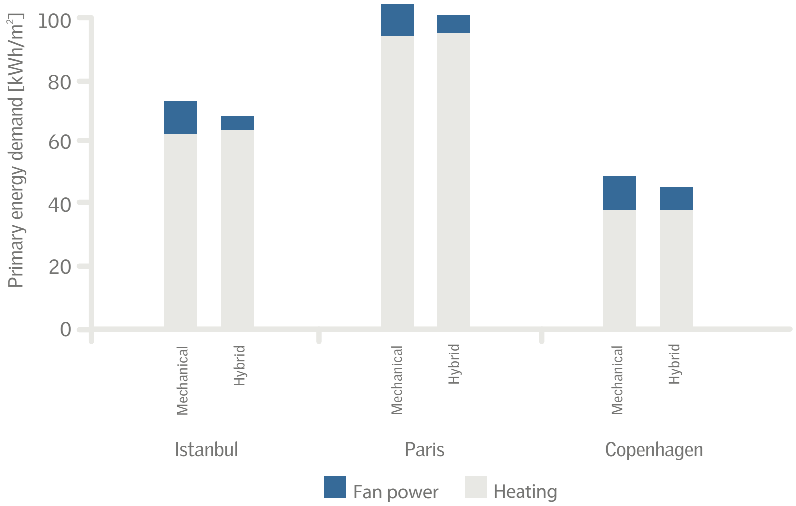


Figure 2.12 Hybrid ventilation is more energy efficient than mechanical heat recovery ventilation in Istanbul, Paris and Copenhagen.

The annual primary energy savings range from 3 kWh/m² in Paris to 5 kWh/m² in Istanbul. This is compared to the maximum primary energy demand in the table below. Three periods of construction are being invesitgated, and it can be seen that the relative reduction increases from 5% for a recent building to 9% for a future building.

	Total maximum primary energy demand for a 150 m² house	Relative reduction from a saving of 4 kWh/m² with hybrid ventilation
2005	85 kWh/m²	5%
2010	61 kWh/m²	7%
2015	42 kWh/m²	9%

Figure 2.12 Potential primary energy savings by using hybrid ventilation instead of mechanical ventilation with heat recovery. Based on requirements from the Danish building code (Danish Enterprise And Construction Authority, 2010)

For newbuilt houses, hybrid ventilation can be a very cost-efficient solution to reduce the energy demand and make the house meet the energy requirements. To achieve a low energy demand, the alternative to hybrid ventilation could be additional insulation, photovoltaics etc., which may be more costly solutions.

Remember

Hybrid ventilation is more energy efficient than mechanical ventilation with heat recovery because of the saved electricity in the summer time.

2.2.4 Demand-controlled ventilation

In reality, the need for ventilation changes constantly and the ventilation rate should be increased when cooking, cleaning or many people are present in the house. When the house is left during the day, the need for ventilation is reduced.

Example: effect of air change rate on air quality

A house in London is investigated with VELUX Energy and Indoor Climate Visualizer. It is occupied by five people, and has an internal floor area of 175 m². The CO_2 level is determined for two constant air change rates: 0.3 ACH and 0.5 ACH.

	Average CO_2 level	Average relative humidity in December, January and February
0.5 ACH	728 ppm (very good)	42% (good)
0.3 ACH	943 ppm (just acceptable)	59% (too high)

The results show that at 0.5 ACH, the CO_2 level will be below 750 ppm, which indicates that the air quality will be very good. At 0.3 ACH, the CO_2 level will be above 900 ppm, which indicates that the air quality is just acceptable for existing buildings and could be improved. At 0.5 ACH, the relative humidity averages 42% during the winter months, while it is 59% for 0.3 ACH. Recommended relative humidity for this part of the year is below 45%; this is achieved at 0.5 ACH, but at 0.3 ACH the relative humidity is too high, which means that there is a risk of mould growth and an increased risk of moisture-related illnesses.

For the investigated house, the air quality will be very good at a ventilation rate of 0.5 ACH and poor at 0.3 ACH.

Remember

For residential buildings, the ventilation rate can be controlled based on the humidity level and CO_2 concentration. The actual need for ventilation changes constantly and demand-controlled ventilation will provide the best compromise between air quality and energy consumption.

» Opening windows is more than just ventilation – opening a window creates the link to the outside and is a symbol of affection for your family «

2.3 Fresh air from outside

There are many important issues in ventilation science other than the strictly technical. There is the basic human need for access to ventilation. Scientific work shows that ventilation with windows or 'fresh air from the outside' is not about 'fresh' or 'air', but rather deals with the notion of creating a 'good indoor environment'. Something that obviously involves many other aspects than fresh air.

The subjects of the different aspects of fresh air are typically divided into three main elements; a functional (practical), an aesthetic (bodily and sensory) and a social (care and impression management) element.

The functional element is related to practical pursuits, like airing out after bathing, washing the floor and doing the beds - but also being able to act in dialogue with the weather and the house itself.

The aesthetic element includes both a bodily and sensory perspective. Factors like regulation of body heat and being able to smell oneself are important. Not only the odour backdrop (good, fresh smell) in the house from activities, but also the enjoyment of a breeze in the home.

The social element deals with the strong wish to be in control. Showing concern for your family's health by airing your home, enjoying the feeling of freedom by being able to open the windows – but also letting in the sounds and scents from outside.

Three very important aspects that all deal with non-technical issues show us that openable windows are a necessity for the indoor environment on many human levels.

Another human aspect is the ability to open the window in the transition periods of our everyday lives – like coming from work to home, going from sleep to waking up or returning home from vacation. Routines and unreflected actions are a part of the transitions – and here opening of windows has been shown as one of the actions that we need to perform.

Home for Life.

2.4 Natural ventilation with roof windows

2.4.1 Driving forces of natural ventilation

Natural ventilation is driven by temperature differences and wind pressure.

Stack effect (temperature difference)

Warm air is lighter than cold air. That causes the stack effect, which means that warm air inside a building will rise. The warm air will leave the building at the top through leakages, stack ducts or open windows and be replaced by cold air entering the building at ground level. The higher the building, the more powerful the stack effect. For the stack effect to work efficiently, there must be air passages through the building.

These can be stairways in combination with windows at both ground level and roof level that can be easily opened at the same time. Due to their position in the roof, VELUX roof windows maximise the ventilation potential of the stack effect.

See section 2.4.3 for an example of stack effect.

Wind (wind pressure)

When a building is exposed to wind, air will enter the building at the windward side and leave through openings at the leeward side. The wind pressure is higher on the windward side than on the leeward side. This will drive air from the windward side of the building through the building to the leeward side. The shape of the building and the surrounding landscape or buildings have an impact on the air flow. The magnitude of the pressure difference generated by wind pressure is determined automatically as part of a simulation in tools like the VELUX Energy and Indoor Climate Visualizer. Typical values can be found in standards (e.g. BS5925:1991, DIN19466:2009).

See section 2.4.3 for an example of wind driven natural ventilation.

Remember

The higher the windows are placed and the larger the temperature difference, the more powerful the stack effect. Therefore, in a building that uses VELUX roof windows for natural ventilation, the stack effect is greater than in a building with only facade windows.

Example from MH 2020:
In the French Model Home, Maison Air et Lumière (MAL), the indoor air quality was evaluated with special focus on the effects of the natural ventilation system during summer. The evaluation was based on the occupied period from September 2012 to August 2013 for the family of four living in the house, with CO_2 levels evaluated to Active House specifications, 2nd edition (Active house, 2013).

There was a general tendency towards better indoor air quality (indicated by lower CO_2 levels) in summer using natural ventilation than in winter using mechanical ventilation. It was shown in the bedrooms, living spaces and mezzanine that openable roof windows help maintain low CO_2 levels. See figure 2.13 below for mezzanine 2 (Plesner et al, 2014).

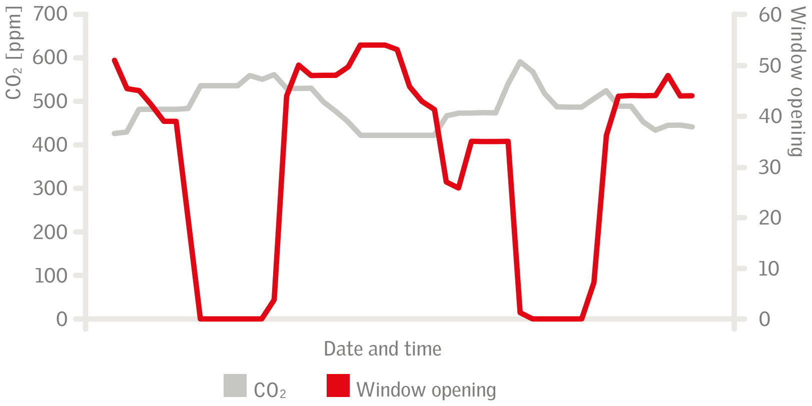


Figure 2.13 Window opening degrees and CO_2 levels for mezzanine 2 (1st floor) in June 2013.

The living room is also shown as a temporal map, illustrating that, for the vast majority of hours when roof windows are open, CO_2 levels below 1 150 ppm (green), are achieved, which, in this case, is considered as satisfactory indoor air quality. There are no periods with open windows and high CO_2 levels.

MAL 2012-13, Living room "VRW"

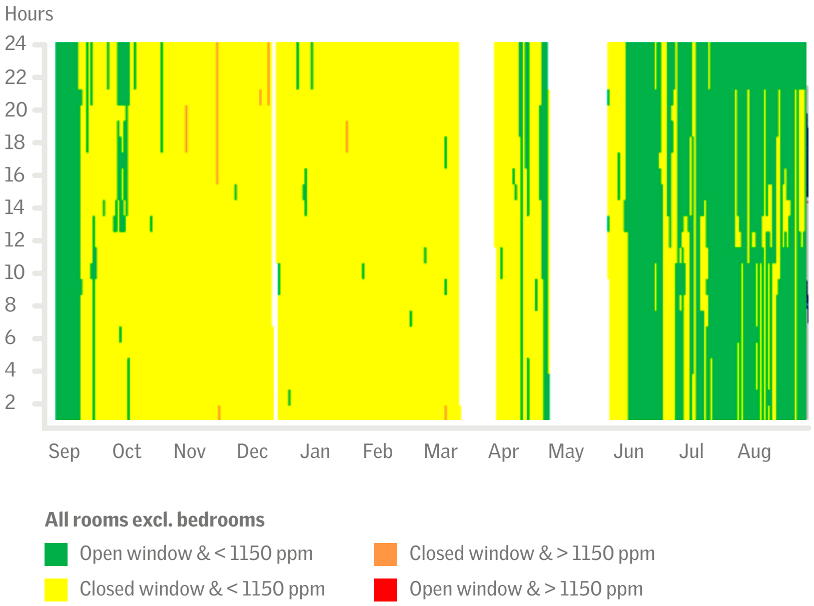


Figure 2.14 Window opening and CO_2 levels for roof windows in living room

All the rooms in MAL were evaluated and achieved category 1-2 (<1 150 ppm) in summer for 95% of the time and category 1-2 for the entire year. The results show a satisfactory indoor air quality for the house. See figure 2.15 below.

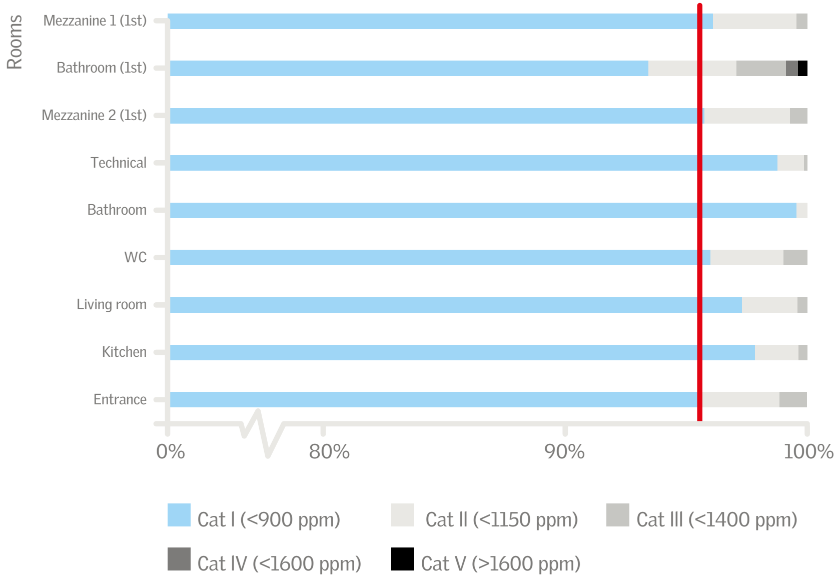


Figure 2.15 All-year average CO_2 levels for all rooms and for all hours excl. bedrooms

2.4.2 Background ventilation with the VELUX ventilation flap

The ventilation flap on VELUX roof windows can be used to provide a continuous flow of fresh air into the building.

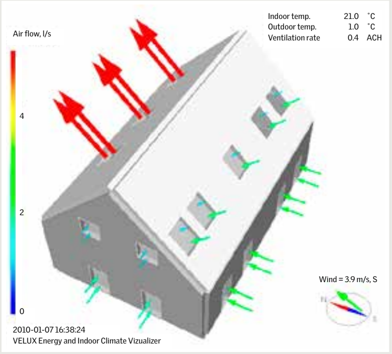


Figure 2.16 Animation of ventilation flows by VELUX Energy and Indoor Climate Visualizer

Example:

Background ventilation with ventilation flap
The example investigates the background ventilation rate that can be achieved with different numbers of roof windows per floor area. Two ratios of windows to floor area are used, i.e. 10% and 20%. The house is in Berlin, Germany.

Figure 2.16 shows the ventilation flows on 7 January, with outflows in the range of 2-6 l/s per window.

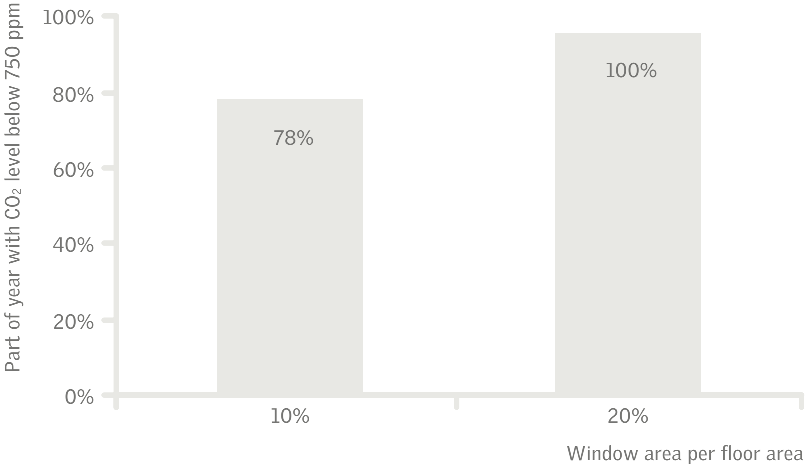


Figure 2.17 The part of the year with a CO_2 level below 750 ppm is used as an indicator of good air quality. This is achieved for 78% of the year with 10% windows to floor area, while it is increased to almost 100% with 20% window area to floor area ratio.

2.4.3 Airing

An airing is a short period with a high ventilation rate due to one or more open windows. Airing removes odours and humidity efficiently at the time and place of generation. The effect of airing depends on how many windows are opened and how they are located in relation to each other. The most efficient airing is when stack effect and wind pressure are used by opening windows at opposite facades and different heights.

Example: airing

Ventilation rates achieved with airing are calculated with the VELUX Energy and Indoor Climate Visualizer. Four windows used for airing, and the ventilation rates achieved with single-sided airings, cross-ventilation and stack ventilation are found for a summer and a winter situation. The house is located in Berlin, Germany.

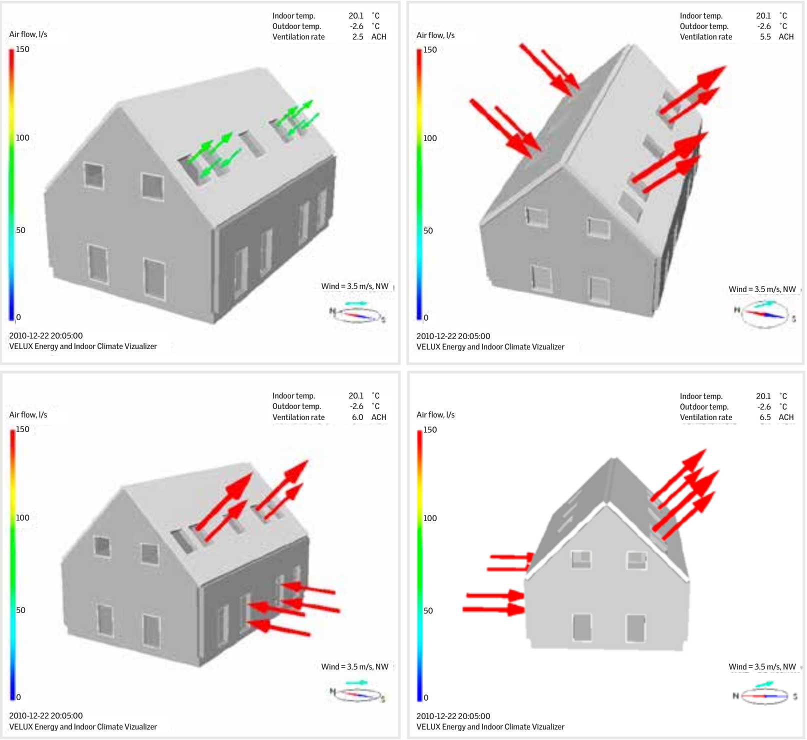


Figure 2.18 Animation of window air flows calculated with VELUX EIC Viz

The images from the animation of ventilation on 22 December during the morning airing show single-sided, cross-ventilation, stack effect and combined stack effect and cross-ventilation. The ventilation rates that occur during the airing are shown in the table below.

	Typical summer day: 3 August	Typical winter day: 12 December
Single-sided	1.5	2.5
Cross-ventilation	2.5	5.5
Stack effect	4.5	6.0
Combined stack and cross-ventilation	5.0	6.5

The ventilation rates achieved with airings are in the range of 1.5 ACH to 5.0 ACH, which is up to ten times higher than the background ventilation rate of 0.5 ACH. The highest ventilation rates in the example were achieved with combined stack effect and cross-ventilation (5.0 6.5 ACH), then stack effect (4.5 – 6.0 ACH), followed by cross-ventilation (2.5 – 5.5 ACH) and single-sided ventilation (1.5 – 2.5 ACH). These ventilation rates are based on specific opening areas. Larger ACH values can be achieved with larger opening areas, which is mainly relevant for ventilative cooling purposes. In the French Model Home, Maison Air et Lumière (MAL), values up to 20 ACH were measured during the summer 2012 (Favre et al., 2013).

The effect on the air quality with combined stack and cross-ventilation is investigated. The part of the year with a CO_2 level below 900 ppm is determined, as well as the additional energy demand (and associated cost). A gas price of 0.085€/kWh is used (Europe's Energy Portal, 2010).

	Part of year with CO_2 level below 900 ppm [%]	Heating demand [kWh/m²]	Energy costs [€/m² per year]
Without airings	62	45.9	3.9
With airings	77	50.3	4.3

The results show that airings increases the part of the year with a CO_2 level below 900 ppm from 62% to 77%, - a substantial increase of 24%. The energy costs increase from 3.9 to 4.3 €/m² per year – a 10% increase.

Remember

Airing through windows is efficient and relevant in many situations:

- In the morning when you get out of bed
- When cooking
- During and after showers
- During and after cleaning
- When drying laundry indoors
- In the afternoon when you return home

2.4.4 Optimal winter ventilation strategy for existing buildings

The ventilation flap can be used to provide background ventilation, which will achieve good indoor air quality when the house is not used to its full capacity. During activities like cooking, cleaning and showering airings should be used. A combination of VELUX roof windows and facade windows provides efficient airings with stack effect and cross-ventilation. The combination of background ventilation and airings is the best strategy to achieve good air quality at a reasonable energy demand, as short airings are more efficient than continuous ventilation (Heiselberg and Perino, 2010; Perino and Heiselberg, 2009).

Airings can cause draughts, but by making short and efficient airings, the problem can be minimised.

See design advice for specific building types in section 2.5.

2.4.5 Summer ventilation

In warm summers, natural ventilation can be used to maintain a comfortable indoor temperature. In this situation there is no heat loss to consider – on the contrary, there is a potential for saving energy for cooling, with air conditioning, if it is installed in the building.

Increased ventilation rates in summer prevent overheating and the increased air motion is pleasant when it is warm. See section 3.5.3 in the Thermal Comfort chapter for an example of use of both solar shading and natural ventilation to maintain thermal comfort. The large air flow rates provided by natural ventilation during summer facilitate very low CO_2 levels in the indoor air – at no energy cost.

The use of natural ventilation to improve thermal comfort in warm periods is explained in more detail in the Thermal Comfort chapter.

See design advice for specific building types in section 2.5.

Remember

Use a combination of background ventilation through the ventilation flap and 2-4 airings per day to achieve the best indoor air quality

2.4.6 Automatic window opening with VELUX roof windows

The VELUX INTEGRA and SOLAR windows can be programmed to open automatically. This can be very helpful in a busy daily routine, where there might not always be time to do the required airings.

Windows in selected rooms of the house can be programmed to open for, say, 10 minutes in the morning and the afternoon, and at midday on weekends. The ventilation flap can be programmed to open when the occupants are at home, or during the entire day or night, to provide background ventilation. Windows installed in bedrooms can be programmed to open the flap during the night. If the occupants accept that the window is opened during the night, a few automatic airings can be programmed during the night as well.

Remember

A consequence of the increased airtightness of buildings is the increased need for additional ventilation in order to obtain a good and healthy indoor environment.

2.5 Ventilation of different building types

Basic human needs are are independent of the building type, but the way ventilation is used to meet those needs can depend on the building type. This is discussed in the following sections.

2.5.1 Renovation of residential buildings

Renovation of existing residential buildings can be performed at different levels.

- Renovation of one room at a time, which can include replacement of windows in the particular room, improved airtightness of building envelope and interior upgrade
- More extensive renovation, which can include additional insulation, replacement of all windows in the house, improved airtightness and more.

Many houseowners are intereted in improving energy performance as part of the renovation. This can have consequences for the ventilation of the house and, therefore, on the indoor air quality. By improving airtightness and replacing old windows with new windows, the unintended infiltration is reduced. This requires that other measures be taken to ensure adequate ventilation. The right ventilation depends on the type of room. Most existing residential buildings use natural ventilation, and the following is based on that assumption.

Bedrooms

Bedrooms are characterised by being a relatively small rooms where people spend a long time, typically 6 to 8 hours per 24-hour period. The bedroom is the room where we spend the most time during our lives. It is very important for our health to ensure adequate ventilation of bedrooms. Many residential buildings have insufficient ventilation of bedrooms even before they are renovated. To ensure adequate ventilation by natural ventilation, at least two windows should be installed. The windows should have ventilation flaps or grilles that can be opened during the night for as much of the year as possible. Windows at two different heights in the room will perform much better than two windows at the same height; they enable the stack effect to work. However, ventilation flaps alone will not always be sufficient to ensure adequate air quality in a bedroom.

Electrically operated windows (VELUX INTEGRA®) provide much better opportunities than manually operated windows, as they can be programmed to make one or two airings during the night. Decentralised, mechanical ventilation can be considered.

The ventilation rate of the bedroom during the night is higher when the bedroom door is open. A study of ventilation rates in typical houses showed the following ventilation rates for different door positions. Closed door: 0.3 ACH; Door ajar: 0.4 ACH; Door open: 0.5 ACH (Bekö et al., 2011).

Children's rooms

The use of a children's room depends greatly on the age of the child, and whether it is used for sleeping only or also for homework, play or entertainment during the day. There are often many toys and electronic appliances in this room, which increases the need for ventilation due to emissions. But children are often unaware of the importance of ventilation. The considerations that are given for bedrooms also apply to children's rooms, but with the additional emphasis on high airings discipline – which many families with children do not have time for. So electrically operated products are particularly relevant in this room.

Living and dining rooms

Living and dining rooms typically have more floor area per person than bedrooms, and we spend less time in living rooms than in bedrooms. This makes it easier to provide adequate ventilation of living rooms. The ventilation must often meet comfort requirements (feeling of fresh air) rather than health requirements. The need for ventilation in a living room can change from low to very high (with guests in the house), and the ventilation design must reflect that. A flexible ventilation design includes two to three operable facade windows and a similar number of roof windows to allow efficient airings when the need is high. Manually operated windows may be sufficient if ventilation flaps are used in combination with a reasonable use of airings. Electrically operated windows can provide additional peace of mind.

Kitchens

Activities in the kitchen generate humidity, smell and fine particles, all of which are most effectively removed by efficient ventilation at the time of the activity. Cooking hoods are important, but their performance is reduced as they get dirty from grease, and airings while cooking is a good habit and an efficient supplement. The airings are most efficient when windows located at two different heights can be opened, e.g. facade windows and roof windows. Due to the heat generated by ovens and stoves, cold draughts are rarely a problem in kitchens. As the need for ventilation is usually easy to sense and smell, it is simple for occupants to make airings at the right time. Humidity-controlled electrically operated windows can be an additional benefit.

Bathrooms

Bathroom activities produce humidity and smells. Mumidity generation is high during baths, but bathrooms are not used much during a 24-hour cycle. An efficient ventilation design therefore allows high ventilation rates for short periods. Bathrooms are often equipped with mechanical extract ventilation, but good possibilities for airings are an advantage. The most efficient airings are achieved with windows at two different heights. As the need for ventilation is usually easy to sense and smell, it is simple for occupants to make airings at the right time. Humidity-controlled electrically operated windows can be an additional benefit.

Natural ventilation exhaust path

In houses with natural ventilation, it is important to consider the flow path of the air in the house when it is renovated. The flow path depends greatly on wind direction, wind speed and external temperature conditions, and a specific window can function both as inlet and extract. However, high-placed windows (and stack ducts) will function mainly as extracts.

In one-storey houses, roof windows in kitchens and bathrooms will often function as extracts and will ensure that air is generally taken into the house through bedrooms and living rooms and extracted through wet rooms.

In two-storey houses, windows at the upper level will often function as extracts. If bedrooms are located on the upper floor, it is important that bedroom windows are not used as extracts, as this may cause overheating and will increase the risk that the air entering the bedroom is from other rooms in the house and therefore less fresh. An efficient solution is to place a roof window above the staircase on the upper floor, as this window will often function as an extract for the lower level.

2.5.2 New residential buildings

The choice of ventilation system in new residential buildings is often heavily influenced by energy legislation and by the energy performance ambitions of the future houseowner. In Northern European countries, mechanical ventilation with heat recovery is becoming a de facto standard, thanks to its ability to reduce heating demand during winter.

Natural ventilation remains the most energy-efficient ventilation system during summer in all European countries, as there is no heat loss and no demand for electricity to drive fans.

In new residential buildings, both mechanical and natural ventilation can meet legislative and performance requirements. Natural ventilation can be the primary mode of ventilation or a supplement to mechanical ventilation.

In situations where mechanical ventilation is selected as the primary ventilation system, it is important to emphasise that natural ventilation is an important addition. Including natural ventilation in the ventilation design of a new building provides these particular benefits:

- No use of electricity in warm part of year (energy-neutral ventilation)
- Increased indoor air quality in warm part of year, as the air change rate can be increased during summer at no additional energy cost
- Allows efficient airings when activities create a specific need for ventilation (e.g. bathing, cooking)
- Provides contact to the outdoor environment and a sense of fresh air (see section 2.3)
- Efficiently prevents overheating through ventilative cooling (see the Thermal Comfort chapter)

Many of the considerations on renovation of existing buildings discussed in the previous section 2.5.1 also apply to new buildings.

MH2020 example of bedrooms

The indoor air quality of the bedrooms in Maison air et Lumière has been evaluated for night hours only, in this case shown below where CO_2 levels are generally lower in summer than in winter. Category 2 is mostly achieved for the majority of the months, although June has elevated CO_2 levels. Overall results show that demand-controlled natural ventilation using VELUX INTEGRA® roof windows can create satisfactory indoor air quality in bedrooms during night (Plesner et al., 2014).

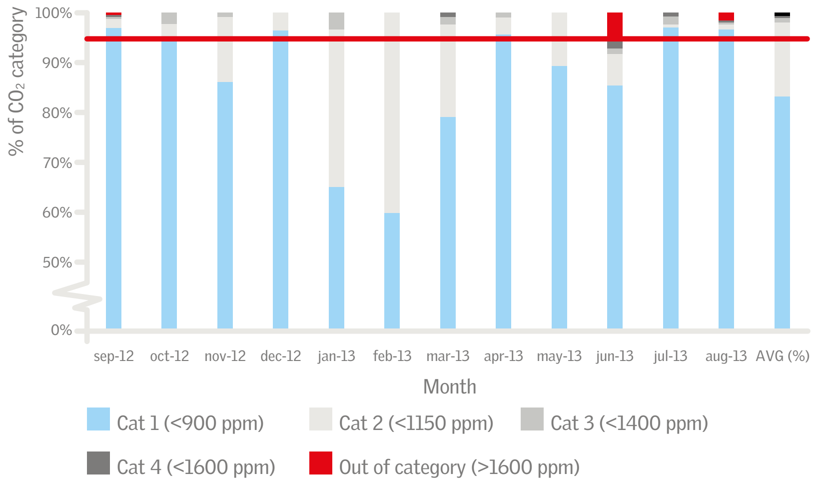


Figure 2.19 Monthly CO_2 levels for bedroom B (1st floor) for night hours in MAL

2.5.3 Schools and kindergartens

Schools and kindergartens are characterised by relatively few m² per person in classrooms and activity rooms, and by a predictable use of the rooms based on predefined schedules. Furthermore, schools and kindergartens are often public buildings with limited budgets, both for construction of new buildings and for renovation of existing buildings. There can be legislative requirements to minimum ventilation rates or maximum CO_2 concentrations.
To ensure a well-performing natural ventilation system for a classroom, the window opening area in relation to the number of students and the floor area are the key design parameters. As much opening area as possible should be achieved. Single-sided ventilation by facade windows alone can be challenging - much better performance is achieved in combination with roof windows. The performance can be verified by a simulation in VELUX Energy and Indoor Climate Visualizer, which determines CO_2 concentrations.

The following considerations can be used to optimise the design:

- Natural ventilation will typically provide a cost-efficient solution

- The breaks between lessons can be used for airings. They should use the maximum window opening area to minimise CO_2 concentration before the next lesson

- During lessons, ventilation flaps and grilles can be used. Students can be sensitive to thermal discomfort, and draughts can limit their use during cold periods

- Visual indicators of the CO_2 concentration, e.g. as a red-yellow-green "traffic light" make students and teachers open windows more frequently and improve the air quality (Wargocki et al., 2012)

- Automatically controlled natural ventilation allows the full potential for natural ventilation and is recommended in schools. If the schedule of lessons and breaks is rarely changed, schedule-based control of ventilation may be sufficient. A CO_2-sensor-based supplement is the optimal solution and often provides adequate air quality (Dhalluin et al., 2012)

- Hybrid ventilation can be a good solution in colder climates in order to reduce draughts and energy use (Steiger et al, 2012).

VELUX roof windows perform well in schools. In larger rooms, VELUX Modular Skylights perform very well.

2.5.4 Commercial buildings

Larger commercial buildings, like office buildings, typically have more complex requirements to control air quality than residential buildings. The internal loads (person density, computers and equipment) are higher than in residential buildings. The occupants spend much time at fixed locations (the desk or meeting rooms), and the dress code is more formal than in residential buildings. The ventilation rate is often determined by the cooling need rather than the need for fresh air supply for the occupants. There can be indoor air quality requirements from occupational health authorities that are not present in residential buildings.

Office buildings can be designed with natural, mechanical or hybrid ventilation. If natural or hybrid ventilation is used, it will most often be automatically controlled, based on sensors, by a central (BMS) system that controls all services in the building.

In office buildingsi it is important to ensure that facade windows do not occasionally (due to wind speed and direction) function as outlets. A typical design with natural or hybrid ventilation is a building with a large atrium in the centre, and offices, meeting rooms, etc. near the facades. Facade windows are designed as inlets, and the roof of the atrium is equipped with a large area of operable windows that function as extracts.

VELUX Modular Skylights are designed for use in this type of buildings and perform well as extract openings in an atrium roof.

2.6 Tools and calculation methods

Indoor air quality is determined by the supply rate of different pollutants, their chemical interaction, the dilution of these substances through ventilation - and their resulting effects on IAQ (the human health or the perceived air quality). These effects are, to a very large extent, unclear or unknown and the IAQ is generally defined through specific air flow rates or through IAQ indicators (see section 2.2.2). So most tools for the evaluation of IAQ are based on ventilation rates. These flow rates may be converted to IAQ indicators such as CO_2 levels by combining an assumed supply rate of e.g. CO_2 and the dilution due to the ventilation.

General calculation methods for natural ventilation are detailed, requiring information on the location and area of window openings, local wind speed, local wind direction, building geometry and interior building design. Surrounding buildings and the local landscape influence the local wind speed and direction. Based on this information, the pressure differences across each window opening are calculated, and the resulting airflow across each opening and through the entire building are determined. Simple cases of the general calculation methods are available for specific building design cases, such as window openings placed on only two opposite sides of a building.

The general methods are described in several guidelines (AIVC, 1996; SBi 202; CIBSE AM 10, 2005) and are also implemented in a number of detailed building simulation tools, such as IDA-ICE, VELUX Energy and Indoor Climate Visualizer (EIC Visualizer), TRNSYS, EnergyPlus, IES VE, etc. The VELUX EIC Visualizer contains state-of-the-art methods for evaluation and illustration of ventilation flow through windows – and can be used by non-experts.

Traditionally, simplified methods for calculating natural ventilation have been very conservative, only taking limited account of the full potential of natural ventilation. Typically, a worst-case approach is used that assumes only single-sided ventilation, which will lead to severe underestimation of the ventilation flow rate. However, the French institute CSTB has developed a simplified calculation method for evaluating natural ventilative cooling. The method will be implemented in the French Building Code for summer comfort in 2014.

As illustrated in the table below, huge differences arise depending on which type of calculation method is applied.

ΔT=0	**Air change rate per hour**						
Wind speed [m/s]	**0**	**1**	**2**	**2.9**	**5**	**6**	**10**
EN 15242 (ΔT=0)	1.2	1.3	1.5	1.7	2.3	2.6	4.1
RT 2012+ (ΔT=0)	0	1.2	2.4	3.4	5.9	7.1	12
RT 2012+, Uniform area (ΔT=0)	0	3.2	6.4	9.4	16	19	32
BS 5925:91 (ΔT=0)	0	1.6	3.1	4.5	7.8	9.4	16
Measurements (ΔT=0)				11			

Figure 2.20 Measured and calculated ACH for specific situations in MAL.

2.6.1 VELUX Energy and Indoor Climate Visualizer

EIC Visualizer is based on the IDA ICE simulation engine. This engine couples airflow and thermal simulations, which is relevant for evaluations with focus on the effects of window openings, natural ventilation and solar shading. The IDA ICE engine has been validated against major European validation protocols.

Ventilation systems in EIC Visualizer can be natural, mechanical or a mix of the two (hybrid). Heat recovery can be used with mechanical and hybrid ventilation. The tool performs a calculation of natural airflows that considers infiltration through the constructions and controlled natural ventilation through windows. The airflow of the mechanical system is included in the total ventilation rate of the building. The mechanical system can be exhaust only, or balanced, with or without heat recovery.

The ventilation can be controlled based on one of two overall strategies, i.e. either "manual" control or demand control. The system can automatically switch between the two modes based on outdoor temperature, to ensure that the most energy-efficient mode of ventilation is used. The "manual" controls for natural ventilation are designed to mimic typical use of windows as providers of natural ventilation. Demand-controlled ventilation is based on CO_2

as indicator of air quality. The categories and associated CO_2 levels as defined in EN 15251 are used (cat. I: 750 ppm, cat. II: 900 ppm, cat. III: 1 200 ppm).

The use of sunscreening is controlled based on the indoor temperature with the purpose of reducing overheating. The VELUX Energy balance and VELUX ACTIVE control systems can be used directly in the tool. See eic.velux.com for more information (Foldbjerg, Asmussen, Roy et al., 2012).

2.7 Building codes and standards

Building codes

In most countries, the building codes express requirements to IAQ by a minimum outdoor air flow through a building. These requirements can be expressed in different ways, e.g. as:

- Air change per hour (ACH)
- Air flow per unit of floor area (l/s · m²)
- Air flow per person (l/s · pers)

In general, the regulatory requirements for ventilation flow rates in residential buildings are based on a humidity balance of the building: All the humidity generated inside the building must be extracted by ventilation to prevent rot or mould damage to the construction and to avoid the hazard to human health that follows such mould formation. In many countries, building code requirements for ventilation of residential buildings are around 0.5 ACH.

Fixed airflow rates are difficult to guarantee with natural ventilation, due to the dependence on the outdoor climate. To provide a simple way of integrating natural ventilation into buildings, the requirement for a specific air change rate in Denmark have been translated into specific opening areas to the outdoor, depending on room usage and size. The openings in living rooms, bedrooms etc. supply fresh air to the building, whereas natural extract air ducts lead the "used air" to the outside from wet-rooms, such as toilets, bathrooms and kitchens.

IAQ indicators are another way of using (automated) natural ventilation to obtain a certain level of IAQ. Unfortunately, almost all building regulations for residential buildings are based on fixed minimum air flow rates, allowing only IAQ indicators to be used for increased ventilation flow rate.

Standards:

National standards and guidelines describe various criteria and levels of IAQ and different calculation methods for natural ventilation.

Criteria for the indoor environment, for design and for energy performance assessment of buildings are described in EN 15251. The standard describes criteria for thermal environment, indoor air quality, lighting and acoustics.

Several ways of describing criteria for the IAQ through airflow rates or IAQ indicator levels are included, depending on the desired use and comfort level. The criteria are defined by classes I to IV, where class I is very high performing and generally for people with special needs. Class IV is low performing and should only be accepted for a limited period of time.

There are several main philosophies for determining the right air flow rates:

- Health-based, where the criteria are based on the impact of ventilation on human health
- Perceived Air Quality-based for unadapted persons (persons entering an occupied room from outside)
- Perceived Air Quality-based for adapted persons (persons staying in the same room for a longer period of time)
- Experience-based requirements that are believed to provide an acceptable humidity level under typical use of the house

A marked difference in required airflow rates is observed between adapted persons and unadapted persons – and between the health-based approach and the Perceived Air Quality for unadapted persons. Using criteria for perceived air quality for unadapted persons will lead to the highest ventilation flow rate – often twice as much or more as for adapted persons. EN 15251 includes examples of airflow rates for adapted and unadapted persons.

For residential buildings, it is reasonable to assume that people are adapted to the indoor air and that air flow rates can be determined accordingly – or according to the health based approach. For office buildings, restaurants, shops etc. where people frequently enter and leave the rooms, it is reasonable to assume that people are unadapted.

The criteria for IAQ in EN 15251 are mainly based on studies of perceived air quality in offices where criteria for the IAQ in residential buildings are less studied. So, in most cases, the regulatory requirements for ventilation flow rates in residential buildings are based on a humidity balance of the building.

The health effects from ventilation have been studied only to a limited extent, but there is some indication that a minimum total air flow rate of 4 l/s pers should always be available for health reasons. This value is included as the minimum recommended ventilation flow rate in EN 15251.

	Standards, Guidelines
Simplifed calculation methods	EN 15242:2009, prEN 15242:2015, DIN 1946-6
Detailed calculation methods	BS 5925:1991, AIVC, CIBSE AM 10, SBi 202

For simplified calculation methods, single-sided natural ventilation is included in EN 15242:2009, whereas the revised version of this standard is expected to cover all types of natural ventilation – and is expected in 2015. For detailed calculation methods, the described documents cover all types of natural ventilation.

Thermal comfort

Thermal Comfort

We try to achieve thermal comfort subconsciously every day. One of the main purposes of buildings is to protect us from extreme outdoor conditions. Thermal comfort is taken for granted by most people, but energy is used to obtain it, through heating or cooling for example. When designing buildings it is important to consider thermal comfort; designs should provide good thermal conditions based on energy-efficient technologies like natural ventilation, solar shading and intelligent building design.

3.1 How to achieve thermal comfort

Thermal comfort can be defined as "that condition of mind which expresses satisfaction with the thermal environment" (CEN, 2005).

Thermal comfort is more than just pleasant conditions; it is part of a vital survival behaviour. Whenever people feel too warm or too cold, a warning system is alerted by our body-controlled basic instincts. The human body is a very efficient piece of machinery and is able to maintain core temperature within a very narrow range of 37°C. Some actions are subconscious, like diverting blood from decentralised areas like hands and feet to keep the vital organs warm in cold environments or to start sweating in warm environments. Conscious actions include removing or adding clothes and adapting our activity level. But whichever way you look at it, the right thermal conditions are needed to survive (Baker, 2009).

And if the thermal environment does not meet expectations, occupants of a building will try to influence the thermal environment to make it do so – by installing local electric heating or cooling units; equipment using additional energy that could have been avoided if the building had been designed with thermal comfort in mind from the beginning.

Many people associate thermal comfort directly with air temperature, but this is not the whole truth, as the temperature subjectively experienced in a room is a combination of several parameters. Arguably, the most important parameter is people's different expectations of thermal comfort. So it can only be calculated for the average human being – and the individual experience is vital.

❗ Remember
Thermal comfort depends on other parameters than air temperature alone, such as activity, clothing and individual preferences of the occupants.

3.1.1 Thermal discomfort

Thermal discomfort occurs when the thermal environment does not meet the requirements of the human mind or body. In cold environments, we feel cold and our hands and feet drop in temperature; we get goose bumps and even start to shiver, in extreme cases resulting in hypothermia. At the other extreme, in warm environments perspiration will start, possibly leading to hyperthermia in extreme cases. All of these responses are reactions to non-comfortable environments. Below are some examples of specific discomfort cases.

Draught

The sensation of draught depends on air temperature, air movement and air turbulence. The human body is not able to sense the actual air movements at low velocity, but it can feel the increased cooling of the skin, which is caused by the air movements.

If not adequately maintained VELUX roof windows can be a source of draught. Older roof windows with a damaged gasket can be leaky and let cold air into a room in winter. So frequent maintenance is needed to keep the window in a good condition. Old and large panes may cause downdraught from the windows, where a cold inside pane temperature cools the air and causes a downward air movement. New low energy panes minimise the risk of draught.

Figure 3.1 Person exposed to uncomfortable air motion.

Radiant temperature asymmetry

This phenomenon can best be likened to a person facing a fireplace on a cold night. One side of the person feels warm, the other feels cold, although the air temperature is the same. The difference in thermal sensation is caused by the difference in radiant temperature between the fireplace and the cold sorroundings.

Radiant temperature asymetry can be seen in two situations with VELUX products:

In winter, when the inside pane temperature is very cold due to the higher heat loss compared to the walls. But, as with draught, new windows will rarely cause problems. An internal blind or external shutter or awning blind can reduce or eliminate the risk.

And in summer, when occupants are exposed to direct sun, solar shading can be used to eliminate thermal discomfort by blocking direct solar radiation.

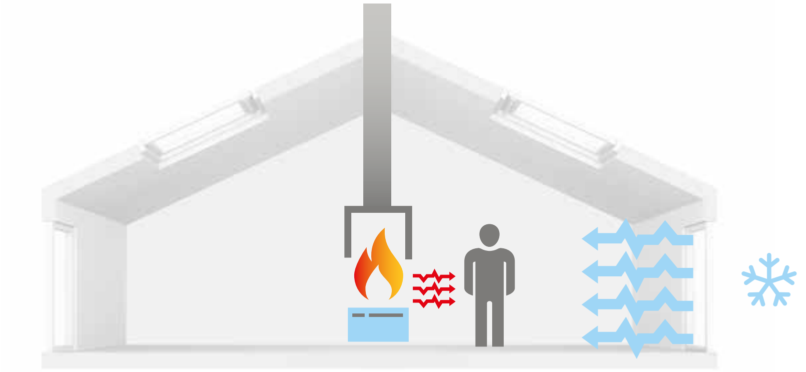


Figure 3.2 Person exposed to one cold and one warm surface.

❗ Remember

In most cases, thermal discomfort can be reduced by user behaviour, such as closing a window, moving to a different position in the room or putting on more clothes.

3.1.2 Parameters influencing thermal comfort

Many experiments have been made to find out what has an influence on our sensation of the thermal environment (Fanger, 1970). The results of these experiments are the basis for the standard ISO 7730 (ISO 2005). Ergonomics of the thermal environment (CEN, 2005).

Six parameters have a major influence on the sensation of thermal comfort:

- The activity of a person, commonly referred to as metabolic rate [met]
- How much clothes a person is wearing, commonly referred to as the clothing index [clo]
- The movement of air (air velocity) [m/s]
- The mean radiant temperature [°C], which is a weighted average of the temperature of the different surfaces (walls, ceiling, floor and windows) in a room seen from the position of the occupant
- The air temperature [°C] in the room
- The relative humidity in the room.

Of the six parameters, four are influenced by windows and their accessories – and hence by VELUX products. Air velocity and relative humidity are influenced by the use of the windows for ventilation; both the ventilation flap and normal opening play a role. Air temperature and radiant temperature are influenced by the heat transfer and sunlight through the window and by the use of accessories such as blinds and shutters.

But there is a seventh parameter that is also important – the human mind. Individual expectations have been shown to have an influence on the acceptance of thermal comfort. In warm climates especially, occupant expectations have been shown to influence comfort ranges.

Remember
People are all different and want different thermal environments.

3.1.3 The preference for variation in temperature

EN ISO 7730 (ISO, 2005) is based on climate chamber studies. They show that people basically have the same thermal preferences, regardless of where they live on earth (de Dear et al., 1997). This philosophy for evaluation of thermal comfort is based on the assumption that neutral is the optimal status for thermal comfort. However, a constant temperature without variation during the day may not be what humans really prefer. Studies show that we tend to prefer variations in temperature, and that changes in around the neutral temperature is experienced as pleasurable. (de Dear, 2006).

As human beings, we may in fact want variations in our thermal environment; we have a need for sensory and physical stimulation. One way to achieve is with fluctuating interior temperatures to counteract "thermal boredom" (McIntyre, 1980; Kwok, 2000). Heschong (Heschong, 1979), argues for environments with physical variations rather than static conditions, describing comfort as a relationship between thermal contentment and human imagination. We as humans are capable of recognising, remembering, and adapting ourselves to most thermal experiences.

3.1.4 Adaptation to a warm climate

At the same time, field studies show that people working in naturally ventilated office buildings in warm climates accept higher temperatures (de Dear and Brager, 1998). The standard EN 15251 (CEN, 2007) provides limits for acceptable indoor temperatures for naturally ventilated buildings. These temperature levels assume that people can freely adapt their clothing and operate windows. Based on the outdoor 'running mean' temperature during the previous week, acceptable indoor temperatures are found in Figure 3.3. A running mean is a weighted average of a time period where the latest time periods has the greatest weight.

In residential buildings, it can be assumed that the occupants will adapt their clothing to obtain comfort and in buildings with VELUX roof windows they will operate the windows, which were the assumptions for using the adaptation method.

The consequence of adaptation is that thermal comfort can be achieved in warm climates, without air conditioning, by using natural ventilation, solar shading and intelligent building design. This allows significant reductions in energy use (see section 5.4.4).

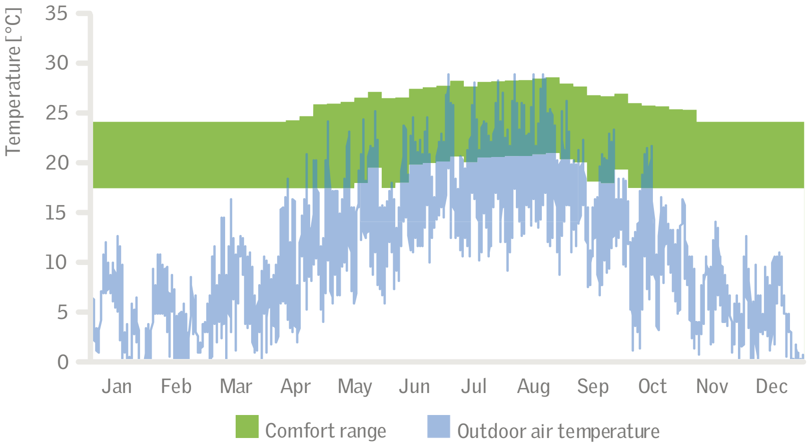


Figure 3.3 The figure shows the comfort range for Denmark. Calculation is based on the principles of adaptation of EN 15251 (CEN, 2007).

3.2 Health impacts of the thermal environment

The previous sections discussed how the thermal environment affects the comfort of building occupants. And the impact on comfort is the main influence the thermal environment has on building occupants. But the thermal environment also has some health issues, which will be discussed in the following.

3.2.1 Heat strokes

Heat stroke is the most serious heat-related condition. It occurs when the body becomes unable to control its temperature: the body's temperature rises rapidly above 40°C, the sweating mechanism fails, and the body is unable to cool down. Body temperature may rise even further within 10 to 15 minutes, and many of the important functions of the body will begin to shut down. Heat stroke can cause death or permanent disability if emergency treatment is not provided.
Infants, children and the elderly are more vulnerable to heat illness than other age groups.

3.2.2 Effect of uniform temperature indoors

Time spent indoors with a fairly uniform temperature may have negative health effects. Spending time indoors with slightly cool temperatures (e.g. below 20°C) may stimulate bodily processes that help prevent obesity (van Marken Lichtenbelt et al., 2009; Bluyssen, 2013).

3.2.3 Sleep quality

The temperature in the bedroom has an impact on sleep quality. There are large personal and cultural variations in preference. Some prefer always to have their bedroom window open and the heating switched off, even in mid-winter, while others prefer the bedroom temperature to be the same as in other rooms of the house. Some prefer thin sheets or blankets, while others prefer a thick duvet.

Surprisingly few studies give a scientific response to this discussion. There is no clear guideline as to what temperature and bedding will give the best sleep quality. What is known is that overheating reduces sleep quality. The bedroom should not be too warm, and it is particularly important that the time at which you fall asleep is not too warm. CIBSE Guide A states that sleep may be impaired above an operative temperature of 24°C (Laverge et al., 2011; CIBSE, 2006).

3.3 Productivity and learning

Most studies on the impact of temperature have been conducted in climate chambers. They show that the ability to learn and perform work tasks is influenced by the thermal environment. For both school work and office work, the relative number of errors made is not influenced by temperature, whereas the relative speed of learning and working is decreased. For both office and school work, the effect is seen when a very high temperature is compared to a more typical temperature; the relative performance is typically improved up to 10%. (Wargocki and Wyon, 2006; Wargocki et al., 2007).

It is not known whether increased temperatures decrease performance in naturally ventilated buildings where the occupants are adapted to the temperature.

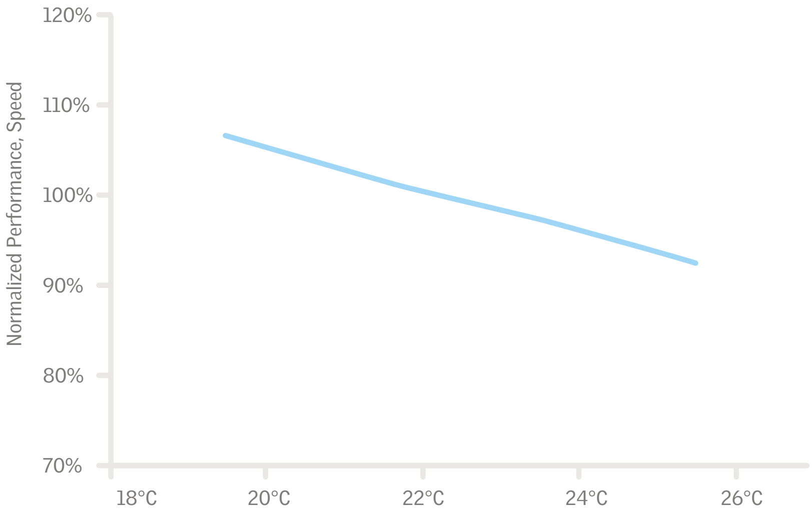


Figure 3.4 The impact of temperature on the relative performance of school work (Wargocki, 2006)

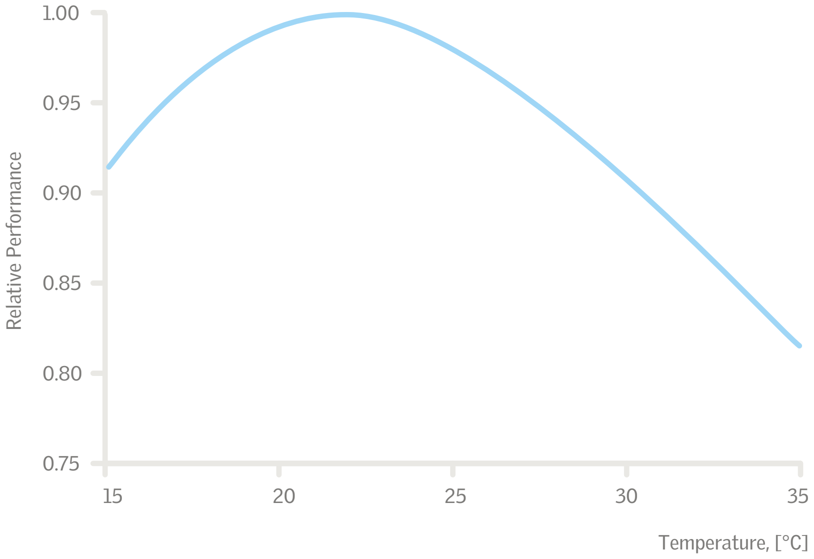


Figure 3.5 The impact of temperature on the relative performance office work (Wargocki, 2006)

Psychological mechanisms may affect how performance is influenced; both office workers and school children may be aware of the number of errors made in a task, and adjust their speed to keep the number of errors at an acceptable level.

3.4 Thermal comfort with roof windows and solar shading

Windows combined with a heat source (e.g. a fireplace) are one of the oldest methods of achieving thermal comfort in buildings during cold periods. Today the simplest way to achieve thermal comfort is to install a system that can adjust the parameters. Most houses have a heating system installed and, in warm climates, possibly a cooling system. However, windows can cool down a building on a warm summer day.

Draught and temperature asymmetry can be caused by windows, as mentioned earlier. It can be difficult to determine whether the sensation of coldness is caused by draught from the windows or by cold radiation. A leaky window can be fixed by replacing the gasket and/or pane – or the whole window could be replaced. To some extent, cold radiation can be limited with the use of an internal blind that will increase the inside surface temperature.

3.4.1 Blinds and shutters

Blinds and shutters block solar radiation and thus reduce the amount of heat entering a room. Overheating during summer can be efficiently reduced, and even eliminated, by the use of proper solar shading. It can also improve the thermal insulation of windows in winter. This can reduce thermal discomfort from cold radiation and temperature asymmetry. Even better, when applied at night, this extra insulation can decrease the demand for heating. In terms of energy, shading should only be used at night during winter, because the solar gains are often of greater importance than the heat loss (see section 5.4.3).

Remember
Expectations of the thermal environment in naturally ventilated buildings are dependent on the outdoor temperature..

Example: solar shading reduces experienced temperature for different glazing and accessories under strong solar radiation.

The measured values are the results of a small experiment. The operative temperature was measured behind a glass unit with different shading accessories to illustrate the effect of different types of shading.

Glazing (V21)	Accessories	Operative temperature [°C]
59 Low energy		34.0
76G Low energy, solar protected		29.3
59 Low energy	RFL Roller blind	29.0
59 Low energy	MHL Awning blind	28.7
59 Low energy	MHL + RFL Awning blind + roller blind	26.6
	Shutter	26.2

Roller blind.

Example: Solar shading as cooling

A study from CSTB in France made for an attic room investigated how solar shading could be used to assist or replace a mechanical cooling system. Simulations were made for Hamburg, Munich and Stuttgart in Germany, and Paris, Lyon and Marseille in France (Couillard, 2010). The conclusion was that the experienced temperature could be lowered by up to 7°C when using a solar shading device for locations in both Germany and France. Energy for cooling was eliminated in all locations except Marseille, where it was reduced by 90%. The figure shows the experienced temperature on a typical hot and sunny summer day in Paris with and without solar shading.

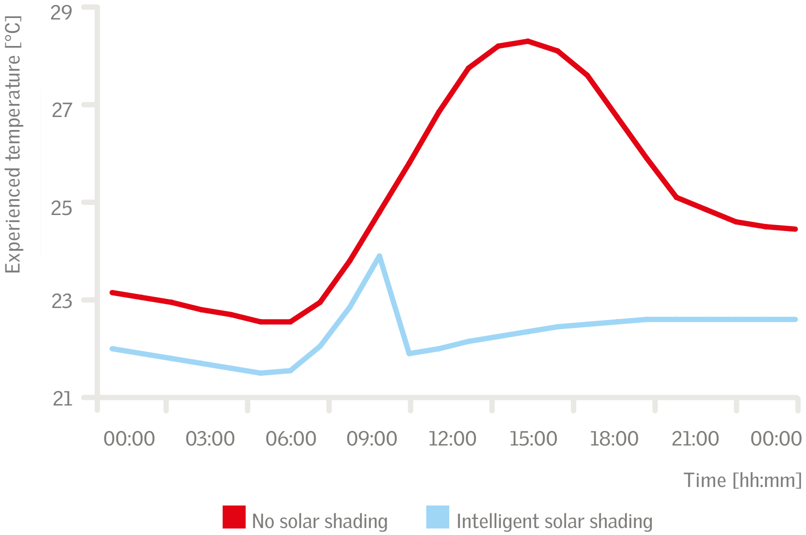


Figure 3.6 Experienced temperature on a hot and sunny day summer day in Paris, France (Couillard, 2010).

3.4.2 Ventilative cooling

Ventilative cooling refers to the use of natural or mechanical ventilation strategies to cool indoor spaces. The use of outside air reduces the energy consumption of cooling systems while maintaining thermal comfort. The most common technique is to use increased ventilation airflow rates and night ventilation. Ventilative cooling is applicable in a wide range of buildings and may be critical to realising low energy targets for renovated or new Nearly Zero-Energy Buildings (NZEBs) (venticool.eu).

Natural ventilative cooling by opening windows is a very direct and fast method of influencing the thermal environment. An open window will cause increased air motion, and if the outdoor temperature is lower than indoors the temperature will fall. Even when the outdoor air temperature is slightly higher than the indoor, the elevated air speed due to increased airflow will increase the cooling of the body and reduce the thermal sensation.
For ventilative cooling, a division could be made between two strategies in terms of natural ventilation – day ventilation and night ventilation.

- Ventilation during the day removes excess heat from the building by creating high air movements by natural ventilation.

- Night ventilation (also referred to as night cooling) will cool down a building's thermal mass at night by using cool outdoor air. The following day, less cooling energy (or none at all) is needed in the building, as the thermal mass has already been cooled down. Buildings with high thermal mass soak up more heat during the day, that needs to be removed – an ideal situation for night cooling strategy (see Figure 2).

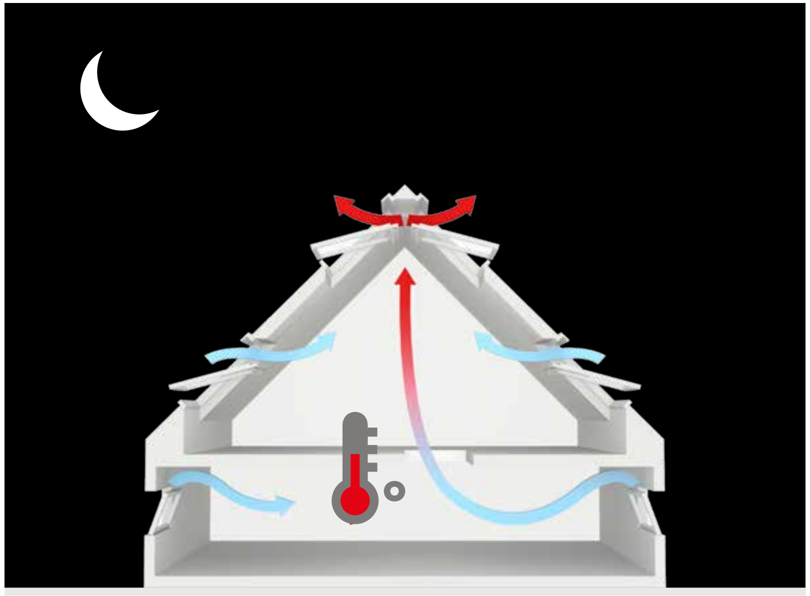


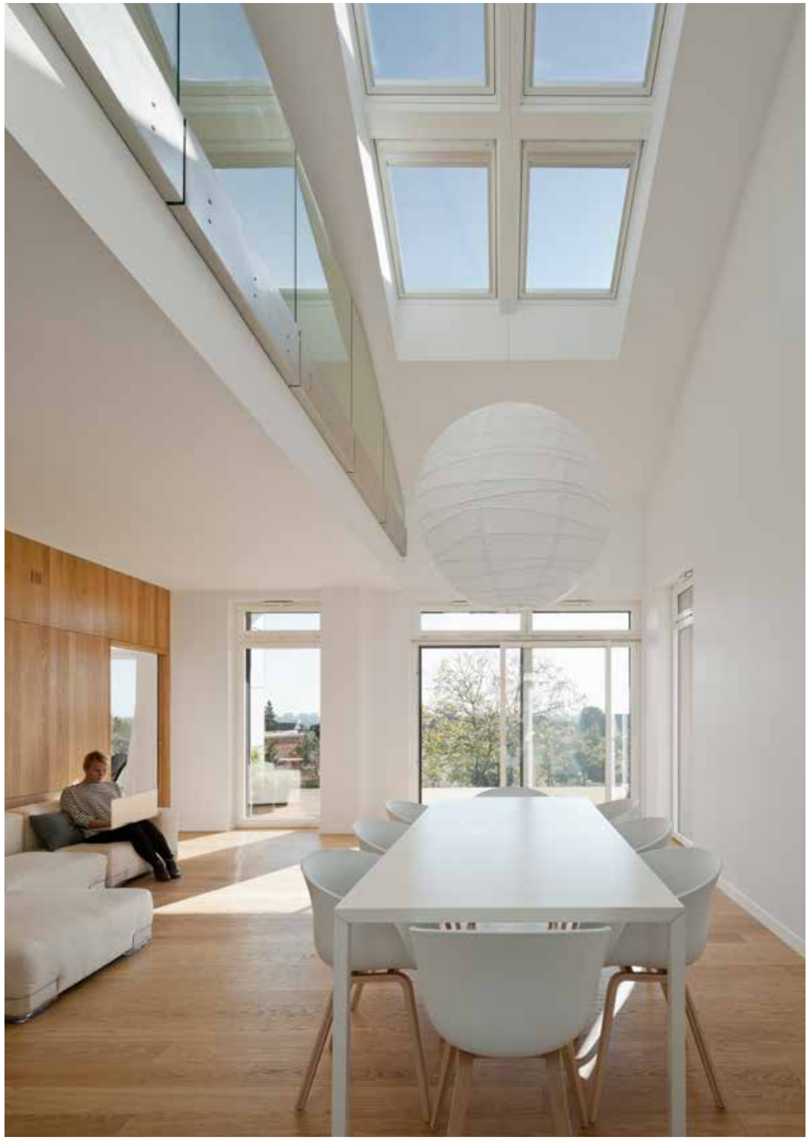
Figure 3.7 – Passive cooling at night (night cooling)

Night cooling is an aspect of ventilative cooling,

see section 3.4.3.

Example from MH 2020:
In the French Model Home, Maison Air et Lumière (MAL), the airing rates and resulting indoor temperature were studied during the summer of 2012. Through a combination of measurements and detailed simulations, the effects of ventilative cooling on indoor temperature were determined by the Institute Armines (Favre, 2013). The first step was to verify the simulation model against the measured values based on the chosen control of the building. The next was to simulate variants of the control using actual weather data. This made it possible to determine the effects of e.g. ventilative cooling (window openings) compared to closed windows.

When ventilative cooling was used as intended, the indoor temperature was typically 5-8°C lower than if it had not been. It was even possible to keep the indoor temperature below the outdoor during daytime (especially when the control system in MAL was used), only opening windows when the net effect on thermal comfort was positive.



Maison Air et Lumière.

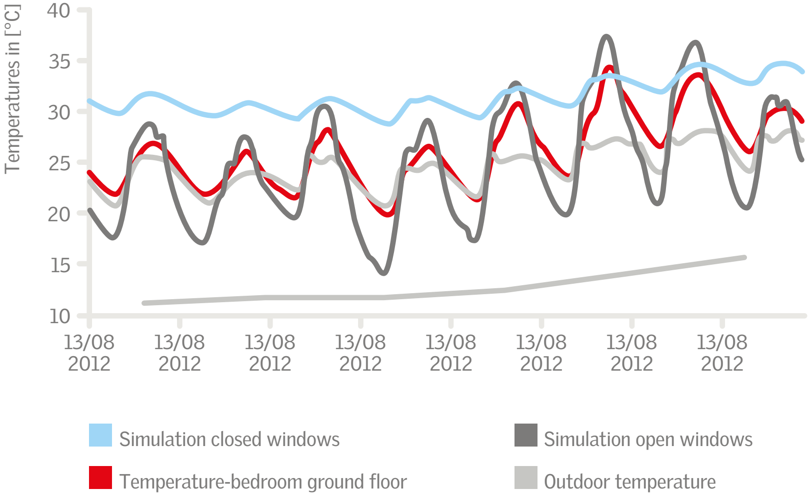
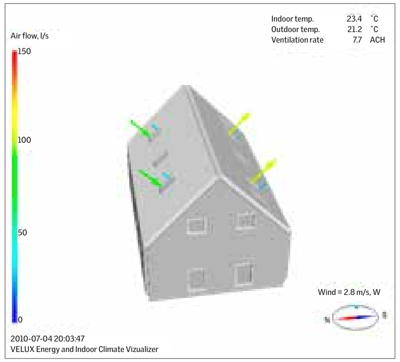


Figure 3.8 Ground floor bedroom in MAL. Blue curve shows the simulated indoor temperature when windows are constantly closed. Dark grey curve shows the simulated indoor temperature when windows are constantly open. Red curve shows the measured indoor temperature when windows are controlled by the MAL control system. Light grey curve shows the outdoor temperature.

Example: Ventilative cooling in northern Europe

The VELUX Energy and Indoor Climate Visualizer is used to find the effect of ventilative cooling in a house in Stockholm. The ventilation flows achieved per window are in the range of 40-70 l/s when the windows are used to maintain a pleasant temperature and the ventilation rate of the house is in the range of 5-8 ACH where 15 windows are opened.



	Occupied part of year with temperatures out of comfort range
No summer ventilation	3% (304 hours)
With summer ventilation	0% (0 hours)

The results in the table show that without ventilative cooling, overheating will occur for 3% of the occupied hours of a year; with ventilative cooling the problem is eliminated. Using natural ventilation thus improves the thermal environment during the summer.

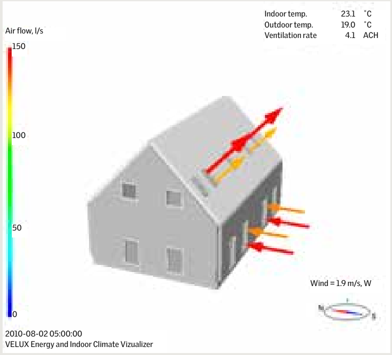
! Remember
Opening of windows reduces overheating efficiently.

3.4.3 Night cooling

Night cooling makes use of the fact that the outdoor temperature is lower during the night than during daytime. When windows are opened during the night, the temperature in the house is reduced to e.g. 21°C in the morning. During the day, the indoor temperature will increase, but the temperature in the afternoon will be lower than if night cooling had not been used. Often, indoor daytime temperatures below the outdoor temperature can be maintained.

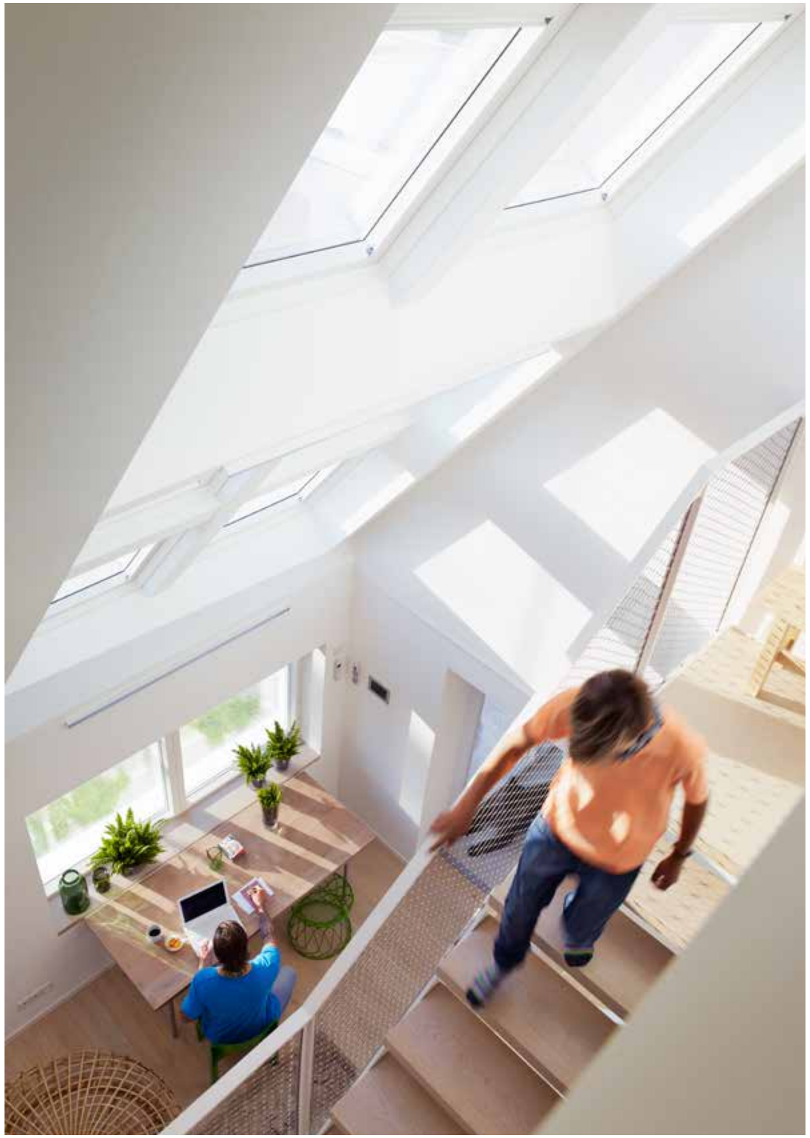
Example: night cooling in Southern Europe.

The VELUX Energy and Indoor Climate Visualizer is used to find the effect of night ventilation in a house in Rome. The ventilation flows achieved per window are in the range of 50-100 l/s when 8 roof windows are used for night cooling, and the ventilation rate of the house is in the range of 4-6 ACH.



	Occupied part of year with temperatures out of comfort range
No night cooling	12% (1043 hours)
With night cooling	9% (757 hours)

The results in the table show that without night cooling, overheating will occur for 12% of the occupied hours of a year; with night cooling the problem is reduced to 9%, which could be further reduced with solar shading. Using natural ventilation for night cooling thus improves the thermal environment in the house.



LichtAktiv Haus.

Example: night cooling in ModelHome 2020 project LichtAktiv Haus

The use of windows for ventilative cooling and particularly night cooling has been investigated in the VELUX ModelHome 2020 projects. The window openings were controlled automatically to maintain an indoor temperature within category 1 or 2. Figure 3.8 from the kitchen-living room in LichtAktiv Haus shows when this was achieved and how windows were used. The overall result is that category 1 or 2 was achieved almost all year, with the exception of approx. 10 afternoons; a very good performance. The dark green indicates closed windows, light green indicates open windows. It is clear that windows were open intermittently during daytime in the spring and autumn, and almost permanently during daytime in summer. It is also seen that during the summer, windows were also open during the night, which means that night cooling was part of achieving the good thermal environment (Foldbjerg et al., 2014).

LichtAktiv Haus

Figure 3.9 Temporal map for kitchen-living room in LichtAktiv Haus showing open or closed window in combination with thermal comfort category according to Active House specification.

3.4.4 Automatic control

An automatic control system for thermal comfort includes those dynamic elements that have an influence on the thermal environment: electric window openers, external shading and/or internal blinds. The most reliable solution is sensor-based control. Time control can also achieve good performance.

The advantage of an automatic control system is the ability to adjust the window and its accessories to match the actual needs of the occupants. If solar gain causes overheating, external shading is used; when it makes sense in relation to energy and comfort, the shading is deactivated.

VELUX ACTIVE Climate Control and Energy Balance are good examples of automatic controls. Energy Balance is a time-controlled feature available in all VELUX Integra and Solar products controlled by io-homecontrol. VELUX ACTIVE Climate Control is a sensor-based control that can also be used with all VELUX electrical products compatible with io–homecontrol®.

The VELUX ACTIVE Climate Control algorithm has been validated by the French building research institute, CSTB, for both German and French locations (Couillard, 2010). Its findings are that dynamic shading control can reduce the experienced temperature by up to 7°C in summer and, in most cases, eliminate overheating (or reduce the cooling demand by up to 90%).

Remember
Automatic control of windows and shading can reduce overheating and the need for mechanical cooling.

Example: Use of external solar shading in ModelHome 2020 project Sunlighthouse

The VELUX ModelHome 2020 project Sunlighthouse is used as an example of how external, dynamic solar shading (awning blinds) is used to prevent overheating. The solar shading was controlled automatically, based on external solar radiation and indoor temperature. Figure 3.9 from the living room in Sunlighthouse shows when solar shading is used and the thermal comfort category. The overall result is that category 1 or 2 was achieved practically all year; a very good performance. The dark green indicates inactive solar shading, light green indicates Active solar shading. Solar shading was used intensively during mid-summer and also often used in spring and autumn. Solar shading played an important role in maintaining good thermal comfort (Foldbjerg and Asmussen, 2013B).

LichtAktiv Haus

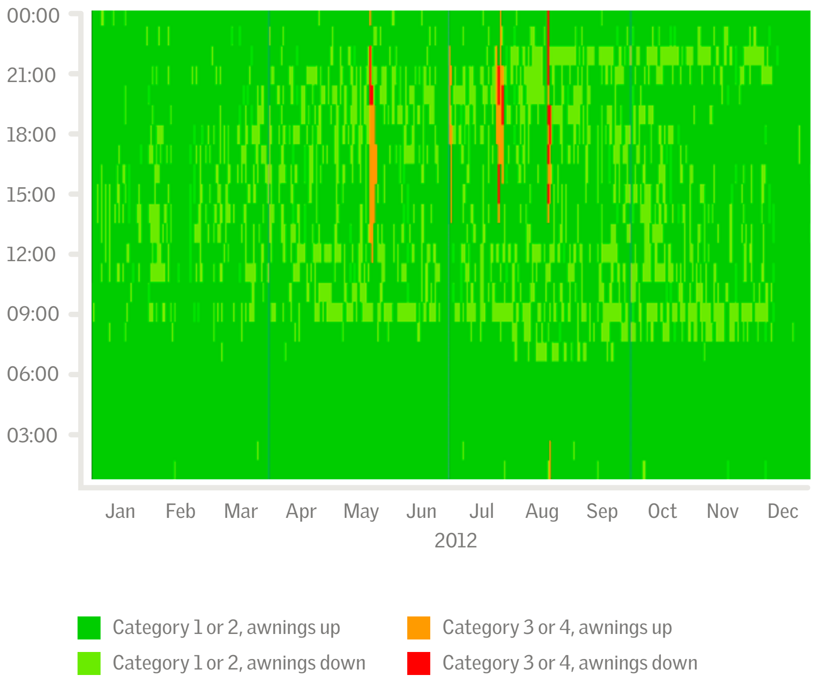
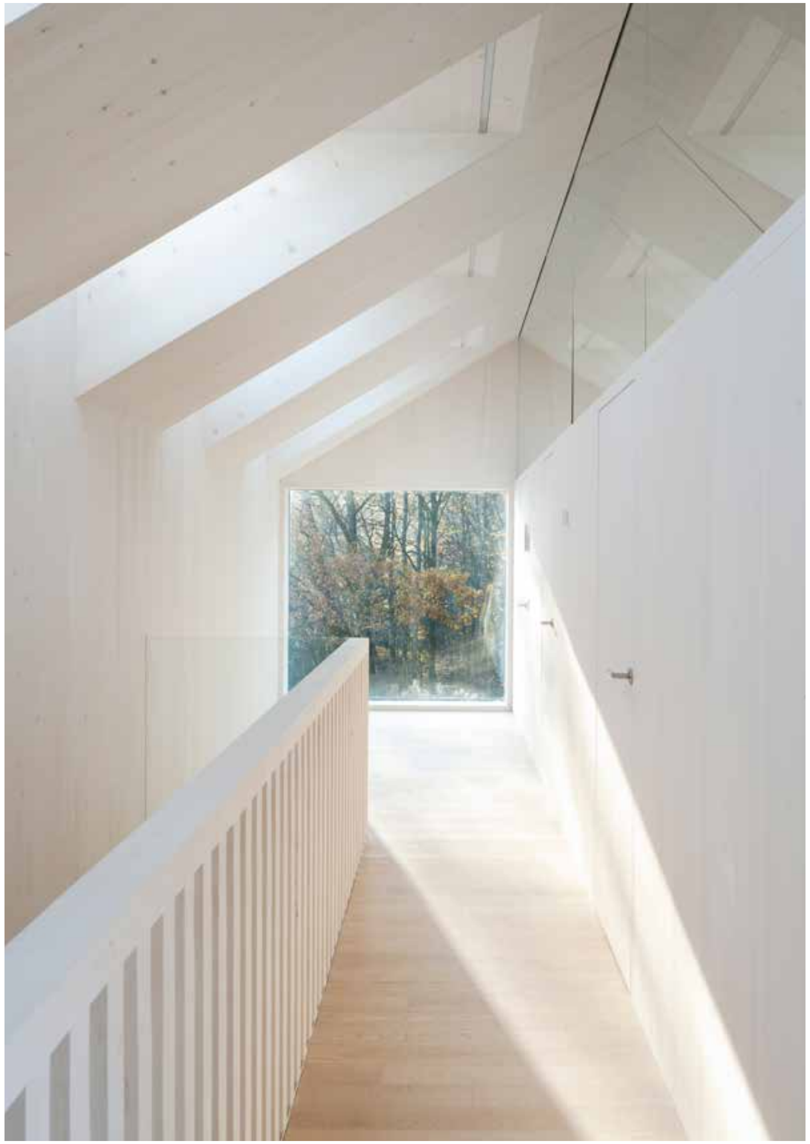


Figure 3.10 Temporal map for Living room in Sunlighthouse showing active or inactive solar shading (awning blinds) in combination with thermal comfort category according to Active House specification.



Sunlighthouse.

3.5 Building types and climate

Many of the considerations in the Ventilation chapter on building types and climate also apply to thermal comfort. The section in this chapter provides additional information specifically related to thermal comfort.

3.5.1 Renovation of residential buildings

Many houseowners are interested in improving energy performance as part of a renovation. This will generally improve thermal comfort during winter, as interior surface temperatures are increased; it is easier to maintain the desired temperature and draughts are less likely. However, renovation can also increase the tendency to overheating. In many situations, measures to prevent overheating need to be added that were not used before the renovation – otherwise overheating is likely to occur more frequently (Orme, 2003; Carmichael, 2011).

Ventilative cooling by natural ventilation, combined with dynamic, external solar shading, has proved to be successful (Foldbjerg et al., 2013C).

Solar protective glazing is an economical alternative to external shading that can be efficient at preventing overheating, but reduces the window's energy performance during winter and reduces daylight transmittance.

It is particularly important to prevent overheating in bedrooms, as it has a negative impact on sleep quality (see section 3.2.3).

3.5.2 New residential buildings

New residential buildings ususally face even greater overheating challenges than renovated buildings. However, in new building projects it is much simpler to include the right measures in the design phase, rather than fixing an inadequate design after the building is completed.

It is important to evaluate the performance on thermal comfort with reliable simulation tools, e.g. VELUX Energy and Indoor Climate Visualizer.

3.5.3 Low-energy buildings

Overheating can occur in most residential and office buildings if no ventilation and solar shading strategy has been implemented from the start. In many buildings, overheating is handled by air conditioning, but natural ventilation (passive cooling) is a good substitute as it saves energy compared to air conditioning.

There have been many cases in the past few years of overheating in low-energy houses, where the main goal has been to achieve a low heating consumption. In these cases, passive technologies, such as solar shading and natural ventilation, are often not fully utilised (Larsen et al., 2011). Learnings from these cases have been to better implement natural ventilation and openable windows into the design of the building to prevent overheating, instead of installing mechanical cooling systems. Buildings built to "Active House" principles focus primarily on user well-being by creating a good indoor climate. In the design of Active Houses, solar shading and natural ventilation allow the full potential of passive cooling to be utilised.

3.5.4 Schools and kindergartens

There may be legislative requirements for the maximum temperature in schools and kindergartens. The following considerations can be used to prevent overheating:

- In summer, opening windows has a good effect on both thermal comfort and indoor air quality and should be done frequently
- Dynamic external solar shading efficiently reduces solar gains
- Automatically controlled natural ventilation allows for the full potential of solar shading and natural ventilation and is recommended in schools. If the schedule of lessons and breaks is rarely changed, a schedule-based control of ventilation may be sufficient (Dhalluin et al., 2012).

Performance can be verified by a simulation in VELUX Energy and Indoor Climate Visualizer (see section 2.6.1), which determines temperatures and includes the effects of solar shading, ventilative cooling and solar protective glazing.

See figure 3.12 for an example of measured thermal comfort in a kindergarten.

VELUX roof windows perform well in schools. In larger rooms, VELUX Modular Skylights perform very well.

3.5.5 Commercial buildings

It is becoming a de facto standard in office buildings to include mechanical cooling (air conditioning) in the design, also in buildings in northern Europe. Some office buildings are designed without mechanical cooling, using natural or hybrid ventilation instead.

VELUX Modular Skylights are designed for use in commercial buildings and perform well as extract openings in an atrium roof. The solar shading that can be integrated in VELUX Modular Skylights, as well as the opportunity to open every second module, provides good opportunities to prevent overheating.

The control of shading and opening of VELUX Modular Skylights will often be performed by the building's BMS system in a control setup that integrates all systems of the building.

3.5.6 Effects of climate change and urban heat islands

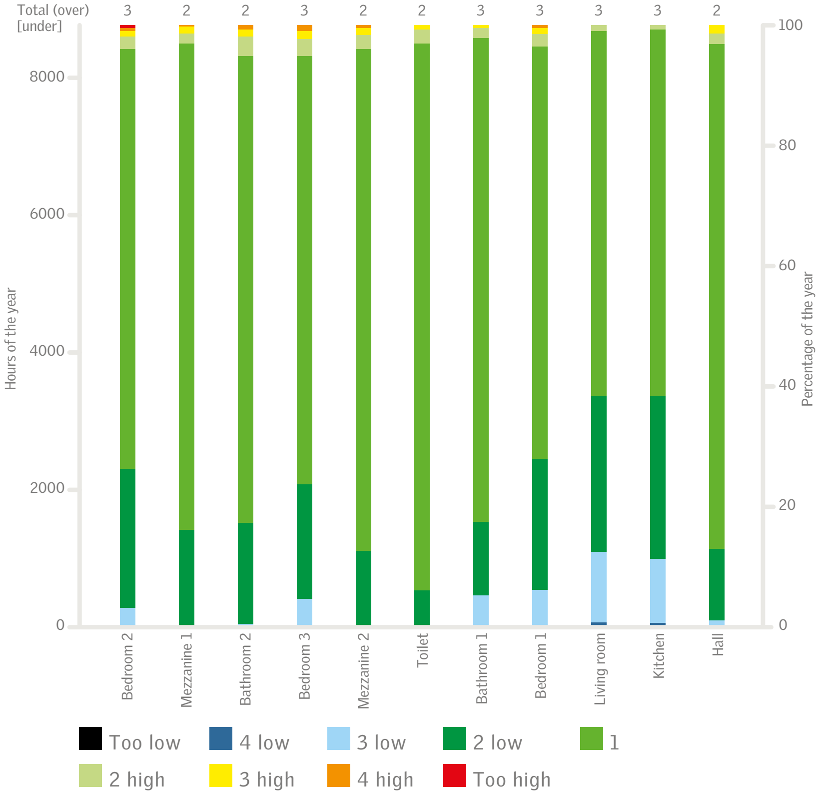
The risk of overheating in buildings will increase as outdoor temperatures increase due to climate change (Orme, 2007). Another effect influencing the risk of overheating is the "urban heat island" effect. Large and densely populated urban areas have a higher temperature than the surrounding countryside, most likely caused by the increased use of energy in urban areas. During the 2003 heat wave in London, temperature differences between the city and the surrounding rural areas at times exceeded 9°C (Carmichael et al., 2011). These two effects underline the importance of not only designing buildings to perform well under today's outdoor conditions, but also considering the conditions that can be expected in the future at the building's location.

Example from the VELUX Model Home 2020 project, Maison air et Lumière

The thermal environment in Maison Air et Lumière has been evaluated according to Active House specifications (see 3.6.4). The high daylight levels in the house increase the risk of overheating, so its prevention has been a top priority. The result is seen in figure 3.12. The house achieves category 1 (corresponding to EN 15251 category I (CEN, 2007)). This excellent performance is achieved by designing the house to take maximum advantage of natural ventilation, and to use shading and window openings to their full potential (Foldbjerg and Knudsen, 2014).

The thermal environment in Maison Air et Lumière has been evaluated according to Active House specifications (see section 3.6.4). The high daylight levels in the house increase the risk of overheating, so its prevention has been a top priority. The result is seen on figure 3.11. The house achieves category 1 (corresponding to EN 15251 category I (CEN, 2007). This excellent performance is achieved by designing the house to take maximum advantage of natural ventilation and to use shading and window openings to their full potential (Foldbjerg and Knudsen, 2014).

Active House Category



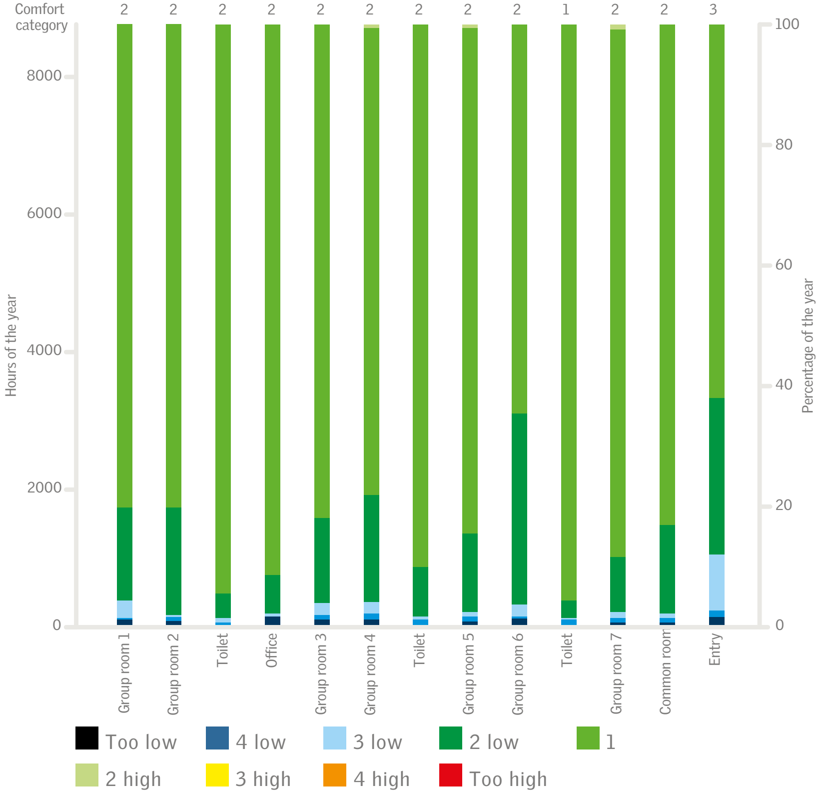
From 2012 Sep 1 to 2013 Aug 31 Thermal comfort in Maison air et Lumière Categories are based on Active House Specifications 2.0

Figure 3.11 Thermal comfort for each of the rooms in Maison Air et Lumière evaluated according to Active House specifications (based on adaptive method of EN 15251 (CEN, 2007)). Criteria are differentiated between high and low temperatures.

Example from the Active House project, Solhuset

The kindergarten Solhuset in Denmark was built to Active House principles. It has good daylight conditions, so prevention of overheating has been a priority. External solar shading (awning blinds) and natural ventilation have been used in an automatically controlled system.
The thermal comfort categories are seen on figure 3.12. It is clear that there is practically no overheating (no red or orange colours on the right side of the coloured bars) – it has been efficiently prevented. The results show that passive measures (solar shading and ventilative cooling) can also be applied in a kindergarten to efficiently prevent overheating (Foldbjerg et al, 2014B).

Active House Category



From 2012 Jan 1 to 2012 Dec 30   Categories are based on Active House Specifications 2.0

Figure 3.12 Thermal comfort for each of the rooms in Solhuset evaluated according to Active House specifications.

3.6 Evaluation methods

3.6.1 Parameters

Operative temperature

The operative temperature is an attempt to provide a figure corresponding to the temperature actually experienced by the body. The operative temperature includes air temperature, radiant temperature asymmetry and air velocity in one figure, which corresponds to the temperature a person would experience in a space with uniform air and surface temperatures and no air movement. The operative temperature is an intuitive representation of the temperature experienced in a room. However, it does not provide an indication of how the thermal environment is experienced, as activity, clothing and expectations are not taken into account in the value.

Predicted Mean Vote (PMV)

PMV is commonly used in scientific literature and is described in ISO 7730. PMV takes into consideration the six parameters mentioned in section 3.1.2 (metabolic rate, clothing index, air velocity, radiant temperature, air temperature and RH). PMV is a seven-point scale ranging from cold (-3) to hot (+3) with 0 as neutral. The PMV value can be a better indication of how the thermal environment is experienced than the operative temperature alone, but it is a more abstract term to many people. From the PMV index, it is possible to calculate the percentage of people who would be dissatisfied with a specific thermal environment (the Predicted Percentage of Dissatisfied, PPD).

Experienced temperature

PMV is a very technical term and can be difficult to communicate. Instead, a fictive temperature, the experienced temperature, can be calculated from the PMV value. This can be done to explain effects of changes in PMV, for instance higher or lower air velocity, humidity or radiant temperature. Experienced temperature can also include the effect of direct solar radiation and is often relevant when the effect of windows in combination with shading is evaluated.

Adaptive comfort

Most of the background for the PMV index is based on studies in climate chambers, which can be very different from a normal office or home environment. As an alternative approach, thousands of building occupants have been involved in field studies in real buildings, where measurements and questionnaires have been used to correlate the temperature to the thermal sensation experienced by the occupants.
The results show that, in buildings with natural ventilation, the outdoor temperature during the previous week has an influence on the temperature we accept indoors on a given day; the higher the outdoor temperature, the higher an indoor temperature we accept. Adaptation requires access to openable windows, and that the occupant has freedom to adjust clothing. Part of the explanation of adaptation is that a psychological process is involved.

See section 3.6.4 for an explanation of how the adaptive approach is used for classification of thermal comfort.

3.6.2 Evaluation of an existing building

Measured results

The thermal environment can be evaluated by measurements of four of the six parameters: air temperature, humidity, radiant temperature and air velocity. The last two parameters need to be estimated from tables, for instance in (CEN, 2005). Measured data can be used to illustrate the effects of changes in the parameters. It cannot always be used to evaluate the thermal environment as it applies only to the situation when measured. Also, other factors influence occupants' thermal sensation. For instance, moods can have a positive or negative effect on expectations.

Occupant surveys

Surveys made by occupants can help identify possible problems with the thermal environment. Alongside measurements, questions like: "Do you feel hot/cool?" or "Would you prefer it to be warmer or colder?" can help to identify user preferences. A disadvantage is that thermal sensation is subjective and is based on expectations. Again, the psychological state of the occupants will play a large role. If a survey is made in a house occupied by one family and adjusted to their preferences based on surveys, other families might not agree with that.

3.6.3 Tools and calculation methods for evaluation during the design phase

Dynamic simulations

A dynamic simulation can be used to predict the risk of overheating in a building. The simulation calculates the heat balance of the building consecutively for each time step. The results show the energy use of the building, but also the temperature. When evaluating dynamic results, the number of hours out of the thermal comfort range is the typical method. The hours to be counted are the occupied hours – 5% of those are allowed to be out of range, based on EN 15251 (CEN, 2007). When making dynamic simulations, the criteria are taken from various standards or legislation and will apply to the average population. The VELUX Energy and Indoor Climate Visualizer can be used for such evaluations. For a description, see section 2.6.1.

Example: passive cooling in warm climates

A study made on passive cooling methods in warm climates is an example of the use of the VELUX Energy and Indoor Climate Visualizer for thermal comfort evaluations. Simulations made for Malaga, Spain show that passive measures, such as airings and the use of solar shading, can almost eliminate the use of a cooling system (Asmussen and Foldbjerg, 2010). The figure illustrates how the operative temperature is kept in the comfort band (shown in grey) with the use of passive cooling methods, whereas no actions result in significant overheating. The results are also quantified as the part of year with good and poor thermal comfort, again showing large improvements of thermal comfort.

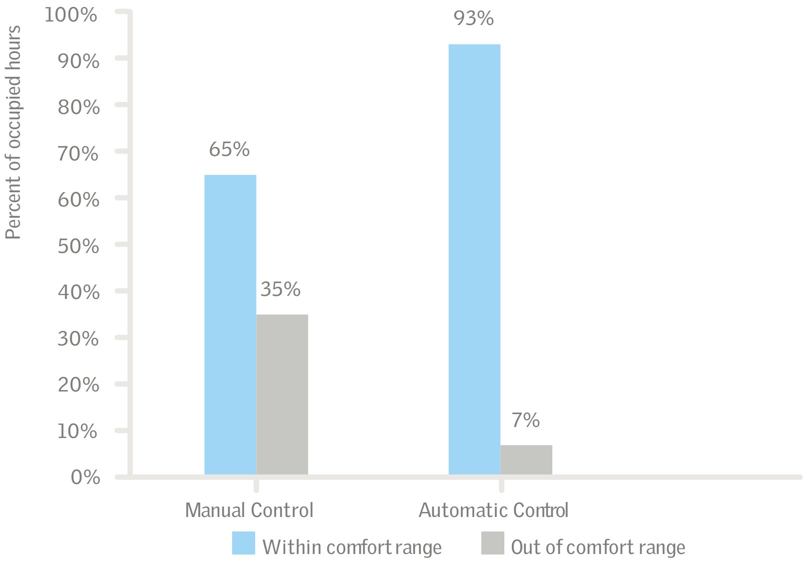


Figure 3.13 The indoor and outdoor temperature by different control methods in June in Malaga, Spain (Asmussen and Foldbjerg, 2010).

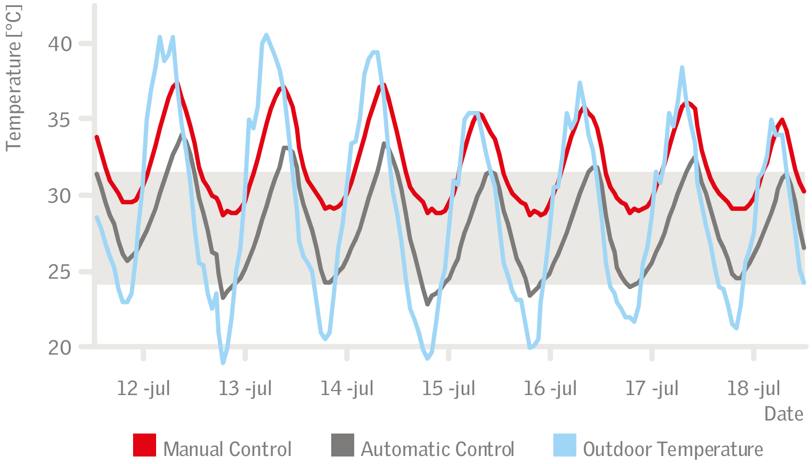


Figure 3.14 The part of year within and out of comfort range by different control methods in Malaga, Spain (Asmussen and Foldbjerg, 2010).

3.6.4 Regulations and standards on thermal comfort

Building regulations have traditionally focused on minimum temperatures during winter to ensure an adequately heated indoor environment. With the move towards more energy-efficient buildings, and the associated increased risk of overheating (as discussed earlier), some countries are introducing requirements for thermal comfort during summer. This can be based on simple indicators, e.g. a maximum temperature of 26°C that can be exceeded for 100 hours per year.

A classification of the thermal environment is defined in most standards. In EN 15251 (CEN, 2007), three classes (I, II, III) are defined. Each class defines a range of temperatures around an "optimal" temperature, e.g. between 21°C and 26°C. When the indoor temperature remains within this range, the room is in category I. For naturally ventilated buildings the adaptive approach is used, so there is no fixed upper limit, see figure 3.15.

Some situations will require an increased use of energy to achieve a higher category – as more heating may be required during winter. It is therefore important to consider the needs of the building occupant when deciding on the design target category. For most building occupants, category II will be sufficient.

The Active House specification 2.0 uses the adaptive method as defined in EN 15251 (CEN, 2007).

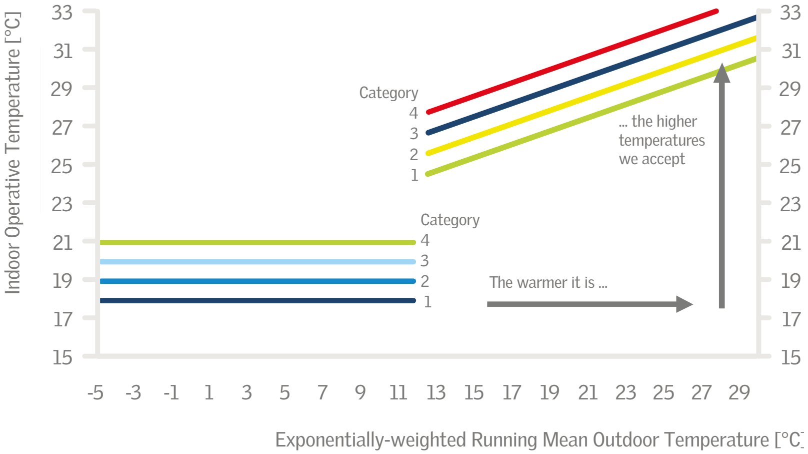


Figure 3.15 The adaptive comfort principle as used in Active House specificatio, based on EN 15251.

Acoustics

Acoustics

One important function of the building envelope is to protect the interior from unwanted outdoor noise. Sound insulation is an important parameter of building components, as outdoor noise can have negative effects on health, mood and learning capabilities.

4.1 Noise or sound

Human perception plays an important role in identifying whether it is noise or sound that we hear. Our ears are always listening and cannot be turned off. Our subconscious mind will constantly evaluate whether a sound is known or unknown, whether it is pleasant or annoying, or whether it represents a danger. If a danger is recognised, we will immediately be in an alert state and ready to run or defend.

Sound is defined as what you as a person can hear; noise is defined as unwanted sound, even at normal or low intensity levels.

Figure 4.1 Noise or sound? What we in one situation describe as noise (e.g. music in the room next to bedroom) can in other situations be perceived as sound.

It is important to have a good acoustic environment for the specific activity taking place, e.g. sleeping, watching TV, talking. What we describe as noise in one situation can be perceived as sound in another. Birdsong in the early hours of the morning, for example, can be perceived as noise and disturb sleep quality. Traffic in the city can have a negative influence and be evaluated as noise, but in other situations it can be perceived as sound; it can make you feel in contact with the surroundings and nature, and allow you to feel included in the community.

Noise can have a significant impact on the health and performance of building occupants. Stress, headache and learning difficulties can all be caused by noise. Sleeping problems and lack of rest can also be caused by noise (National Institute of Occupational Health in Denmark, 2006).

Scientists believe that noise can:

- Lower productivity
- Cause increased metal fatigue
- Trigger stress
- Result in extra sick leave.

It is known that noise can cause premature death. In 2003, it is believed to have been instrumental in the deaths of an estimated 200-500 people in Denmark (Danish Ministry of Environment, 2003).

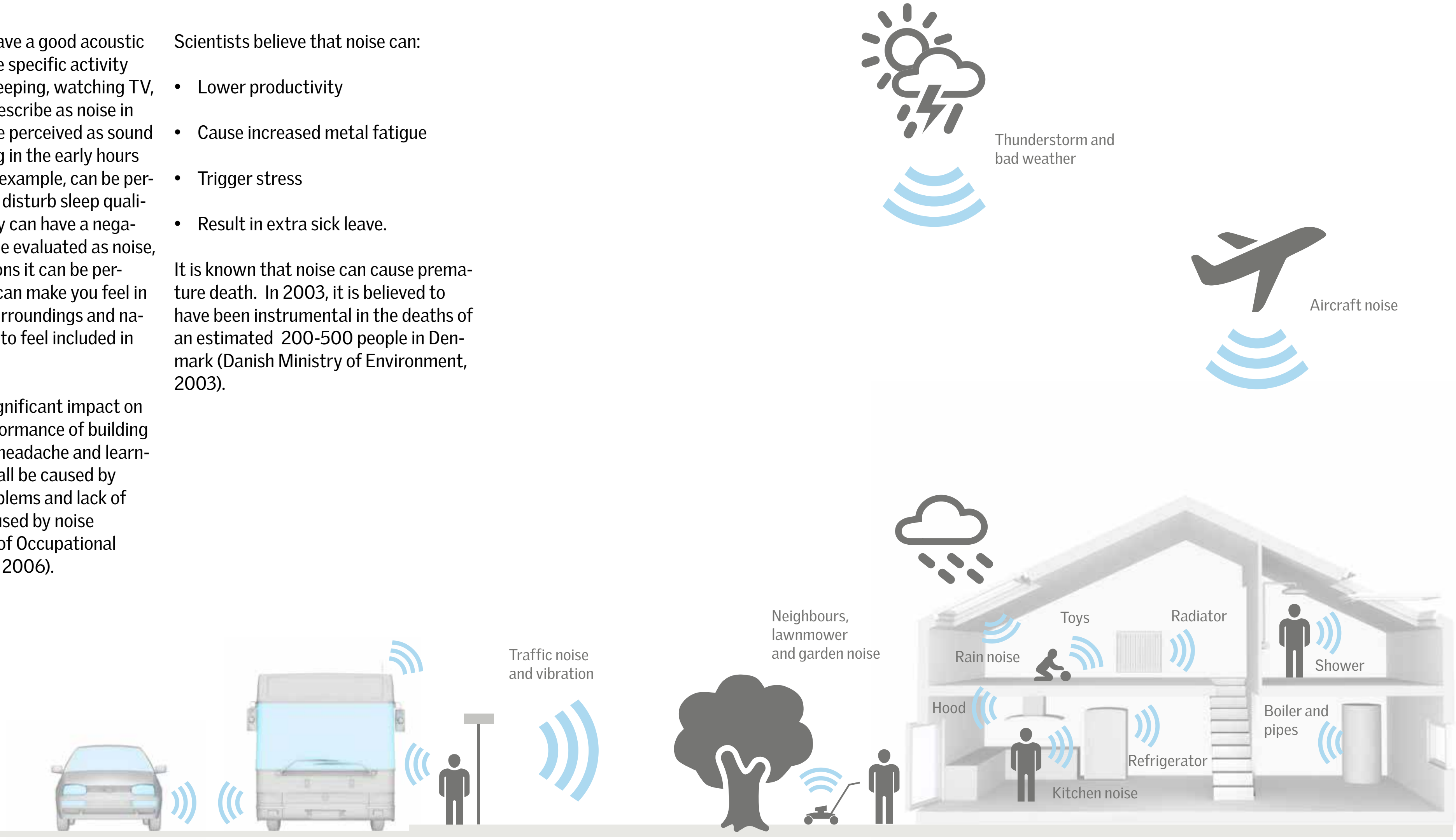


Figure 4.2 The complexity of acoustics environment in buildings

❗ Remember
Noise can cause stress, headache and learning problems.

4.1.1 Technical description of noise or sound

The physical description of sound is vibrations (longitudinal waves) of the air with a frequency (in Hz) that people can hear. Decibel (dB) is the unit used to measure sound level; it is a logarithmic unit that describes a ratio. Sometimes you see decibel written as dB(A) instead of decibel in dB. The (A) means the sound measured is a total sound level (consisting of many individual frequencies) that is "A-weighted" and thereby corresponds to human subjective perception of sound. In the figure below, typical sound levels and sound pressure levels (CEN, 2007; WHO, 2009; SBI, 2014b) are given.

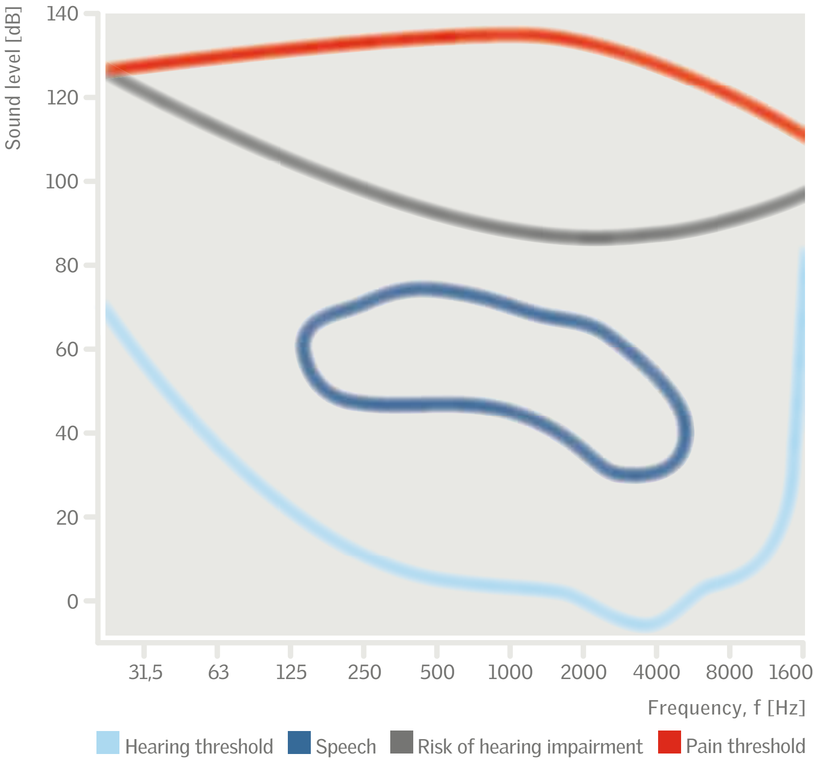


Figure 4.3 Sound pressure levels for speech and threshold levels

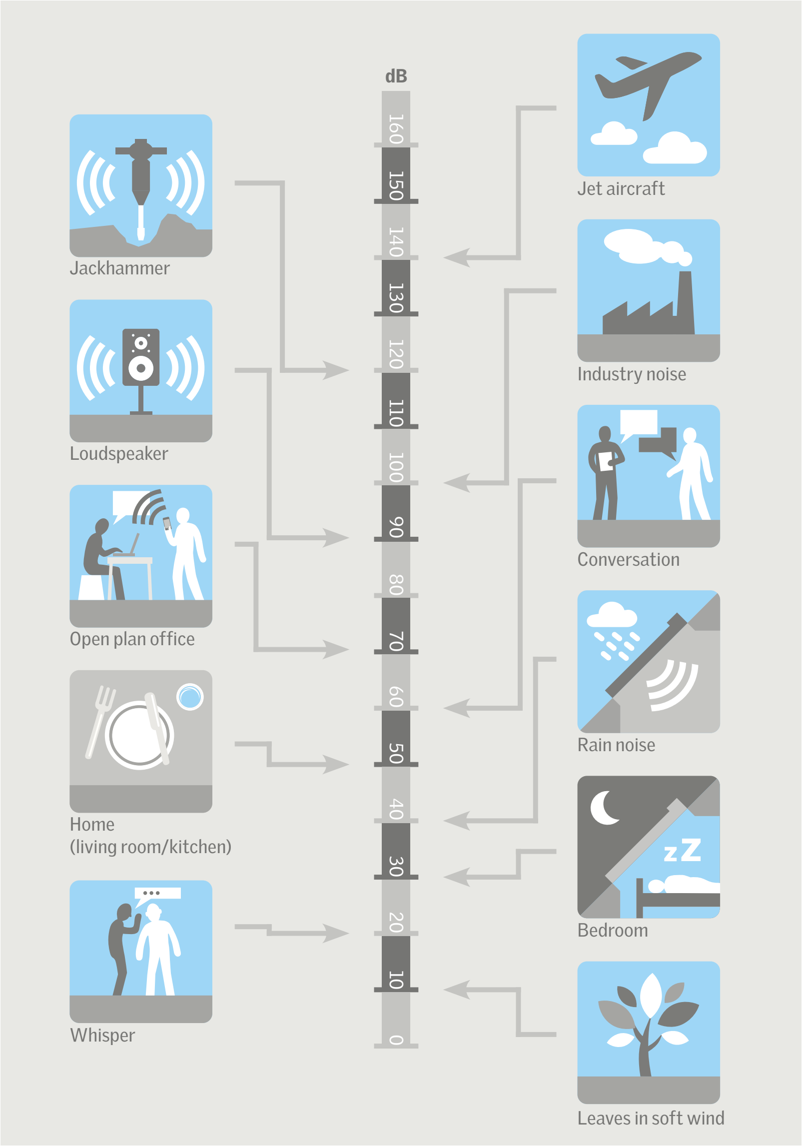


Figure 4.4 Typical sound levels

4.2 Good acoustic environments

Describing or defining good acoustic environments is a complex and multidisciplinary task. Below, different aspects are examined but they are far from comprehensive.

Like any other building parameter, a good acoustic environment must fulfil basic needs such as:

- Helping occupants to live with and follow the daily and seasonal cycles of the outdoor environment
- Enabling occupants to adapt to changing conditions (daily, seasonal) and needs
- Protecting the occupant from noise and allowing him to be in control.

The acoustic environment provides the framework of the sound picture, but there are sounds that are "expected" and "wanted", more acceptable and desirable – the sounds of street life through an open window during daytime, for example. And sounds of nature (birdsong, flowing water) can help alleviate stress..

Sound and noise preferences are individual.

Remember
Our mood influences our perception of sound and noise
Choice of interior surfaces influence the quality of the acoustic enviromnemt.

4.3 Indoor noise

4.3.1 General

In principle, sound generated inside a building can be separated into two sources of transmission – airborne sound and sound transmitted through the building itself. Airborne sound, from human activities in adjacent living spaces or from mechanical noise, travels through air, walls, floors and ceilings. Building-transmitted sound can come from occupants in living spaces above, or low frequency noise transferred through the ground and buildings. Measures for controlling noise and reducing unwanted sound are interior sound reverberation reduction, inter-room noise transfer mitigation and exterior building skin augmentation.

Reverberation time is an important parameter for the acoustical experience of indoor spaces. Buildings with 'soft' interior surfaces are often more appreciated by occupants and visitors. Typical examples of expected reverberation time are; 3-10 seconds in a church; 2 seconds in a concert hall or auditorium; 0.6-1 second in a classroom: and 0.5 second in a home (SBI 2014b).

Intelligibility of speech is often a key factor in a room – and large rooms, with hard, paralle surfaces, can be a challenge.

Stimulation/absence of stimulation: the level of stimulation from environmental factors (light, sound, air, temperature) should be higher during day than night.

Silence/sounds: the presence of sound and contact to sounds from outdoors are desirable during daytime, whereas quiet spaces are needed at night.

The correct internal acoustics can play a major role in overall well-being.

4.3.2 Bedroom, living room and kitchen

Adequate sound insulation between rooms and adjacent dwellings (neighbours) is important to acoustic privacy. Both quiet and noisy activities must be possible without disturbing others or being disturbed by others.

Noise at night is perceived as being particularly annoying, and special consideration must be taken with sound insulation of bedrooms (Miljøstyrelsen, 2010).

4.3.3 Mechanical equipment

Installation noise levels should be kept below 25-30 dB (A) in the main living spaces.

At night, even lower noise levels are desired. It is important that occupants can adjust the settings of ventilation systems manually in order to limit noise levels when needed. Noise from heating and cooling systems must also be limited. Modern, energy-efficient buildings have increasingly complex service systems (e.g. heat pumps) – the noise from these has been a problem in numerous cases.

Remember
Roof windows in a house situated in farmland will normally require less sound insulation than roof windows in a city house.

4.4 Outdoor noise

4.4.1 General

There is often a trade-off effect in noise control. For example, higher noise levels can be accepted in meeting a specific need; though this usually requires that the occupant is in control.

Many parameters will affect the outdoor noise level at a specific location. Some of these are described here.

4.4.2 Parameters affecting outdoor noise level

Location

The surroundings of a building have a major influence on the expected outdoor noise level. For example, the average outdoor noise level can be 60 dB(A) in a city centre and 50 dB(A) in a suburban residential area (ÖNORM, 2006).

The distance to the noise source has a decisive influence on the perceived sound level. Doubling the distance from the source reduces the sound level by approximately 3-6 dB. Unobstructed noise from a single source will be reduced more than noise from a linear source, such as traffic.

The presence of noise barriers, and reflections from and absorption in their surfaces, will affect the sound level at a specific location.

The source itself plays a role – traffic generates low frequency noise, birdsong high frequency noise.

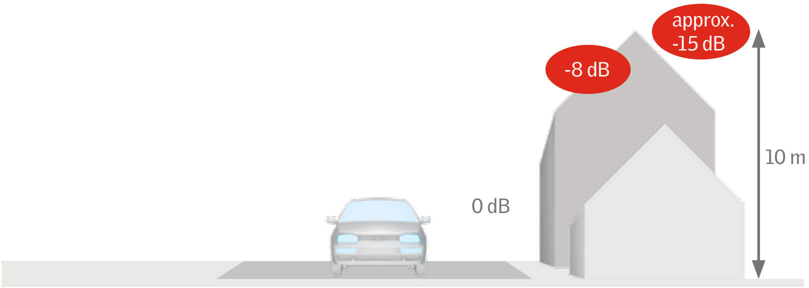
Other factors that affect the sound level – and how it can be redirected – are a building opposite, trees (summer or winter appearance), and the geometry of the noise barrier and its surface absorption properties.

4.4.3 Traffic noise

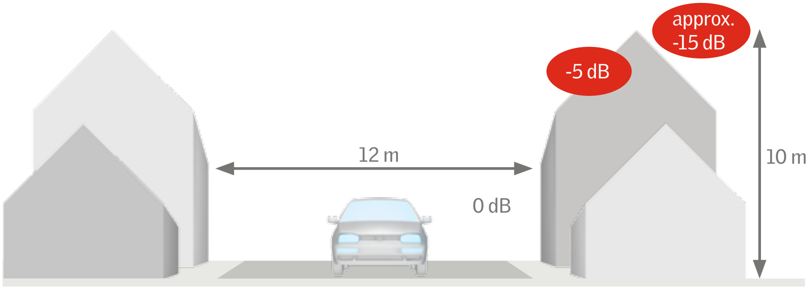
Traffic noise increases stress levels and the risk of cardiovascular diseases. A conservative estimate is that between 200 and 500 people in Denmark are dying prematurely from cardiovascular diseases and hypertension every year in Denmark because of traffic noise (Miljøstyrelsen, 2010).

In the first example shown below, a roof window experiences 8 dB lower noise levels than a facade window in the same building. For a roof window facing the back yard, that figure even falls to approximately 15 dB lower noise levels.

The second example shows that an opposing building will reflect some of the noise and reduce the diminution in noise level experienced by the roof window by 5 dB (ÖNORM, 2006).



1) shows the reduction of the outdoor noise level on the building envelope when there are no buildings opposite.



2) shows the reduction of the outdoor noise level on the building envelope when there are buildings opposite.

Figure 4.6 The examples show that facade windows experience higher outdoor noise levels than roof windows situated in the roof.

! Remember
A roof window will experience an outdoor noise level that is typically 5 dB lower than a facade window.

Figure 4.7 Illustration of noise levels in a city.

4.4.4 Rain noise

The sound/noise of rain on the roof is perceived differently. For some it is a pleasant sound, for others it is noise. At night, most will perceive it as noise if they are woken up by it.

To enable comparison of different products, the international test standard EN ISO 140-18 (CEN, 2006) has been developed to measure rainfall sound pressure levels.

Furthermore, French authorities have made requirements limiting the rainfall indoor sound pressure level to SPLmax<50 dB so children will not be woken up by the sound of rain (Ministère De La Santé, 2005).

The VELUX Group has developed the first roof window that can reduce rain noise. With a sound pressure level of 48 dB, it fulfils the French authorities' recommendation of a rainfall sound pressure level of max. 50 dB indoors.

4.4.5 Heavy noise (aircraft, trains, trucks)

Aircraft, trains and trucks generate very high noise levels (aircraft engines emit more than 110 dB), often in the low frequency area, which are difficult to reduce.

13% of the population of Europe is highly disturbed by the noise of road traffic, 5% by air traffic and 3% by railways (WHO, 2009).

Due to the high-energy noise and its low frequency range, noise distribution and noise reduction solutions must be calculated by specialists.

Remember
The VELUX Group has developed the first roof window capable of reducing rain noise so children will not be woken by it at night.

VELUX roof window with rain noise reduction.

4.5 Evaluation and measurements

4.5.1 General aspects

The most effective way of reducing the noise is by the reducing the "source" – e.g. reduce traffic noise by reducing the number of cars, prohibiting trucks, imposing speed limits or installing noise barriers close to the road. If this is not possible, the building envelope's ability to reduce the noise level has to be evaluated/calculated (see principle below) so as to obtain acceptable noise levels for the occupants (SBI, 2014a).

4.5.2 Sound insulation

Individual building components, and joints between components, contribute to the overall sound insulation of the building envelope.

The consequence is that a building envelope that fulfils a certain sound insulation level can consist of various building components with lower and higher sound insulation, but together they will reach the required level.

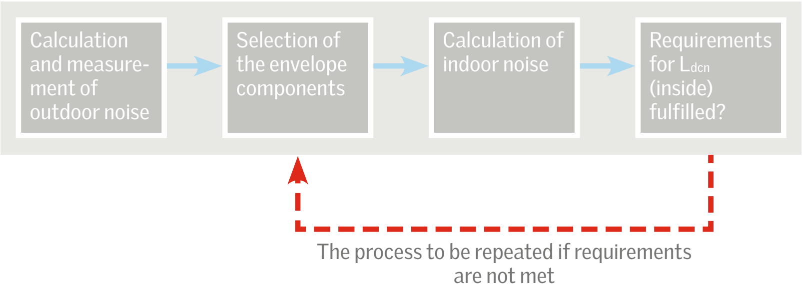


Figure 4.9 Main principle of process by calculations of indoor traffic noise levels (L_{den} (inside)). The process is repeated if the requirements for the highest value of L_{den} (inside) have not been met.

4.5.3 Measurement of sound insulation according to European standards

EN ISO 10140 series and EN ISO 717-1 (CEN 2010; CEN, 1997) apply to the testing and classification of the sound insulation of a window. The sound insulation found from the measurement is expressed as Rw(C, Ctr) in dB. The Rw value expresses the ability to reduce noise from outside to inside the building. Two correction factors (C and Ctr) are also found from the measurement.

The C factor should be used if the source of sound is speech, Ctr if the source of sound is rhythmic music or traffic noise.

A typical roof window with a standard construction of 2 layers of 4 mm glass, 16 mm cavity and 4 mm glass will attain an Rw of 32 dB.

If further sound insulation is needed, then windows with a pane construction of 2 layers with different glass thickness (4mm and 6 mm) will achieve a better sound insulation than a window with a standard glazing unit. Panes with 3 layer glass units with different distances between glass, and glass thickness, also perform better than the standard solution. Using a different gas filling will also have an effect – krypton gives better sound insulation. And finally, laminations are another way to achieve higher sound insulation of the glazing unit.

Example
Roof window with a glazing unit of 4 mm glass, 16 mm cavity with argon, and 4 mm glass (4-16-4)

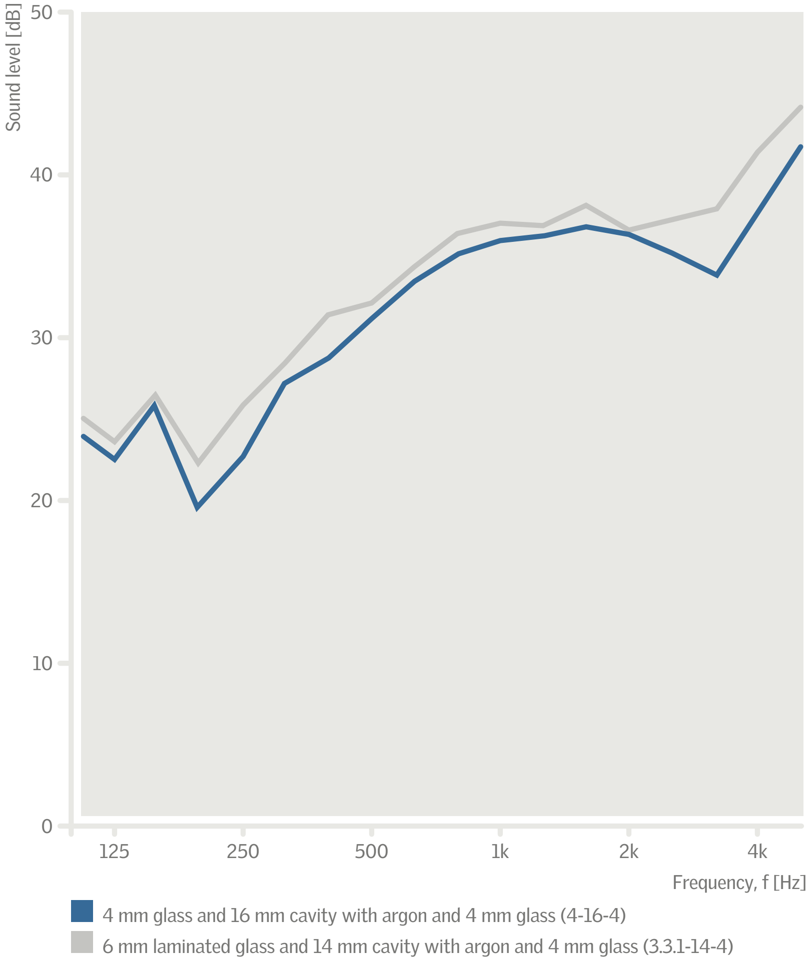
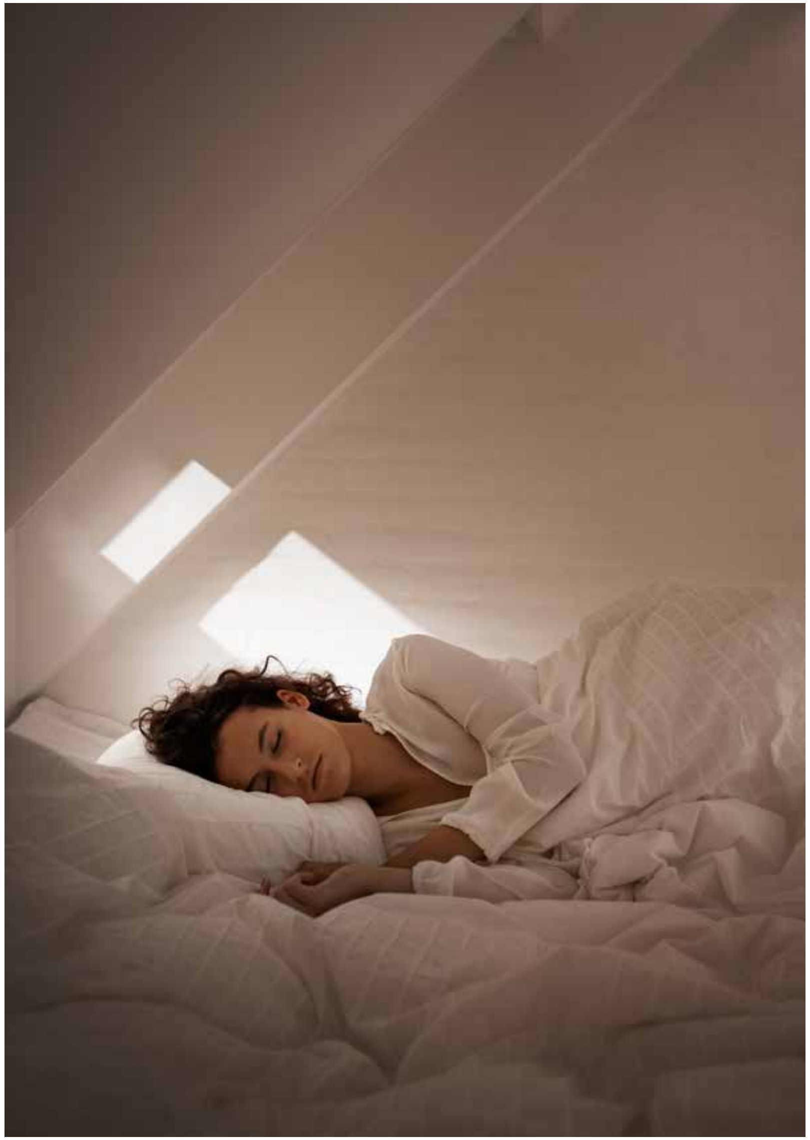


Figure 4.10 Example of sound insulation of roof window with two glazing types.



Keep noise in bedroom low.

4.6 Acoustics requirements in building codes

The building envelope is a mix of construction units with different sound insulation properties. A window cannot be compared to more compact building parts such as external brick walls or a roof construction.

The various building components will contribute with different levels of sound insulation. It is reasonable, therefore, that regulation of noise impact is made for the building as a whole – and not for the components alone.

A location on the roof will alter the outdoor road noise level – and the sound insulation required can be less for a window facing the back yard than for the facade facing the road. A typical change in the outdoor sound level would be -5 till -8 dB on the roof constructions facing the road and app. -15 db for the roof constructions facing the back yard (ÖNORM, 2006), see figure 4.6.

Legislation should take into account the fact that the various building components have different sound insulation properties, and that the variation of the outdoor sound level depends on the building location (city/country) and the location in the building envelope.

Energy

Energy

During recent decades, there has been an increasing focus on energy consumption, not least on the energy consumption of buildings, where efficient use of energy is an important part of the solution. Reduced dependence on fossil fuels and increased use of renewable energy are also important.

5.1 Energy

The world's energy demand has doubled in the last 40 years (International Energy Agency, 2009) and the increasing amount of fossil fuel used to meet this demand has had, and is still having, a severe impact on the climate (IPCC, 2007). Estimates suggest that, with our present dependence on fossil fuels, we will only have supplies for the next 200 years (Europe's Energy Portal, 2010). All over the world, there is increasing concern about these issues and most countries are taking steps to reduce both the the amount of energy we consume and our dependence on fossil fuels.

In Europe, buildings account for 40% of all energy consumption (European Commission, 2002). In the European Union, there is a saving potential of 20-50% by refurbishment of existing buildings and, with more stringent regulations, of new buildings (Eichhammer, 2009). Products such as solar thermal systems, PV panels and more costly options like small windmills, make it possible for homeowners to produce their own renewable energy and thereby change the source of energy.

The VELUX Group supports the use of onsite cost-optimal renewable energy when it is used directly in buildings, like solar thermal energy for hot water and space heating. However, renewable energy produced and exchanged with an external energy system, like the electricity grid, should be evaluated and based on cost-optimal levels and strategies for the energy system.

5.2 Energy sources

Energy for use in buildings can be produced locally at the building or at a remote location. Local production is often a furnace burning oil, natural gas, wood and so on, or it can be a geothermal resource utilised by e.g. a heat pump. Furnaces are mainly used for heating and hot water. Other local supplies are renewable sources such as solar collectors or photovoltaic panels (PV).

Remote production of electricity is based mainly on the combustion of fossil fuels, biomass or waste, or by nuclear power. Heat can also be produced in a remote location in the form of district heating. This can be generated in combination with electricity plants (combined heat and power, CHP) making it a more energy-efficient method. In recent years, central solar heating plants have been built in connection with district heating systems. Generally speaking, there is a great interest in renewable energy sources but most of the world's energy demand is still met by fossil fuels.

Fossil fuels emit CO_2 when converted into heat or electricity. The CO_2 causes climate change (IPCC, 2007) and reserves are on their way to depletion. Renewable sources (wind energy, hydro power, solar power, etc.) are all powered by the sun, a virtually unlimited source of energy.

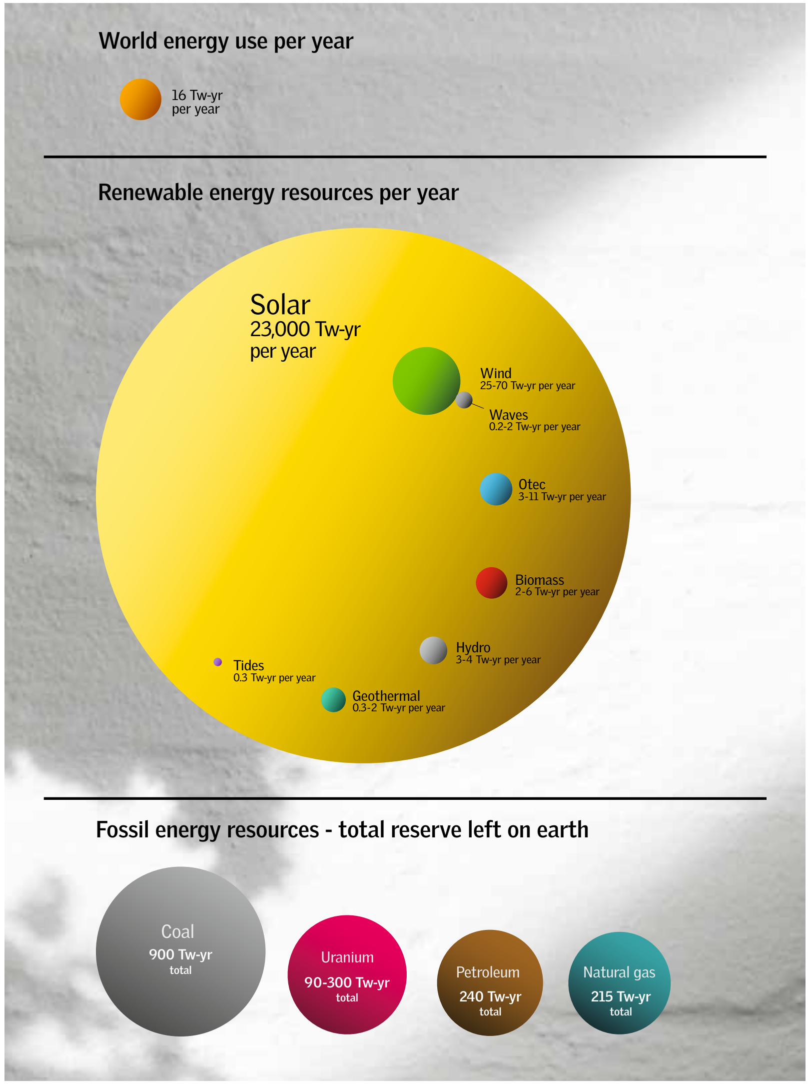


Figure 5.1 Total energy resources are compared to total energy demand. Estimates suggest that we will run out of oil and gas in the 21st century and coal and uranium in the 22nd century (Europe's Energy Portal 2010), whereas the sun will not burn out for billions of years.

5.3 Energy terminology

The VELUX Group's current terminology on energy use and windows includes two concepts: Energy Performance and Energy Balance (VELUX Group 2009).

Energy performance refers to the total yearly energy demand of a building, including heating, cooling, hot water and electric lighting (household appliances or other electrical equipment are not included). Energy performance is often expressed in kWh per year per m² of heated floor area (kWh/m²). The lower the value, the better. Energy performance can be used to find the difference between two scenarios, e.g. impact of more or fewer VELUX roof windows on the energy performance of a building. It can be calculated with dynamic simulation tools, among others the VELUX Energy and Indoor Climate Visualizer.

❗ Remember

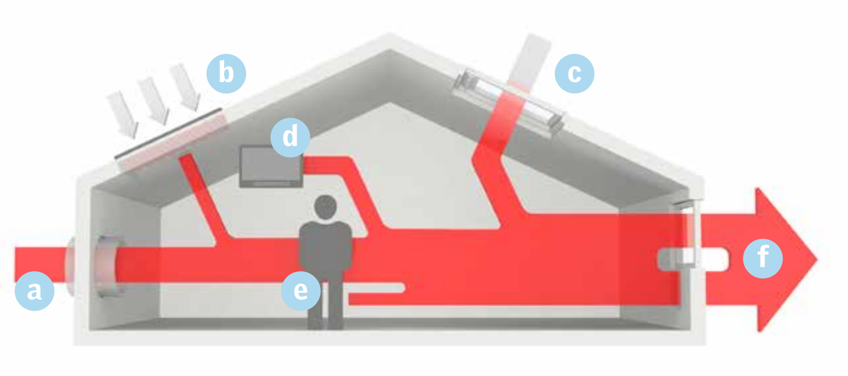
Buildings represent 40% of the energy consumption in the EU. Windows have a substantial impact on the energy consumption in buildings and on the indoor environment. However, the effect can be both positive and negative and care must be taken to use the advantages of windows and avoid the disadvantages.

For more information, see section 2.6.1. Energy balance refers to a single window and is expressed in kWh/m² per year for the window. The value expresses the energy efficiency of the window alone and can be used to compare different windows with regard to type, size, pane and other parameters. For more information on this subject, see section 5.5.3.

5.4 Energy use in buildings

Most of the energy used in buildings is used to maintain a comfortable indoor environment in terms of thermal comfort (heating or cooling) and air quality (ventilation). Other energy uses are electric light, domestic hot water and household appliances or other electrical equipment (refrigerators, computers, TVs etc.).

While energy consumption for heating in Denmark has been reduced during the last four decades due to efforts in legislation, electricity consumption has risen (Marsh et al., 2006). Similar trends in electricity consumption are expected to be seen in the rest of the western world. The reason is an increased number of consumer electronics, such as TVs, computers, stereos, portable music players, etc., which apart from stand-by consumption, are not covered by legislative requirements for energy efficiency.



a) External energy source e.g. fossil energy.
b) Renewable energy from e.g. solar collectors.
c) Solar gain.
d) Electrical devices e.g. television, kitchen aids
e) Warmth from humans and pets.
f) All energy will eventually leaving the building.

Figure 5.2 Illustration of the flow of energy through a building on an annual basis. The amount of energy supplied from an external source is less than the total heat loss of the building, because occupants, electrical devices and especially windows add "free" energy.

When designing a building or planning for refurbishing, it is important to use energy-efficient solutions, and perhaps even more important to do so without compromising the quality of the indoor environment. In the end, buildings are built to protect us from the weather and keep us comfortable and healthy. However, considerate design can reduce energy demand significantly.

5.4.1 Primary energy vs net energy

Net energy (or final energy) is often the result of energy performance calculations. Different energy sources have different utilisation factors and different impact on the environment, and should, therefore, be weighted differently. The concept of "primary energy" is that a factor for each energy source is used to weigh each source with regard to environmental impact. The factor is multiplied by the energy demand and can be different for different types of energy.

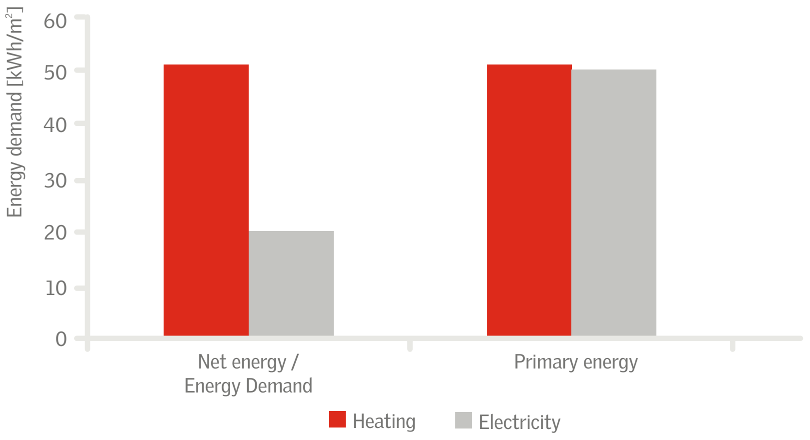


Figure 5.3 Energy demand of an existing Danish house for heating and electricity (cooling, ventilation fans and lighting) compared with the primary energy (factor = 2.5).

In Norway and Sweden, a considerable proportion of electricity production is hydro powered and thus has no great impact on the environment; the primary energy factor for electricity in Sweden is 2.35 (Smeds and Larsen, 2007). In Germany, the main energy source for electricity production is still coal, which has a much greater impact; the primary energy factor for electricity in Germany is 2.7 (Reiser, 2008). For some types of energy use, the conversion factor may become less than 1. An example is district heating in Denmark, where the factor is 0.8 due to the increasing amount of renewable energy in the supply of district heating.

In the UK, the primary energy factor for natural gas is 1.02 and 2.92 for electricity, (British Research Establishment, 2009). Figure 5.3 illustrates the difference between net energy and primary energy; the net heating demand is substantially higher than the net electricity demand, whereas the primary energy demand for heating and electricity is approximately the same.

Remember

Primary energy is different from net energy. Primary energy includes the effect of "converting" e.g. coal to electricity. Electricity production requires more fuel (e.g. coal or gas) than heat production, which is the background for the primary energy conversion factor - between 2.5 and 3.0 for most European countries.

5.5 Window systems

5.5.1 U value

The U value of a building component expresses the amount of energy transmitted from the warm side to the cold side. The lower the U value, the less energy is transmitted. It is often the aim to reduce the U value of building components in order to reduce the heat loss, and thereby the heating demand, of the building.

The U value is expressed in W/m^2K. In glazing constructions, heat is transferred from the inside through the insulating glass unit to the outside by radiation, convection (warm air rises, cold air falls) and conduction. The U value for windows is denominated U_w and is a combination of the frame Uf value, the glazing U_g value and the cold bridge effect between glazing and frame, ψ. To reduce the convection loss inside the glazing cavity, the cavity can be filled with gas, e.g. argon or krypton. To reduce the radiation heat transfer, low emissivity coatings can be applied to the glass panes facing the cavity. Low emissivity coatings are thin layers of metal, invisible to the eye but with emissivity values down to almost 0. A standard glass pane has an emissivity of 0.84. By adding internal or external shading devices to the window, the U value can also be lowered by reducing the radiation to the sky and by improving the thermal resistance.

The optimum cavity thickness is about 15 mm for argon and about 10 mm for krypton. VELUX roof windows are usually made with argon.

U value for sloped windows (roof windows)

As roof windows are installed in sloped constructions, the U_w value will be higher than for windows installed vertically. The convection in the gas between the glass panes is minimum for a vertical glazing, increases when the glazing starts sloping, and is at maximum with horizontal glazing. Convection also depends on the type of gas and cavity thickness. In general, the cavity is independent slope when the cavity thickness is around 10 mm or less.

This has an effect on the energy performance of a building, since the heat loss through the roof window is increased due to the larger U_w value. On the other hand, the solar gain and daylight are also increased. Roof windows are also exposed to a larger part of the sky than facade windows and are normally installed without any constructive shadows, thus increasing the amount of daylight and solar gain, as seen in section 1.5.3.

Traditionally, the U value is the single parameter used for evaluating the energy performance of windows. It is common practice to declare U_w for roof windows at 90°, i.e. as facade windows.

> » Dynamic window systems with VELUX ACTIVE Climate Control improve both the winter and summer energy balance of window systems «

Even though heat transmittance increases with increased slope, passive solar gains increase even more. So the vertical value leads to fairer indication of the performance than the sloped value. VELUX is striving to have the U value of windows replaced by energy balance (see section 5.5.5).

5.5.2 g value

The g value (total solar energy transmittance) is quantified by the amount of solar energy entering through the glazing. The g value is defined as the ratio between the solar gain transmitted through the glazing and the incident solar gain on the glazing. g value will be in the range of 0–1 (or 0 – 100%).

Dynamic window systems

The g value of a combination of window and accessories (for example solar shading) is dynamic and can be changed according to indoor and outdoor conditions. The shading can be controlled by the user or automatically with VELUX ACTIVE Climate Control.

Coatings

By using coated glass, part of the solar gain is blocked by reducing the g value. Depending on the type of coating, different parts of the spectrum can be blocked. For solar protective coatings the goal is usually to block as much as possible of the near-infrared radiation and allow as much of the visible radiation as possible to penetrate the coating. For clear coatings, the goal is usually to allow as much of the total solar radiation as possible to penetrate the coating. Even clear uncoated glass will reduce some wavelengths more than others. Coated glass will always affect colour perception indoors.

5.5.3 Energy balance

The term energy balance is used to describe the energy characteristics of a window. The intention is to communicate the balance between solar gain and heat loss. Energy balance is calculated as the sum of usable solar gain through the window during the heating season minus any heat loss. Energy balance is a more accurate way of describing the energy characteristics of a window than the U value alone, as energy balance includes both U_w value and g value to provide a more complete picture.

Methods

In general, the energy balance of a window is evaluated by determining the amount of useful solar gain during a year and subtracting from that the total heat loss through the window. However, since solar gain during the heating season contributes positively to heating demand, it may have a negative effect during a possible cooling season.

> »Roof windows have in general a better energy balance than facade windows during the heating season «

The higher the energy balance, the better. Energy balance is quantified in kWh per m² of window.

The amount of solar gain has to be determined for both the heating and the cooling season. For the heating season, the useful solar gain is determined by a utilisation factor multiplied by the amount of incident solar gain on the window. It is very dependent on the building type and location.

If a building is well insulated, the utilisation factor is low (about 70%), while for a poorly insulated building it is high (about 90%) .

Solar gain (g value) Heat loss (U value) Energy balance

The amount of solar gain reaching the window is dependent on the slope of the window and its orientation.
The total heat loss from a window is dependent on U_w value and air permeability. The heat loss through a window is found for both the heating and the cooling season, and determined by the number of heat degree hours for a year where there is heat loss in the heating and the cooling season. It is dependent on the building type (insulation level) and climatic conditions.

The energy balance of windows for the heating season can be expressed as:

$$\text{Energy Balance} = I_{solar} \times g_w - D \times (U_{w,\ slope} + L_{air\ permeability})\ [\text{kWh/m}^2]$$

$L_{air\ permeability}$ expresses the heat loss through the window due to air permeability.

In some European countries (UK, DK) a simplified definition of energy balance for facade windows during the heating

» The use of energy balance ensures that the best available window product can be chosen. The higher the energy balance, the better the window performs «

season has existed for some years. It is important to note that the energy balance for roof windows during the heating season is generally better than the energy balance for facade windows, which is why it is important that they are distinguished from each other.

The simplified method for energy balance considers only existing buildings with a specific distribution of windows per orientation. This method is shown in (Kragh et al., 2008). In the 2010 Danish Building Regulations (Danish Enterprise And Construction Authority, 2010), energy balance for windows is recognised as a legislative requirement for window replacements.

The VELUX Group is convinced that energy balance is a more correct and robust metric for the performance of windows than U_w value and it is working for the acceptance of a standardised method for determining Energy Balance (ISO, 2009).

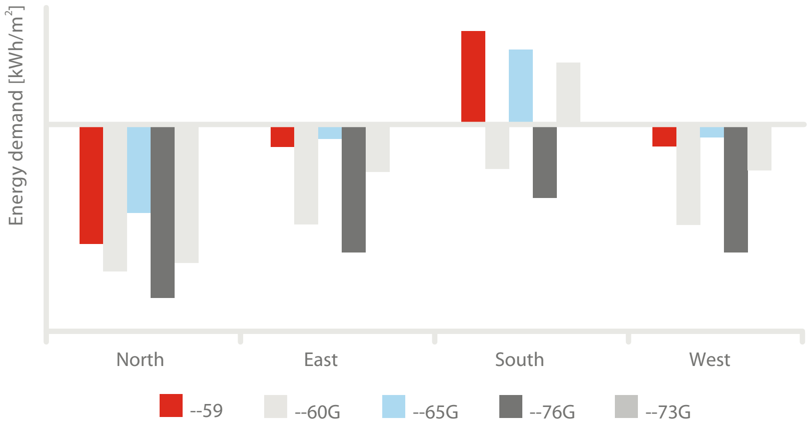


Figure 5.4 Energy balance for roof windows for each orientation during the heating season based on the method proposed for the Danish 2010 Building Regulations (Danish Enterprise And Construction Authority, 2010).

Remember
Energy balance is expressed in kWh/m² window. If the figure is positive, the window adds energy to the building. ! Remember The Energy balance for south-orientated windows is better than other orientations.

» For existing buildings the tendency is that the g value is at least as important as the U value for the energy performance «

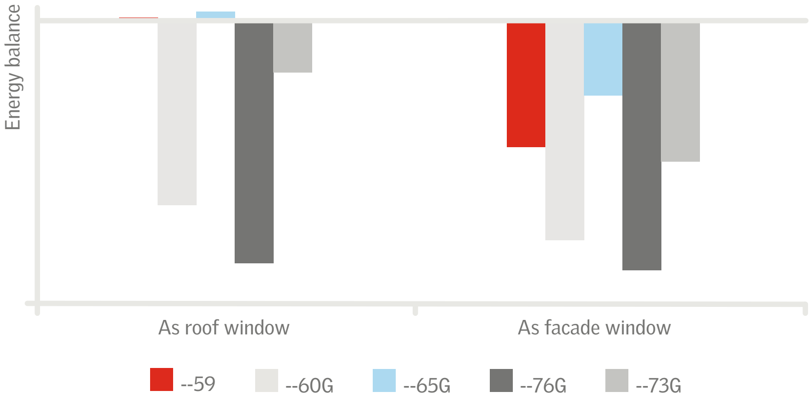


Figure 5.5 Energy balance for roof and facade windows with different pane types for the heating season, based on the current draft for the Danish 2010 Building Regulations (Danish Enterprise And Construction Authority, 2010).

Remember
The energy balance of a window depends on the type of building in which the window is installed, the orientation and slope of the window, and the geographical location.

5.6 Energy performance of different building types

5.6.1 Energy aspects of daylight

By using daylight to its full potential, the electricity demand for lighting during daytime can be significantly reduced or even eliminated.

The Architectural Energy Corporation has stated (Architectural Energy Corporation, 2006) that "Daylighting can drastically improve the energy efficiency of a space with adequate control of electrical lighting and solar heat gain". In offices, the electricity demand for lighting can account for as much as 40-50% of the total energy demand (Walitsky, 2002), which can result in significant savings if replaced by daylighting. In order to quantify the energy savings on electric lighting, the number of hours for which daylight is an autonomous light source in the interior must be known. The relevant light levels for residential buildings were discussed in section 1.7.1.

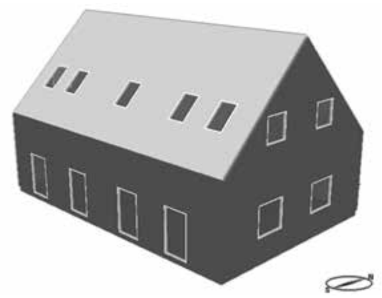
The optimal use of windows in buildings to provide good daylight conditions with good energy performance requires careful selection of the window characteristics τ_v, g (and U_w). Due to the laws of physics, the g value will always be at least 50% of τ_v.

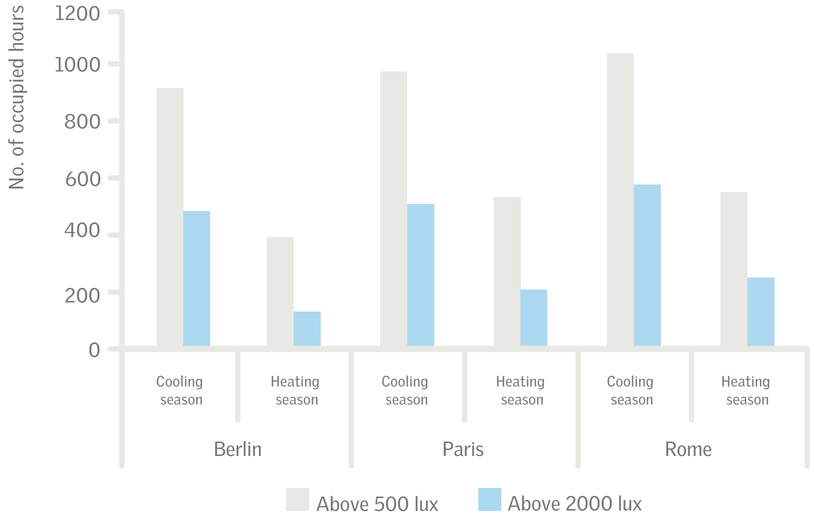
The best solution is often a combination of window and solar shading. A window with high g value and high τ_v value will generally provide a good result. High values of g and τ_v will perform well in that part of the year with least light; in parts of the year with excessive light, solar shading should be used. It is important that the design of the building and the placement of windows in it are planned as part of a holistic process where the requirements for daylight and energy performance are continuously evaluated and used as design parameters (Moeck, 2006).

The following example illustrates that high light levels are achieved with daylight and that windows are very energy-efficient light sources.

Example: Energy performance of a house with no windows

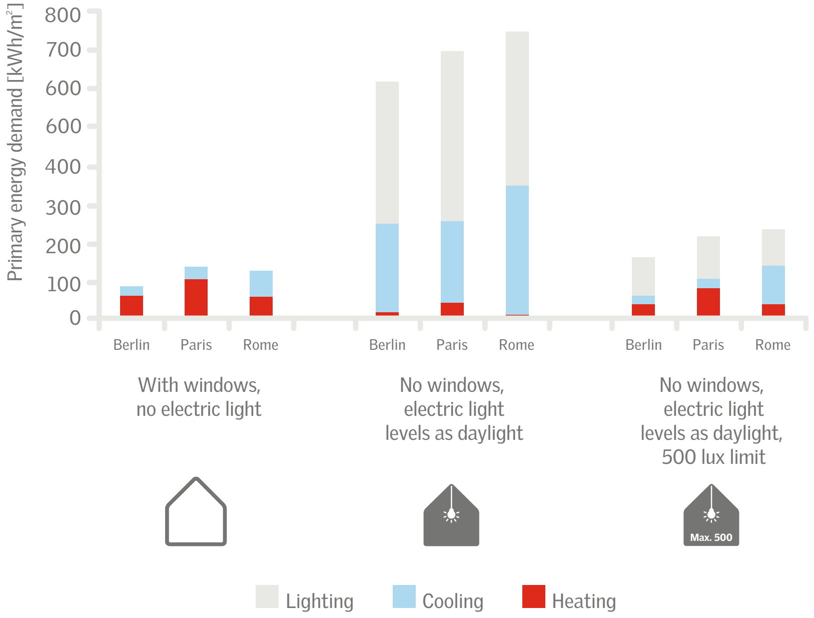
In a typical house, the light level achieved with daylight is determined for every hour of the year. Four locations are investigated: Berlin, Paris, Rome and Istanbul. High light levels (above 2 000 lux) are achieved achieved all year round, as illustrated in the figure below.





What impact does daylight have on the energy use in a building? To answer this, it has been investigated what would happen if there were no windows in the house and the light levels had to be achieved with electric lighting. As the amount of electric light influences the heating and cooling need, the resulting energy use for lighting, cooling and heating in the building must be evaluated together. The results from VELUX Energy and Indoor Climate Visualizer are shown in the figure.

» Windows are low-energy light sources «



For each location, the lowest total primary energy demand is achieved by the building with light provided by windows. The energy demand of the building with no windows is approximately five times higher than that of the building with windows if we use electric light to obtain the same light levels. This underlines the fact that windows are low-energy light sources (Foldbjerg, 2010).

» The use of roof windows will result in higher daylight factors «

Example: Impact of roof window area on daylight and energy performance
It was shown in the Daylight chapter that roof windows deliver more daylight than facade windows. For an actual building that means that a specific daylight factor can be achieved with less window area if roof windows are used.

A low energy 1-storey house with an 8 x 18 m footprint located in Berlin has been investigated. The VELUX Daylight Visualizer was used to find combinations of roof and facade windows areas that reach a daylight factor of 4% and 6% respectively.

By increasing the percentage of roof windows, a higher daylight factor can be achieved. A total window area of 25 m² of facade windows only will provide a DF of 4%, while 25 m² with a mix of 64% facade windows and 36% roof windows will provide a DF of 6%, as indicated by the dotted lines on the figure.

Next the VELUX Energy and Indoor Climate Visualizer was used to determine the heating demand for each combination of RW and FW. The results are shown in the figure below

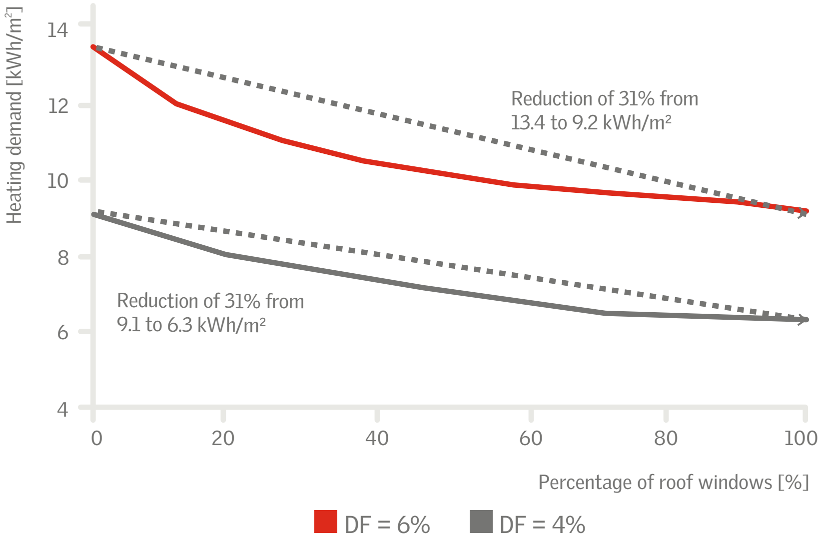


Figure 5.6 The energy performance is improved by increased roof window area. With DF = 4%, the heating demand is reduced from 9.1 to 6.3 kWh/m², and with DF = 6%, from 13.4 to 9.2 kWh/m². Both reductions correspond to 31%.

» Natural ventilation combined with mechanical ventilation is more energy efficient than mechanical ventilation alone «

5.6.2 Energy aspects of ventilation

Ventilation – and particularly natural ventilation – has an influence on the energy demand for heating, cooling, and electricity for fan operation.

Ventilation and heating

When the outdoor temperature is below the indoor temperature, energy for heating is required to raise the temperature of the fresh air to the desired indoor temperature. The magnitude of the energy demand depends on the ventilation rate and the temperature difference.

Heat recovery units can be used to recover (reuse) most of the heat in the extract air to heat up the fresh outdoor air before it is supplied to the building. Heat recovery systems are generally only available with mechanical ventilation as it requires a physical unit through which both the supply and extract air can be circulated. Up to 90% of the heat can be recovered.

Electricity is used to operate the mechanical ventilation system, but this amount of energy is small compared to the amount of energy that can be recovered when the outdoor temperature is low. So mechanical ventilation with heat recovery is an energy-efficient solution for new, airtight buildings during winter. However, leaky buildings will have less benefit from heat recovery as mentioned in section 2.2.2. Mechanical ventilation also requires maintenance (filter changes, cleaning, etc.), which should be taken into consideration.

When the outdoor temperature is in the range of 14-18°C (depending on the building), there is no need for energy to heat the supply air. In this situation, natural ventilation is more energy efficient than mechanical ventilation, since no electricity is used for fan operation. The combination of natural and mechanical ventilation is called hybrid ventilation. See section 2.2.3 for an example of the energy savings that can be achieved with hybrid ventilation, and section 2.1.4 for an example of the impact on energy demand of the ventilation rate.

Natural ventilation and cooling

When the outdoor temperature, in combination with solar gains, causes the indoor temperature to rise, there is a risk of overheating. In some buildings this is handled with air conditioning, but natural ventilation is an efficient alternative that saves energy. Natural ventilation can be used during daytime (summer ventilation) to control the temperature, as mentioned in section 2.4.5.

Remember
Hybrid ventilation uses no electricity for fan operation during the summertime.

Natural ventilation can also be used at night (night cooling), to cool the building and thus eliminate the need for air conditioning the following day, as mentioned in section 2.4.6.

Night cooling works by cooling the constructions in the house. The effect is larger if the building is "heavy". Concrete and bricks are "heavy" materials, so a building with concrete or bricks as wall, ceiling or floor materials is heavy".

5.6.3 Energy aspects of solar shading

Solar shading has an important influence on the energy performance of buildings. The use of solar shading affects both g value and U value, so solar shading can be used both in warm and cold climates to improve the energy performance of buildings. And as solar shading is dynamic – it can be activated when needed – it is an important part of the window system.

External shading prevents solar heat gains more efficiently than internal shadings. External shading is, therefore, the best choice when the purpose of shading is to prevent overheating and reduce the electricity demand for cooling.

Internal shading does, though, provide some reduction of overheating. Internal shading is generally more efficient at increasing the insulation of the window system, which means that the heating demand of the building can be reduced if used correctly. Internal shading also serves the purpose of controlling daylight.

VELUX ACTIVE Climate Control is an example of a dynamic window system in which the use of the solar shading is optimised automatically, with no interaction from the user. It thus reduces the need for heating and cooling, yet improves indoor comfort significantly (Philipson, 2010).

5.6.4 Building energy performance in cold climates

In cold climates, an important design objective is to minimise the heating demand and the electricity demand for lighting. Secondarily, the electricity demand for fan operation (etc.) should be minimised and the building should be designed with no need for cooling. The latter has been shown to be of increasing importance – the over-heating challenge has been overlooked in the design of many low-energy buildings. Windows provide useful solar gains every month of the year, also during the summer months. However, solar gains are a double-edged sword and may lead to overheating. The energy evaluation should, therefore, be based on annual

calculations for which tools such as the VELUX Energy and Indoor Climate Visualizer can be used. The example in Figure 5.7 shows that the useful solar gains in May to August in Denmark are substantial, which means that even though there are cold days and nights in summer as well, heating is usually not needed during the warm months.
The importance of solar gains during the summer is illustrated in the following example.

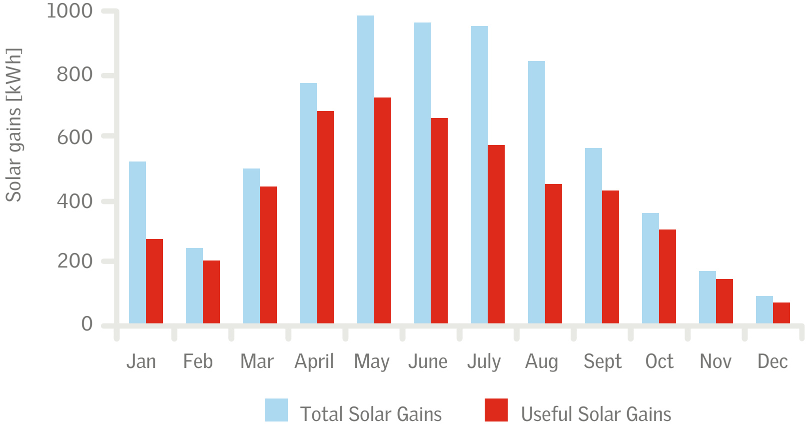


Figure 5.7 Example of useful solar gains in an existing building in Denmark.

! Remember
Windows provide solar gain all year round – not just in the wintertime. The solar heat gain through windows is the main reason why we can often turn off the heating during summer, even in cold climates.

5.6.5 Building energy performance in warm climates

In warm climates, the main design objective is to achieve thermal comfort during the warm part of the year. Secondarily, to minimise the heating demand during the cold part of the year. As seen in the previous sections, the electricity demand for cooling can be minimised, and often eliminated, by using natural cooling technologies. Such technologies include ventilative cooling and solar shading. In combination with intelligent building design that takes into account the shape, thermal mass and orientation of the building, peak cooling loads can be kept low or even eliminated. Automatic control will enable the maximum potential of natural cooling.

It was shown in section 3.3 that thermal comfort in naturally-ventilated buildings can be achieved at indoor temperatures above 26°C due to adaptation.

The main target should, therefore, be to design the building without a cooling system and instead use solar shading and natural ventilation to avoid unnecessary energy use.

5.6.6 Consequences of future requirements for better energy performance

Current trends in European and national legislation point towards a continued focus on energy in building legislation, which means that the minimum requirements for the energy performance of new buildings as well as refurbishments will be tightened.

> **» The energy performance of an existing house could be worsened if the windows were removed «**

Example: energy performance of a house with no windows

The heating energy performance of a building with windows is compared to a building with no windows. The building is located in Berlin. The table below shows the results for four different construction periods. The calculations were performed in BSim.

	GGL 59	GGL 65G	No windows
Low-energy building (2020)	25 kWh/m²	20 kWh/m²	20 kWh/m²
New building (2005)	61 kWh/m²	56 kWh/m²	61 kWh/m²
Existing building (1980)	87 kWh/m²	82 kWh/m²	93 kWh/m²
Existing building (1940)	146 kWh/m²	143 kWh/m²	162 kWh/m²

For a new or future building, the energy performance of the house with no windows is of the same magnitude as the house with windows, which means that the solar gains of the windows are of the same magnitude as the additional heat loss.

For existing buildings, the house with windows performs better than the house with no windows.

Cold climates

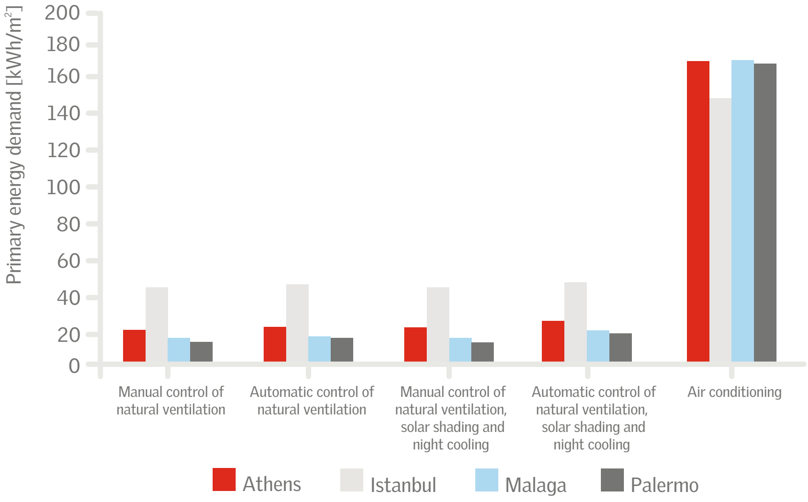
As seen in section 5.4.3, the energy balance of windows depends on the building where they are installed. In section 5.5.5, there was an example of how much of the annual solar gains can be utilised in an existing building in northern Europe. In a high-performing building the heat loss is low, so less solar gain can be used.

In high-performing buildings, the focus of windows will be on low U_w value rather than high g value.

The example shows that the relative saving by using 3-layered glazing is largest for low energy buildings, while only small savings are seen for existing buildings.

Example: solar shading and natural ventilation provide good energy performance and thermal comfort in warm climates.

The performance of a typical building in four cities in warm climates was investigated with the VELUX Energy and Indoor Climate Visualizer. Different combinations of solar shading and natural ventilation were investigated and compared to an air-conditioned house. The investigated cities were Athens, Istanbul, Malaga and Palermo (Asmussen, 2010). The energy performance of the building with air conditioning was in the range of 150 – 160 kWh/m2, which is 3 to 10 times worse than the buildings without air conditioning.



The houses without air conditioning also achieve acceptable thermal comfort. The graph below represents results from Athens and shows that acceptable thermal comfort can be achieved for 98-99% of the time with automatic control of natural ventilation, solar shading and night cooling.

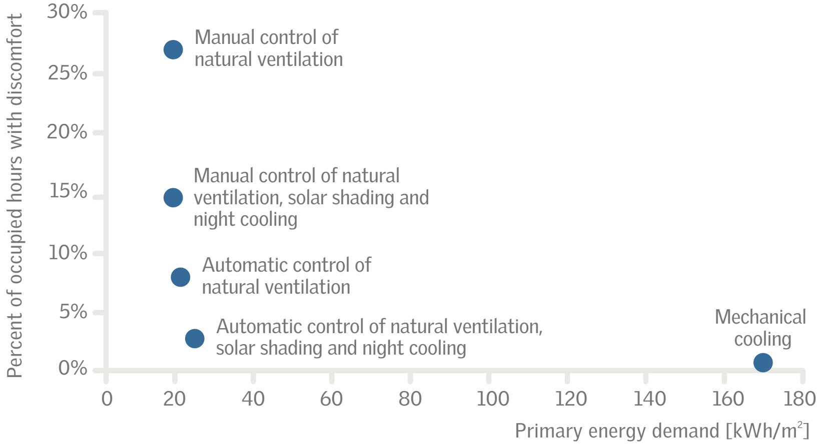


Figure 5.8 The figure shows both energy performance and thermal comfort for Athens and shows that the thermal comfort achieved with automatic control is as good as with mechanical cooling.

Example: relevance of 3-layered glazing in high-performing buildings

The previous example showed the impact of using 2-layered vs 3-layered glazing in Berlin in a typical house of four different construction periods. In the table below, the relative reductions by using a 3-layered pane compared to a 2-layered pane are shown.

	Low-energy building (2020)	New building (2005)	Existing building (1980)	Existing building (1940)
Relative reduction of heating demand	17%	7%	6%	2%

Remember

For high-performing buildings, the window U value is becoming increasingly important compared to the g value, because less solar gain can be used in low-energy buildings

5.7 Renewable solar energy supply

In the previous sections on energy, it was discussed how the space heating and cooling demand of buildings can be reduced by using the optimal combination of windows and accessories. The focus of this section is the potential of using renewable energy from the sun to supply part of the remaining energy demand of a building.

Apart from daylight and passive solar gains, the energy from the sun can be utilised in the building for two main applications:

- Solar thermal system, providing hot water.
- Photovoltaic system (PV), providing electricity.

The two systems both use panels to collect the solar energy, very often installed on the roof of the building, but the two systems are based on very different technology.

The area of solar panels required for a specific house depends on the solar intensity at the location of the house. The annual energy gain from the sun in southern Europe is approximately 40% higher than that in northern Europe. Solar panels have the highest performance when they are installed on a south-facing roof with a 42-60° slope, depending on the location in Europe. Nevertheless, panels installed at a different slope or orientation will still have a performance close to optimal. For instance, south-facing solar thermal collectors perform at 91% if installed close to vertical or horizontal position, as illustrated by the table below. The optimal slope for solar thermal collectors and solar cell modules (PV) is slightly different, because of the utilisation of the produced energy.

Figure 5.9 Solar energy gain depends on the orientation and slope of the panels.

	South		SE or SW		East or west	
Slope 15°	91%	97%	89%	95%	82%	89%
Slope 30°	96%	100%	92%	96%	82%	86%
Slope 45°	100%	98%	95%	95%	81%	82%
Slope 60°	101%	93%	96%	89%	79%	76%
Slope 75°	98%	84%	93%	81%	75%	67%
Slope 90°	91%	71%	85%	69%	69%	58%

The table shows the approximate relative performance of solar thermal collectors and solar cell modules depending on slope and orientation located in Denmark.

5.7.1 Solar thermal system

A solar thermal system only produces energy when there is daylight. Most solar thermal systems are designed to produce domestic hot water (DHW), as described in the following.

Solar energy will heat up a glycol/water mix in the panels on the roof (called collectors), from where the heat will be transferred to a storage tank by use of a pump and a controller. The most common collector type is the Flat Plate collector, which can be installed either on the roof or integrated into the roof material. Less common is the Evacuated Tube collector, which can only be installed on the roof. Evacuated Tube collectors are more suitable for high temperature applications like cooling and industrial applications, where as Flat Plate collectors are used for lower temperature ranges for commercial and private applications.

The heat is stored in a water tank, of a size that can store the domestic hot water consumption of a house for 1-2 days - for a typical family, 200-300 litres. The optimal area of solar collectors for a building will meet the daily domestic hot water demand of a house during the summer months. In the less sunny parts of the year, the solar thermal system will also produce energy, but will need a supplementary heater.

Solar fraction

The heat produced by the solar thermal system in a year is divided by the domestic hot water demand of the house; this number is called the solar fraction and expresses how large a part of the domestic hot water demand is supplied by the solar thermal system. Systems are designed to provide a solar fraction between 60% and 75%.

The only running cost associated with solar thermal systems is the electricity for the pump and control system, which is only about 80 kWh annually.

Figure 5.10 Diagram of a solar thermal system for domestic hot water production.

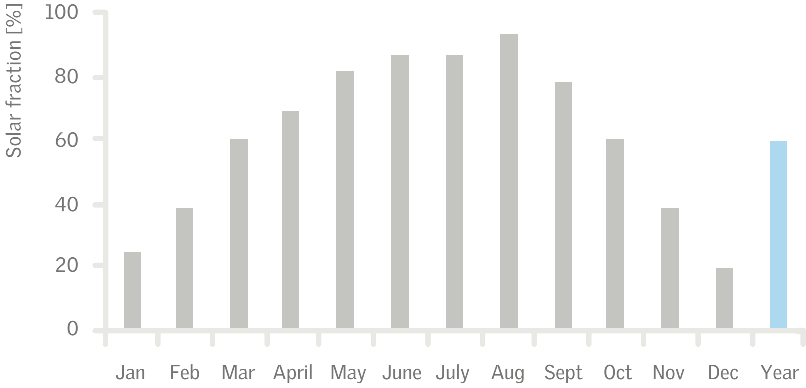


Figure 5.11 Example of the monthly solar fraction in London, UK. The solar fraction is almost 90% in the summer and 60% on an annual basis.

! Remember
Solar collectors can provide up to 75% of the energy demand for domestic hot water.

5.7.2 Photovoltaic system (PV)

A photovoltaic system consists of solar cells, arranged in modules, that produce electrical energy when it is daylight. The solar cell modules (or arrays) can be installed on the roof or integrated into the roof material (BIPV). Solar radiation generates electricity in the solar cells. The electrical current produced will normally be led to an inverter, which changes DC to AC current. The inverter is connected to the house's energy meter, from where it can be used by any electrical appliance in the house – or exported to the grid.

Performance of solar cell systems (PV systems)

The yield from a solar cell system depends on many parameters, but mostly on the solar cell materials, mainly monocrystalline or polycrystalline silicon cells (highest efficiency) or thin film cells (lower efficiency). The cells are connected in a module, in series and/or parallel, so efficiency and other technical parameters should be based on module/array or system figures. But performance also depends on the same solar parameters mentioned in the Daylight section (solar irradiation, module orientation and slope). The influence of orientation and slope can be seen from table below figure 5.9.

The temperature of the cells also has a great influence on efficiency, most influence on the crystalline cells and less on the thin film cells. Ventilation around the modules is therefore very important.

Because the square-metre efficiency of a solar cell module is generally less than that of a solar thermal collector, a PV system requires much more space on the roof than a solar thermal system to provide the same amount of energy.

Figure 5.12 Diagram of a solar cell system for private house application.

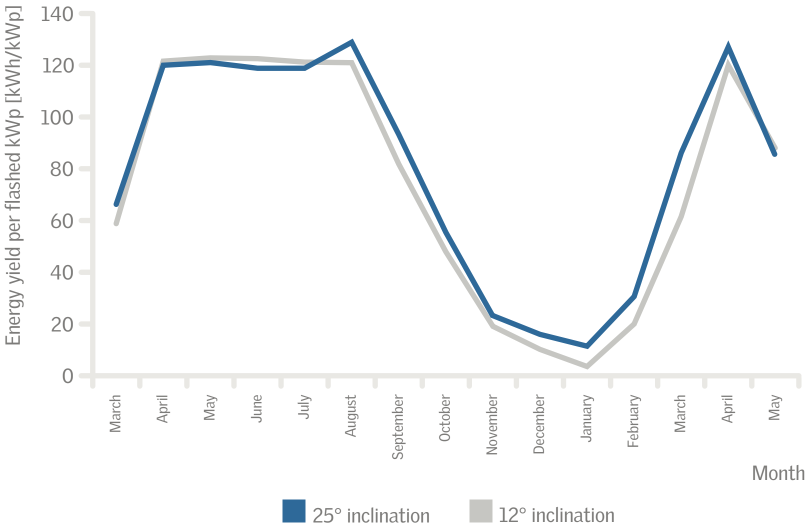


Fig. 5.13 Examples of PV yield curve for two modules with 12° and 25° inclination.

Building Integrated PV (BIPV)

For aesthetic reasons, Building Integrated Photovoltaic systems (BIPV) are becoming much more popular. The modules are integrated into the roof, more or less at the same level as the roof material. However, it is important to consider the ventilation of the modules in the roof, as a temperature rise in the module will reduce the performance of the system.

However, the BIPV gives further opportunities for integrating the modules together with one or more roof windows. VELUX A/S offers two solutions for the integration of certain types of PV modules together with a VELUX roof window.

Easy roof solution

The Easy Roof mounting system consists of frames that match the sizes of PV modules from several suppliers and that can be installed directly onto the roof laths. Specially designed frames for VELUX roof windows with BDX in the sizes MK06 and MK08 permit a complete BIPV solution.

InDax solution

Another BIPV solution is the Indax mounting system - PV modules from Monier, integrated with a VELUX roof window with EDO flashing.

Remember
Use of solar energy is still beneficial even when the slope is not optimal and orientation is not directly to the south.

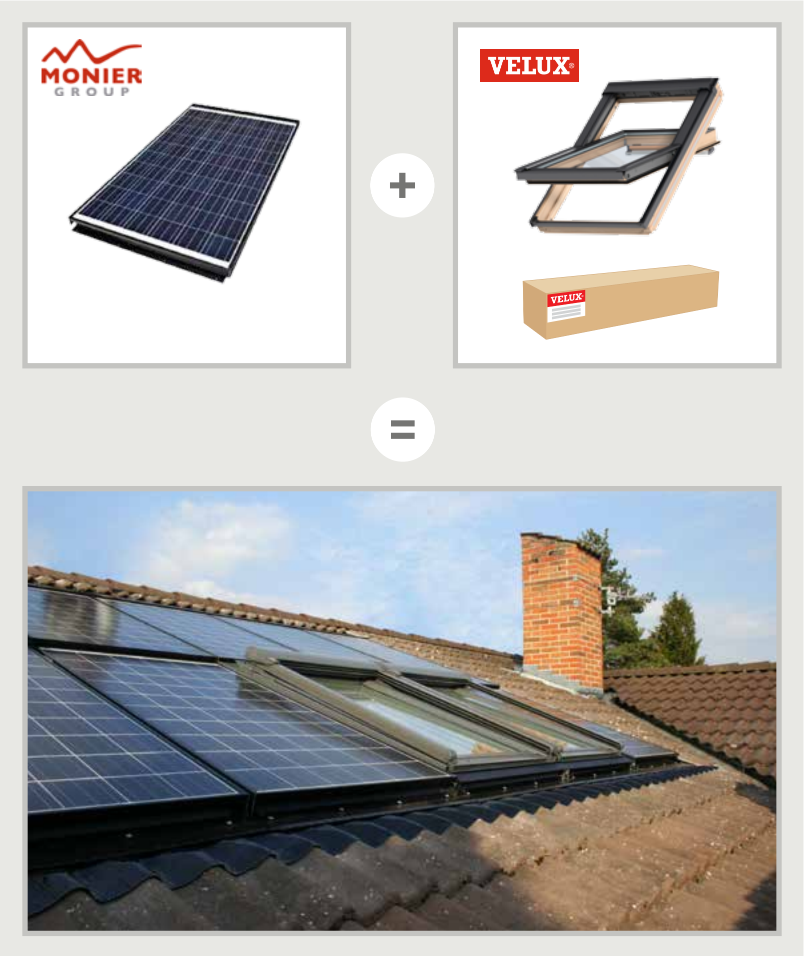


Figure 5.14 Illustration of package solutions – with photo of VELUX flashing for BIPV

5.8 Index

1) Flat Plate collector:
   A Flat Plate collector consists of an absorber plate, covered on the top by a flat glass pane and insulated at the bottom and at the sides by insulation material.

2) Evacuated Tube collector:
   An Evacuated Tube collector consists of several vacuum tubes installed together in a rack. In each tube, an absorber strip has been inserted into the glass tube and insulated by a surrounding vacuum.

Environment

Environment

The basis for most environmental assessments, environmental legislation and private schemes are life cycle thinking and life cycle assessments (UNEP, 2009).
This chapter will introduce you to life cycle assessments, the methodology for assessing sustainability of buildings, and assessments of buildings and construction products.
It will also provide an overview of the most important environmental legislation in the EU, with emphasis on chemicals.

6.1 Life Cycle Assessments

A life cycle assessment (LCA) is an assessment of a given product´s global, regional and local environmental impacts and consumption of resources throughout its whole lifetime.

6.1.1 LCA

An LCA consists of various stages, as shown in figure 6.1.

- The extraction and production of the **raw materials**.

- The **manufacture** of the product.

- The **use** of the product (e.g. the energyconsumed whilst used by the customer).

- The **End-of-Life (EOL)** of the product. It can either be landfilled, energy recovered or recycled.

- Between the various stages is the **transport** of the raw materials, the finished product, and the used product on its way to EOL.

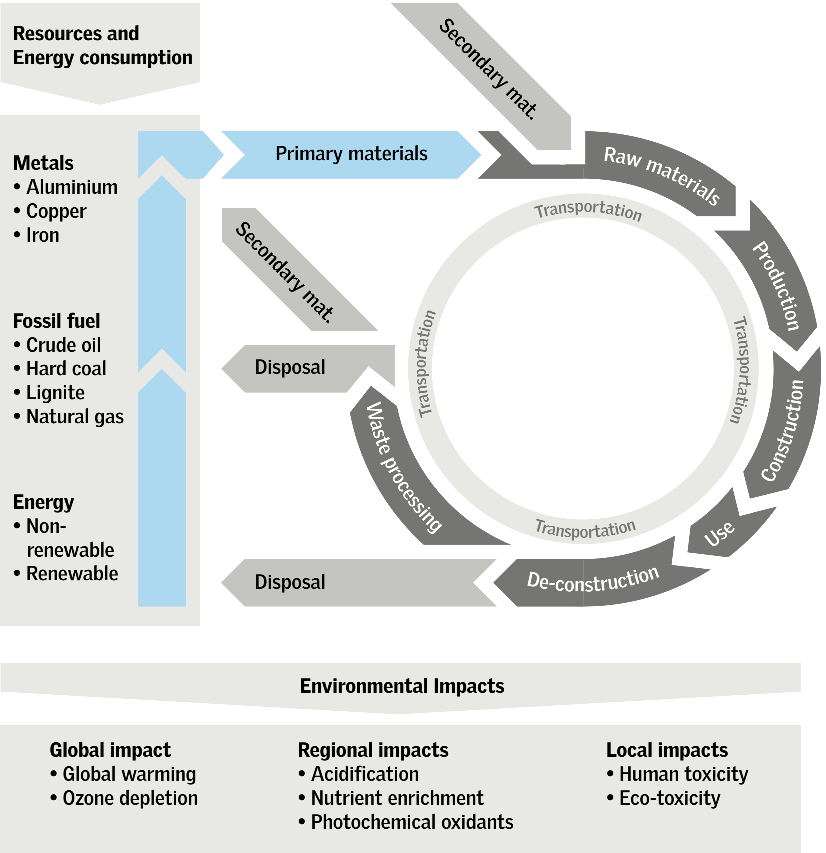


Figure 6.1 Life cycle assessment (LCA)

Figure 6.1 shows the life cycle of a product from the extraction of raw materials, to the manufacture of the product, the use phase and the EOL, which is divided into landfill, recycling and energy recovery. Transport is incorporated in all the life cycle stages.

Environmental impacts are divided into global (effects on a global scale), regional (effects on a regional scale), local impacts (effects on a local scale) and resource and energy consumptions Local impacts are not dealt with further in this book.

Global environmental impacts

Global environmental impacts comprise two parameters:

- Global warming (emissions – e.g. CO_2)
- Ozone Depletion (emissions of CFC gases)

Regional environmental impacts

Regional environmental impacts comprise three parameters:

- Acid lakes, acid rain (acidification of soil and water)
- Algal blooms (eutrophication)
- Summer smog (photochemical ozone creation)

Resource and energy consumptions

In an LCA, two types of consumptions are assessed; use of abiotic resources like metals (materials) and use of fossil energy.

- Consumption of primary resources (depletion of abiotic resources – elements)
- Consumption of fossil fuels (depletion of abiotic resources – fossil fuels)

6.1.2 Other parameters of life cycle assessments

Carbon footprint

A carbon footprint is a subset of a full LCA, where only greenhouse gas emissions (e.g. CO_2) are evaluated.

Cradle-to-gate

Cradle-to-gate is an assessment of a given product in which only the extraction of the raw materials (cradle), transport and production are included.

Cradle-to-grave

A cradle-to-grave assessment consists of a full life cycle assessment. It thus includes extraction of raw materials, manufacture of the product, use of the product and EOL.

Cradle-to-cradle

Cradle-to-cradle is almost the same as cradle-to-grave but with a different approach to EOL. The approach is that all materials should always be recycled into new products. Hence chemicals should be used with great care in order to prevent discharge to the environment. In cradle-to-cradle, energy consumption is not taken into account because it is presumed that all energy is renewable (ECO platform, 2014).

6.2 The European methodology for assessing sustainability of buildings

6.2.1 Framework

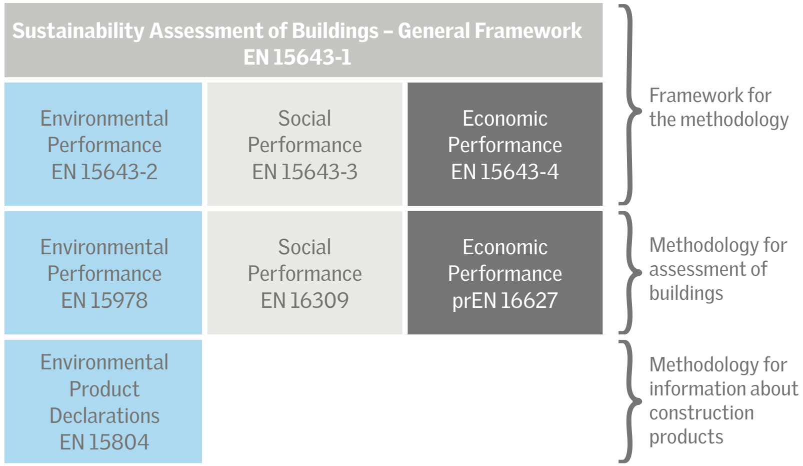
The EU has asked the European standardisation organisation CEN to develop a common European methodology for assessing sustainability of construction works.

Today, the series consist of ten European standards and technical reports (CEN, 2012) – probably with more to come. The standards are voluntary, but created on a mandate given from the Commission; the methodologies are expected to become mandatory.

The standards fulfil the general principles for LCA (see 6.1) and sustainability, described in international standards ISO 14040 and ISO 14044 (CEN, 2006a; ISO, 2006b) and by UNEP and SETAC (UNEP, 2009; EPEA, 2014)
All major private scheme operators have declared that they will follow the principles of these standards or at least acknowledge data derived from applying the methodology (EPEA, 2014).

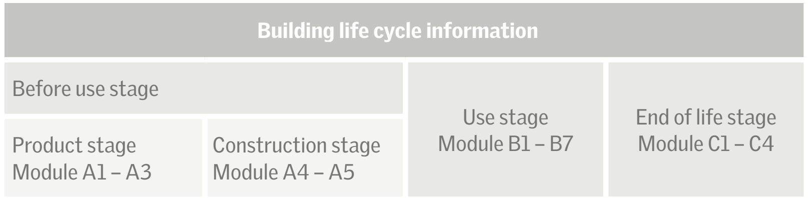
EN 15643-1 to 4 describes the framework for the methodology, which is a modular system.

A full sustainability assessment of a building requires investigation into its environmental, social and economic performance at all stages of its life cycle. The life cycle stages are divided into "before use", and "EOL".



Sustainability Assessment of Buildings – General Framework EN 15643-1			
Environmental Performance EN 15643-2	Social Performance EN 15643-3	Economic Performance EN 15643-4	Framework for the methodology
Environmental Performance EN 15978	Social Performance EN 16309	Economic Performance prEN 16627	Methodology for assessment of buildings
Environmental Product Declarations EN 15804			Methodology for information about construction products

Figure 6.2 Sustainability assessment of buildings – standards overview.



Building life cycle information			
Before use stage		Use stage Module B1 – B7	End of life stage Module C1 – C4
Product stage Module A1 – A3	Construction stage Module A4 – A5		

Figure 6.3. Modular system for the building life cycle in the TC 350 standards.

Together, these two principles (Figure 2 and Figure 3) form a modular system in which the methodology can be described and the assessment performed. For each of the modules A1 to C4 there is, in principle, a description of how to assess the environmental-, social- and economic performance of that aspect of a building in the methodology standards.

6.3 Assessments of Buildings

There are many different schemes for assessment of buildings. The majority are private programmes with or without official recognition by national authorities. It is always advisable to check the background and reputation of a scheme.

The purpose of certifications of sustainable buildings is to define the quality level for sustainability. Based on performance criteria, different buildings can be compared and benchmarked. The number of global certification systems is growing. There are many national systems but the best-known international systems are the English BREEAM and the American LEED. Two newer systems are the French HQE and the German DGNB.

6.3.1 Active House

Active House principles are used to design and renovate buildings that contribute positively to human health and well-being by focusing on the indoor and outdoor environment and the use of renewable energy. An Active House is evaluated on the basis of the interactions between energy consumption, indoor climate conditions and impact on the environment. An Active House is energy efficient, with all its energy requirements met by renewable energy sources, either integrated in the building or from the local collective energy system and electricity grid – thus making it CO_2 neutral.

An Active House creates healthy and comfortable indoor conditions for the occupants and ensures a generous supply of daylight and fresh air.

An Active House interacts positively with the environment by means of an optimised relationship with the local context, focused use of resources, and on its overall environmental impact throughout its life cycle.

The vision of an Active House is to *create buildings that give more than they take.*

The Active House Specifications 2.0 are openly available and include a self-assessment tool, attractive for design scenarios, homeowners and other interested people, www.activehouse.info. A radar is used to illustrate the parameters evaluated. Below is an example from the French Model Home, Maison Air et Lumière (MAL).

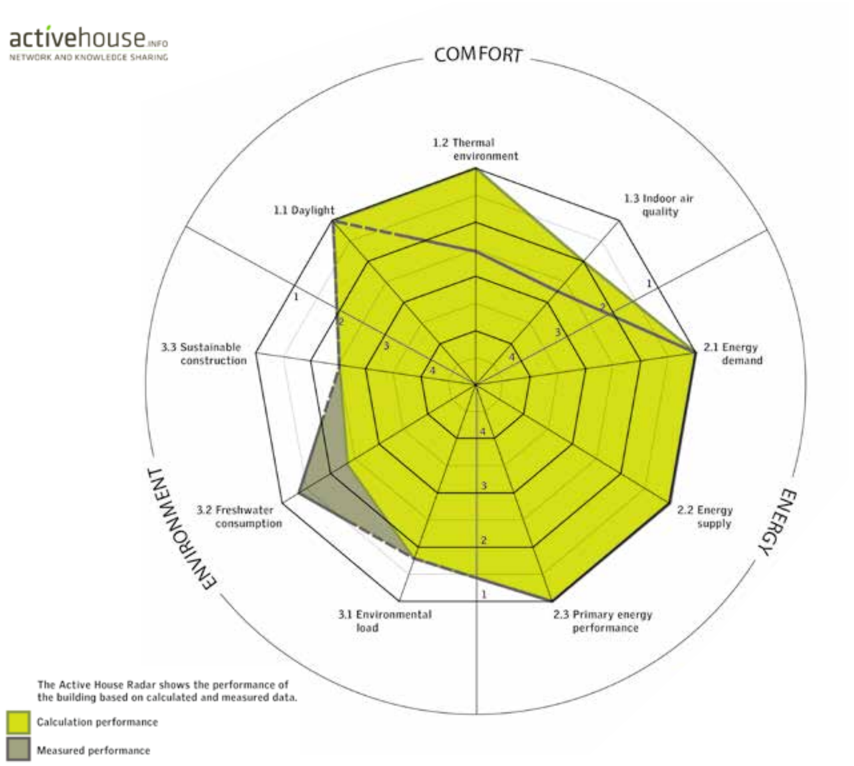


Figure 6.4 Active House radar for the calculated performance of the French Model Home, Maison Air et Lumière (MAL).

6.3.2 BREEAM

BREEAM®

The BRE Environmental Assessment Method (BREEAM) was established in the UK in 1990 by the Building Research Establishment (BRE). It considers performance criteria for sustainability in ten categories. Projects certified to BREEAM are rated on a scale of Pass, Good, Very Good, Excellent and Outstanding. BREEAM is used by Green Building Councils in United Kingdom, Holland, Spain, Norway and Sweden. http://www.breeam.org/

6.3.3 German Sustainable Building Council (DGNB)

DGNB

The DGNB method was developed by the German Sustainable Building Council (DGNB) and the German Government. There are 49 criteria in 6 categories. Certifications are awarded in bronze, silver and gold. DGNB is very closely linked to European standards and is currently in use in Germany, Austria, Switzerland, Bulgaria and Denmark, adapted to national standards. http://www.dgnb.de

6.3.4 French Haute Qualité Environnementale (HQE)

HQE
ASSOCIATION

HQE is the French system for certification of sustainable buildings. The approach is to promote sustainable buildings in accordance with HQE principles. They comprise 15 goals, whose achievable levels are "high performance", "performance" or "base". Several environmental impacts (e.g. energy performance, use of resources, recyclability and indoor air quality) are taken into account. http://www.behqe.com/

6.3.5 LEED

The LEED method was developed by the US Green Building Council and is one of the oldest systems. A building can be certified silver, gold and platinum, based on an assessment of eight different categories of indicators. LEED is used in Romania, Italy, Spain, Sweden, Norway, Finland, Poland, Germany and France. http://www.usgbc.org/leed

6.3.6 Passive House

The Passive House concept has existed in Germany since the 1990s, providing target values for heating requirements, building airtightness and total primary energy demand. The Passive House concept is a certification scheme with calculations for annual energy consumption for heating, hot water and household electricity evaluated against the system's requirements.
http://www.passivehouse-international.org/

3.3.7 Green Building Councils

Green Building Councils support a certifications scheme and the development of Green buildings in their area. There is a Green Building Council in more than a 100 countries.

The best place for more information is the World Green Building Council – www.worldgbc.org – an umbrella organisation for Green Building Councils worldwide.

6.4 Assessment of construction products

6.4.1 Construction products and Environmental Product Declarations

In building assessments, construction products are assessed by Environmental Product Declarations (EPDs) performed in accordance with EN 15804 (CEN, 2012), when applying the European methodology.

All results of the assessment of the product are given within the modular system of the methodology, with modules A1-A3 (Chapter 6.2.1 – product stage) as the mandatory part.

An EPD cannot tell whether a construction product is sustainable or not. This conclusion can only be reached in a whole-building context.

VELUX Environmental Product Assessment (VEPA)

A VEPA is a statement from VELUX A/S regarding the environmental impacts and use of resources of products. It is assessed and structured as an Environmental Product Declaration (EPD) in accordance with EN 15804 (CEN, 2012).

Other Environmental Performance Declarations (EPDs)

VELUX France has conducted EPDs according to the French standard NF P 01-010, known as FDES. There are three different EPDs on Wooden Roof Windows, PU Roof Windows and Flashings. The EPD is the result of assessments done on a group of products typically sold in France. The EPDs are published in the INIES database.

http://www.base-inies.fr/Inies/Consultation.aspx

6.4.2 Other types of labels

There are many other types of labels for assessment of construction products, including materials labels and health labels.

French indoor air quality labelling

French indoor air quality labelling is a mandatory labelling system for products on the French market. The legislation covers interior products. The labelling system covers four categories: C, B, A and A+, of which A+ is the best category. Electric motors, blinds and other decoration products are not included in the labelling system. Most VELUX products have achieved A+.

http://www.developpement-durable.gouv.fr/Chapitre-I-Mode-d-emploi-de-l.html

Oeko-Tex®

Oeko-Tex® is an international voluntary label used to certify textiles. The label concerns emissions and content of selected dangerous substances. Some VELUX blinds are certificated to Oeko-Tex® standards.

https://www.oeko-tex.com/en/manufacturers/manufacturers.xhtml

PEFC/FSC

The Programme for the Endorsement of Forest Certification (PEFC) and the Forest Stewardship Council (FSC) are two labels concerning sustainable and responsible forest management. VELUX has obtained both labels. More information can be found here:

http://www.velux.com/velux_group/social_resopnsibility/environment/raw_materials,

http://www.pefc.org/ or

https://ic.fsc.org/

6.5 Overview of EU legislation

Environmental issues and sustainability are addressed more and more in legislation. An overview of some of the most important and well known legislation is given below.

6.5.1 Construction Products Regulation (CPR)

The Construction Products Regulation (CPR) (European Commission, 2011b) determines how construction products should be CE marked as the "license to sell" on the European Market. The CE marking on construction products is a performance declaration; the requirements for which performance should be declared are called Basic Work Requirements, BWR. Requirements regarding environment and sustainability are BWR 3 and BWR 7.

6.5.2 Registration, Evaluation and Authorisation of Chemicals (REACH)

The Registration, Evaluation and Authorisation of Chemicals (European Commission, 2006a) (REACH) Regulation is the main European Regulation regarding chemicals. The main objective of REACH is for all chemicals used in Europe to be registered and evaluated before use. The most harmful chemicals can only be used with official authorisation. In most cases, VELUX A/S will be considered a downstream user of chemicals, which means it is obliged to provide information about chemical substances on the so-called candidate list.

6.5.3 Restriction of Hazardous Substances (RoHS)

The scope of the Restriction of Hazardous Substances (European Commission, 2011a) (RoHS) Directive is to regulate the use of six different chemicals in electrical and electronic equipment. VELUX electrical and electronic products will be covered by the RoHS Directive of 22 July 2019.

6.5.4 Battery Directive

The scope of the Battery Directive (European Commission, 2006b) is to regulate the use of and disposal of batteries in the European Union. In practice, it means that manufacturers of batteries or products with batteries are responsible for the correct disposal of those batteries. Manufacturers are obliged to design products so that all batteries are labelled and can be disposed of separately. VELUX A/S is a member of battery collection schemes in EU countries and its products are covered by the Battery Directive.

6.5.5 Waste of Electrical and Electronic Equipment (WEEE)

The scope of the Waste of Electrical and Electronic Equipment Directive (WEEE) (European Commission, 2012) is to prevent Waste of Electrical and Electronic Equipment (WEEE) and to reduce waste by setting targets for collection, reuse and recycling. It obliges manufacturers of products containing electrical or electronic equipment to label all such components and be responsible for their correct disposal.

6.6 Index

Global environmental impacts

Global warming
Global warming potential, GWP (CO_2 equivalents), is a product's potential contribution to global warming in the course of its lifetime. Global warming potential is the measure of how much a given mass of greenhouse gases (e.g. CO_2 and CH_4) contributes to global warming. The potential of any greenhouse gas is converted to the CO_2 equivalent.

Ozone Depletion
The depletion potential of the stratospheric ozone layer, ODP (kg CFC 11 equivalents), is a product's potential contribution to the breakdown of the ozone layer.

Regional environmental impacts

Acidification for soil and water
Discharge of sulphur and nitrogen causes a high degree of acidity, which induces the death of fish (acid lakes) and forest decline (acid rain). Acidification potential, AP (kg SO_2 equivalents), is a product's potential to release sulphur- and nitrogen dioxides in its combustion.

Eutrophication
Discharge of the nutrients nitrogen and phosphorus from agriculture and combustion processes leads to eutrophication in lakes and seas – also known as algal blooms. The eutrophication potential, EP (kg $(PO_4)^{3-}$ equivalents, is a product's potential to cause eutrophication during its lifetime.

Photochemical ozone creation
Photochemical ozone is better known as summer smog. The photochemical ozone creation potential, POCP (kg Ethene equivalents), is the reaction between volatile organic compounds (VOCs) and sunlight.

Resource and energy consumptions

In an LCA, two types of consumption are assessed: use of abiotic resources like metals (materials) and use of fossil energy.

Depletion of abiotic resources-elements
Abiotic depletion potential ADP elements for non-fossil resources (kg Sb equivalents), refers to the consumption of primary resources such as aluminium, copper, iron or rare earth metals, a problem that is becoming increasingly global in scale.

Depletion of abiotic resources-fossil fuels
Abiotic depletion potential (ADP - fossil fuels) for fossil resources (MJ, net calorific value) refers to the consumption of fossil fuels, like natural gas and crude oil.

References

References

[1] Active House Alliance (2013) Active House – the specifications.

[2] activehouse.info (2010) network and knowledge sharing, http://www. activehouse.info/ (accessed 2010-06-04).

[3] American Speech-Language- Hearing Association (2010) Noise and Hearing Loss, http://www.asha. org/public/hearing/disorders/noise.htm (accessed: 2010-05-31)

[4] Architectural Energy Corporation (2006) Daylighting Metric Development Using Daylight Autonomy Calculations In the Sensor Placement Optimization Tool – Development Report and Case Studies, CHPS Daylighting Committee

[5] Ariës, M. B. C., Veitch, J. A., and Newsham, G. R. (2010) Windows, view and office characteristics predict physical and psychological discomfort. Journal of Environmental Psychology, 30(4), 533-541.

[6] Asmussen, T. F., Foldbjerg, P. (2010) Efficient passive cooling of residential buildings in warm climates, Submitted for PALENC 2010.

[7] Baker N. (2009), Daylight inside and the world outside, Daylight and Architecture, vol. 11.

[8] Bakó-Biró, Z. and Olesen, B. W. (2005) Effects of Indoor Air Quality on Health, Comfort and Productivity Overview report, International Centre for Indoor Environment and Energy, Technical University of Denmark.

[9] Bekö, G., Toftum, J. and Clausen, G. (2011) Modeling ventilation rates in bedrooms based on building characteristics and occupant behavior. Building and Environment, 46(11), 2230–2237.

[10] Bekö, G. (2009) Used Filters and Indoor Air Quality, ASHRAE Journal, vol. 7, no. March.

[11] Bluyssen, P. M. (2009) The Indoor Environment Handbook, RIBA Publishing.

[12] Bluyssen, P. M. (2010) Understanding the indoor environment - putting people first, Daylight and Architecture, vol. 13

[13] Bluyssen, P. M. (2013) The healthy indoor environment - How to assess occupants' well-being in buildings. Earthscan from Routledge.

[14] Bornehag, C. G., Blomquist, G., Gyntelborg, B., Nielsen, A., Pershagen, G. and Sundell, J. (2001) Dampness in Buildings and Health between Exposure to ' Dampness ' in Buildings and Health Effects (NORDDAMP) Indoor Air, 11, 72–86.

[15] Boubekri, M. (2004) An Overview of The Current State of Daylight Legislation, Journal of the Humam Environmental System, vol. 7, no. 2, pp. 57-63.

[16] Boyce, P., Hunter, C. and Howlett, O. (2003) The Benefits of Daylight through Windows, Lighting Research Center, Rensselaer Polytechnic Institute.

[17] Brainard, G. C. (2002) Photoreception for Regulation of Melatonin and Circadian System, 5th International LRO Lighting Research Symposium.

[18] BREEAM (2010) the Environmental Assessment Method for Buildings Around The World, http://www. breeam.org/ (accessed: 2010-06-04).

[19] British Research Establishment (2009), The Government's Standard Assessment Procedure for Energy Rating of Dwellings, Department of Energy and Climate Change, United Kingdom.

[20] British Standard (2002) BS 5250: Code of practice for control of condensation in buildings.

[21] Brown, M. J., and Jacobs, D. E. (2011) Residential light and risk for depression and falls: Results from the LARES study of eight European cities. Public Health Reports, 126 (Supplement 1), 131-140.

[22] Bråbäck, L,, Hjern, A., Rasmussen, F. (2004) Trends in asthma, allergic rhinitis and eczema among Swedish conscripts from farming and non-farming environments. A nationwide study over three decades, Clinical and experimental allergy, vol. 34, no. 1, pp. 38-43.

[23] Carbon Footprint (2010) http://www.carbonfootprint. com/ (accessed: 2010-06-09).

[24] Caring for our forests globally (2010) http://www.pefc.org/ (accessed: 2010-06-04).

[25] Carmichael, K., Anderson, M., Murray, V. (2011) Overheating and health : a review into the physiological response to heat and identification of indoor heat thresholds.

[26] CEN (1995) EN ISO 140-3: Acoustics - Measurement of sound insulation in buildings and of building elements - Part 3: Laboratory measurements of airborne sound insulation of building elements, CEN

[27] CEN (1997) EN ISO 717-1: Acoustics - Rating of sound insulation in buildings and of building elements - Part 1: Airborne sound insulation

[28] CEN (2005) EN ISO 7730: Ergonomics of the thermal environment.

[29] CEN (2006) EN ISO 140-18: Acoustics - Measurement of sound insulation in buildings and of building elements - Part 18: Laboratory measurements of sound generated by rainfall on building elements

[30] CEN (2007) EN 15251: Indoor environmental input parameters for design and assessment of energy performance of buildings.

[31] CEN (2010) EN ISO 10140 serie: Acoustics - Measurement of sound insulation of building elements

[32] CEN (2012a) EN 15804 Sustainability of construction works. Environmental product declarations. Core rules for the product category of construction products

[33] CEN (2012b) TC 350 standards Sustainability of construction works

[35] Christoffersen, J., Petersen, E., Johnsen, K., Valbjørn, O. and Hygge, S. (1999) Vinduer og dagslys – en feltundersøgelse i kontorbygninger (SBi - rapport 318) Hørsholm: Statens Byggeforskningsinstitut.

[36] CIBSE Guide A. (2006) Environmental design. Chartered Institution of Building Services Engineers, London.

[37] CIBSE (2002) Code for Lighting, Oxford: Chartered Institution of Building Services Engineers.

[38] CIBSE (2006) Guide A: Environmental design. Chartered Institute of Building Services Engineers, London

[39] CIBSE (2011) Indoor Air Quality and Ventilation (CIBSE Knowledge Series KS17) CIE (1970). Daylight. CIE 16-1970. International Commission on Illumination (CIE)

[40] CIE (2004a) Ocular lighting effects on human physiology and behaviour (No. CIE 158:2004) Vienna, Austria: Commission Internationale de l'Eclairage

[41] CIE (2004b) Proceedings of the CIE Expert Symposium on Light and Health (Vol. CIE x27:2004) Vienna, Austria: Commission Internationale de l'Eclairage

[42] CIE (2006) CIE 171:2006 Test Cases to Assess the Accuracy of Computer Lighting Programs.

[43] Circadian House report (2013) Circadian House - Principles and Guidelines for Healthy Homes. VELUX report http://thedaylightsite.com/library-3/research-publications/papers/ ((accessed: 2014-12-10)

[44] Couillard, N. (2010) Impact of VELUX Active Sun screening on Indoor Thermal Climate and Energy Consumption for heating, cooling and lighting. Case study for Germany Research project, Centre Scientifique et Technique du Batiment.

[45] Danish Building Research Institute (2014a) Lydisolering af klimaskærm – SBI anvisning 244

[46] Danish Building Research Institute (2014b) Lydisolering af bygninger teori og vurdering – SBI anvisning 245

[47] Danish Enterprise And Construction Authority (2010) – The Danish Ministry of Economic and Business Affairs, Building Regulations.

[48] Danish Ministry of Environment (2003) Den danske vejstøjstrategi. http://mst.dk/borger/stoej/hvad-er-stoej/ (accessed: 2014-09-19).

[49] de Dear, R., Brager, G. S. (1998) Developing an Adaptive Model of Thermal Comfort and Preference, ASHRAE Transactions, vol. 104, no. 1.

[50] de Dear R., Brager, G. S.,Cooper, D. (1997) Developing an Adaptive Model of Thermal Comfort and Preference – RP 884, ASHRAE.

[51] de Dear, R. (2006) The Theory of Thermal Comfort in Naturally Ventilated Indoor Environments – "The Pleasure Principle" International Journal Of Ventilation, 8(3)

[52] Dhalluin, A.,Limam, K. (2012) Comparison of Natural and Hybrid Ventilation Strategies used in Classrooms in Terms of Indoor Environmental Quality, Comfort and Energy Savings. Indoor and Built Environment, 23(4), 527–542. doi:10.1177/1420326X12464077

[53] ECO platform (2014) http://www.eco-platform.org/ (accessed: 2014-11-07).

[54] Edwards, L., Torcellini, P. (2002) A Literature Review of the Effects of Natural Light on Building Occupants, National Renewable Energy Laboratory, U.S. Department of Energy.

[55] Eichhammer, W. (2009) Study on the Energy Savings Potentials in EU Member States, Candidate Countries and EEA Countries, Fraunhofer-Institute for System and Innovation Research.

[56] Ellermann, T., Brandt, J., Hertel, O., Loft, S., Andersen, Z. J., Raaschou-Nielsen, O., Sigsgaard, T. (2014) Luftforureningens indvirkning på sundheden i Danmark. Nationalt Center for Miljø og Energi – DCE

[57] Environmental Protection Encouragement Agency (2010) (EPEA) Internationale Umweltforschung GmbH, http://epea-hamburg.org/en/home.html ((accessed: 2010-06-09).

[58] EPEA (2014) http://epea-hamburg.org/index.php?id=69 (accessed: 2014-11-07).

[59] Espiritu, R. C., Kripke, D. F., Ancoli-Israel, S., Mowen, M. A., Mason, W. J., Fell , R. L. et al. (1994) Low illumination experienced by San Diego adults: Association with atypical depressive symptoms. Biological Psychiatry, 35(6), 403-407.

[60] Europe's Energy Portal (2010) www.energy.eu (accessed: 2010-06-08.)

[61] European Comission (2007) Technical University of Berlin, NEST project; Innovative Sensor System for Measuring Perceived Air Quality and Brand-Specific Odours

[62] European Commission (2002) Directive 2002/91/EC of the European Parliament and of the Council of 16 December (2002) on the energy performance of buildings, European Union.

[63] European Commission (2006a) Regulation 1907/2006/EC 18 December (2006) REACH

[64] European Commission (2006b) Directive 2006/66/EC 6 September (2006) Batteries

[65] European Commission (2011a) Directive 2011/65/EU 8 June 2011 RoHS

[66] European Commission (2011b) Regulation 305/2011/EU 9 March 2011 Construction Products

[67] European Commission (2012) Directive 2012/19/EU 4 July 2012 WEEE

[68] Fanger, P. O. (1970) Thermal comfort, Danish Technical Press.

[69] Favre, B., Cohen, M., Vorger, E., Mejri, O., Peuportier, B. (2013) Evaluation of ventilative cooling in a single family house (pp. 1–131)

[70] Foldbjerg, P., Asmussen, T. F. (2013C) Ventilative cooling of residential buildings: strategies , measurement results and lessons-learned from three active houses in Austria , Germany and Denmark. In Proceedings of AIVC 2013.

[71] Foldbjerg, P., Knudsen, H. N. (2014) Maison Air et Lumière a case from model home 2020 project. REHVA Journal (June), 55–57.

[72] Foldbjerg P., Asmussen, T. F., Duer K. (2010) Hybrid ventilation as a cost-effective ventilation solution for low-energy residential buildings, Proceedings of Clima2010.

[73] Foldbjerg P., Asmussen, T. F., Sahlin P., Duer, K., Ålenius, L. (2010), EIC Visualizer, an intuitive tool for coupled thermal, airflow and daylight simulations of residential buildings including energy balance of windows, Proceedings of Clima2010.

[74] Foldbjerg P., Roy N., Duer K., Andersen, P. A. (2010) Windows as a low-energy light source in residential buildings: Analysis of impact on electricity, cooling and heating demand, Proceedings of Clima2010

[75] Foldbjerg, P., Asmussen, T. F., Roy, N., Sahlin, P., Ålenius, L., Jensen, H. W., Jensen, C. (2012) Daylight Visualizer and Energy and Indoor Climate Visualizer, a Suite of Simulation Tools for Residential Buildings. In Proceedings of BSO 2012.

[76] Foldbjerg, P., Rasmussen, C., Asmussen, T. (2013B) Thermal Comfort in two European Active Houses : Analysis of the Effects of Solar Shading and Ventilative Cooling. In Proceedings of Clima2013.

[77] Foldbjerg, P., Asmussen, T. F., Christoffersen, J. (2014B) Indoor Climate in a Danish Kindergarten built according to Active House Principles : Measured Thermal Comfort and use of Electrical Light. In AIVC conference 2014 (pp. 188–197)

[78] Foldbjerg, P., Asmussen, T., and Holzer, P. (2014) Ventilative Cooling of Residential Buildings - Strategies, Results and Lessons-Learned from three Active Houses in Austria, Germany and Denmark. International Journal of Ventilation, 13(2), 179–191.

[79] Forest Stepwardship Council (2010) , http://www.fsc.org/ (accessed: 2010-06-04).

[80] Franchi, M., Carrer, P., and Kotzias, D. (2004) et al., Towards healthy air in Dwellings in Europe, European Federation of Allergy and Airways Diseases Patients Associations.

[81] Galasiu, A. D., Newsham, G. R., Suvagau, C., and Sander, D. M., (2007) Energy-saving lighting control systems for open-plan offices: a field study. Leukos, 4(1) pp. 7–29 (http://www.mcclungfoundation.org/Documents/EnergySavingLightingControlSystems.pdf)

[83] German Sustainable Building Council (2010) http://www.dgnb.de/ (accessed: 2010-06-04).

[83] Grimaldi, S., Partonen, T., Saarni, S. I., Aromaa, A., and Lönnqvist, J. (2008) Indoors illumination and seasonal changes in mood and behavior are associated with the health-related quality of life. Health and Quality of Life Outcomes, 6, 56. doi: 10.1186/1477-7525-6-56

[84] Grinde, B., and Grindal Patil, G. (2009) Biophilia: Does Visual Contact with Nature Impact on Health and Well-Being? International Journal of Environmental Research and Public Health. September; 6(9): 2332–2343.

[85] Hathaway, W. E., Hargreaves, J. A., Thomson G. W., Novitsky, D. (1992) A study into the effects of light on children of elementary school age - a case of daylight robbery, Alberta Department of Education.

[86] Hauge B. (2009) Antropologisk undersøgelse og analyse af betydningen af Frisk luft Udefra ind i privatboligen, University of Copenhagen.

[87] Heiselberg, P., and Perino, M. (2010) Short-term airing by natural ventilation – implication on IAQ and thermal comfort, Indoor Air, pp. 126-140.

[88] Heiselberg, P. (2002) Principles of hybrid ventilation, IEA Annex 35, Aalborg University.

[89] Heschong Mahone Group. (2003) Windows and Offices: A Study of Office Worker Performance and the Indoor Environment (No. P500-03-082-A-9) Sacramento, CA: California Energy Commission.

[90] Heschong, L. (1979) Thermal delight in architecture. The MIT Press.

[91] Heschong, L. (2002) Daylighting and Human Performance, ASHRAE Journal, vol. 44, no. 6, pp. 65-67.

[92] Hopkins, R. G. (1963) Architectural Physics: Lighting, London: Her Majesty's Stationery Office.

[93] ESNA (2013). LM-83-12: Approved Method: IES Spatial Daylight Autonomy (sDA) and Annual Sunlight Exposure (ASE). The Illuminating Engineering Society of North America (IES). http://www.ies.org/store/product/approved-method-ies-spatial-daylight-autonomy-sda-and-annual-sunlight-exposure-ase-1287.cfm (accessed: 2014-12-10)

[94] International Energy Agency (2006) Light's Labour's Lost Policies for Energy-efficient Lighting (http://www.iea.org/publications/freepublications/publication/lights-labours-lost.html)

[95] International Energy Agency (2009) Key World Energy Statistics, IEA.

[96] IPCC (2007) Climate Change 2007: Synthesis Report, Change, Intergovernmental Panel on Climate Change, United Nations.

[97] ISO (2006a) ISO 14040: Environmental management – Life cycle assessment – Principles and framework

[98] ISO (2006b) ISO 14044: Environmental management – Life cycle assessment – Requirements and guidelines

[99] ISO (2009) ISO 18292: Energy performance of fenestration systems - Calculation procedure.

[100] ISO (2014a) ISO 10916:2014 Calculation of the impact of daylight utilization on the net and final energy demand for lighting

[101] Joarder, A.R., Price, A.D.F.(2013), Impact of daylight illumination on reducing patient length of stay in hospital after coronary artery bypass graft surgery, Lighting Res. Technol.; 45: 435–449

[102] Johnsen K., Dubois M., Grau K. (2006) Assessment of daylight quality in simple rooms, Danish Building Research Institute.

[103] Kaplan, R. (1993) The role of nature in the context of the workplace. Landscape and Urban Planning Volume 26, Issues 1–4, October, 193–201.

[104] Kaplan, R. (2001) The nature of the view from home: Psychological benefits. Environment and Behavior, 33(4), 507-542.

[105] Kim, J. J. and Wineman, J. (2005) Are windows and views really better? A Quantitative Analysis of the Economic and Psychological Value of Views, Rensselaer Polytechnic Institute, Lighting Research Center, New York: Daylight Dividend Program

[106] Klepeis, N. E., Nelson, W. C., Ott, W. R., Robinson, J. P., Tsang, A. M., Switzer, P., Behar, J. V., Hern, S. C., Engelmann, W. H. (2001) The National Human Activity Pattern Survey (NHAPS): A resource for assessing exposure to environmental pollutants. Journal of Exposure Analysis and Environmental Epidemiology, 11(3), 231-252.

[107] Kragh, J., Lautsen, J. B, Svendsen, S. (2008) Proposal for Energy Rating System of windows in EU, Department of Civil Engineering, Technical University of Denmark.

[108] Kropf, S., Zweifel, G. (2002), Validation of the Building Simulation Program IDA-ICE According to CEN 13791, Hochschule für Technik+Architektur Luzern.

[109] Krzyanowski, M. (1999) Strategic approaches to indoor air policymaking, WHO European Centre for Environment and Health.

[110] Kwok, A. G. (2000) Thermal Boredom. In PLEA 2000 (pp. 1–2) Cambridge.

[111] Labayrade, R., Fontoynont, M. (2009) Assessment of VELUX Daylight Visualizer 2 Against CIE 171:2006 Test Cases, ENTP, Universite de Lyon.

[112] Lam, W. (1977) Perception and Lighting as Formgivers for Architecture, McGraw-Hill.

[113] Larsen, T. S., Jensen, R. L., and Daniels, O. (2011) The Comfort Houses (p. 98) Aalborg University report.

[114] Laverge, J., Janssens, A. (2011) Physiological and Sensory Human Response to IEQ Indicators While Asleep. Proceedings of Indoor Air 2011, Austin, Texas

[115] Leech, J. A., Nelson, W. C., Burnett, R. T., Aaron, S., Raizenne, M. E. (2002) It's about time: A comparison of Canadian and American time-activity patterns. Journal of Exposure Analysis and Environmental Epidemiology, 12(6), 427-432

[116] Liddament, M. W. (1996) A guide to energy-efficient ventilation, AIVC

[117] Lighting Research Center (2014) Rensselaer Polytechnic Institute, Daylighting Resources – Productivity, http://www.lrc.rpi.edu/programs/daylighting/dr_productivity.asp (accessed: 2014-11-06).

[118] Loutzenhiser, P., Manz, H., Maxwell, G. (2007) Empirical Validations of Shading/Daylighting/Load Interactions in Building Energy Simulation Tools, International Energy Agency.

[119] LRC (2003) The Benefits of Daylight. http://www.lrc.rpi.edu/programs/daylightdividends/)

[120] Mardaljevic, J., Andersen, M., Roy, N., Christoffersen, J. (2012) Daylighting, Artificial Lighting and Non-Visual Effects Study for a Residential Building, VELUX.

[121] Mardaljevic, J., Andersen, M., Roy, N., Christoffersen, J. (2012) Daylighting, Artificial Lighting and Non-Visual Effects Study for a Residential Building

[122] Mardaljevic, J. (2008), Climate-Based Daylight Analysis for Residential Buildings – Impact of various window configurations, external obstructions, orientations and location on useful daylight illuminance, Institute of Energy and Sustainable Development, De Montfort University.

[123] Mardaljevic, J. (2012) Daylight, Indoor Illumination and Human Behavior in Encyclopedia of Sustainability Science and Technology Springer-Verlag New York Inc, New York. ISBN 978-0-387-89469-0, pp 2804-2846

[124] Marsh, R., Larsen, V. G., Lauring, M., Christensen, M. (2006) Arkitektur og energi, Danish Building Research Institute.

[125] Mathisen, H. M., Berner, M., Halvarsson, J., Hansen, S. O. (2008) Behovsstyrt ventilasjon av passivhus – Forskriftskrav og brukerbehov, Proceedings of Passivhus Norden.

[126] Matthias, A. (2000), Validation of IDA ICE with IEA task 12 – Envelope BESTEST, Hochschule Technik+Architektur Luzern.

[127] McIntyre, D. A. (1980) Indoor Climate. Applied Science Publishers.

[128] Miljøstyrelsen (2010) : Tips om støj, http://www.mst.dk/Borger/ Temaer/Fritiden/Stoej/ (accessed: 2010-05-31).

[129] Ministère De La Santé (2005) Etudes scientifiques sur la perturbation du sommeil. Bruit et santé.

[130] Moeck, Yoon, Bahnfleth, et al. (2006) How Much Energy Do Different Toplighting Strategies Save?, Lighting Research Center, Rensselaer Polytechnic Institute.

[131] Moosberger, S. (2007), IDA ICE CIBSE-Validation, Hochschule Technik+ Architektur Luzern.

[132] National Institute of Occupational Health in Denmark (2006) Støj fra menneskelig aktivitet - Et udredningsarbejde.

[133] National Research Counsil Canada (2010) : Acoustics Principles, http:// www.nrc-cnrc.gc.ca/eng/projects/ irc/cope/principles-acoustics. html (accessed: 2010-05-31).

[134] Nazaroff, W. W. (2013) Four principles for achieving good indoor air quality. Indoor Air, 23(5), 353–6. doi:10.1111/ina.12062

[135] Newsham, G. R., Brand, J., Donnelly, C. L., Veitch, J. A., Aries, M. B. C., Charles, K. E. (2009) Linking indoor environment conditions to job satisfaction: a field study. Building Research and Information, 37(2), 129 - 147.

[136] Nilsson, C. (2008) Air, Swegon Air Academy.

[137] Orme, M. S., Palmer, J. (2003) Control of overheating in future housing, Design guidance for low- energy strategies. Hertfordshire, UK, Faber Maunsell Ltd.

[138] Orme, M. (2003) Control of overheating in future housing, Design guidance for low-energy strategies. Hertfordshire, UK: Faber Maunsell Ltd.

[139] Osram (2010) The new class of light, http://www.osram.com/ (accessed: 2010-06-07).

[140] Passivhaus Institut (2010) http://www. passiv.de/ (accessed: 2010-06-04).

[141] Pechacek, C. S., Andersen, M., Lockley, S. W. (2008) Preliminary method for prospective analysis of the circadian efficacy of (day)light with applications to healthcare architecture. Leukos, 5(1), 1-26)

[142] Perez, R. (2009) Making the case for solar energy, DaylightandArchitecture, vol. 9.

[143] Perino, M., Heiselberg P. (2009) Short-term airing by natural ventilation – modeling and control strategies, Indoor Air, no. 19, pp. 357-380.

[144] Philipson, B. H., Foldbjerg, P. (2010) Energy Savings by Intelligent Solar Shading, Submitted for PALENC 2010.

[145] Plesner C., Duer, K. (2014) Evaluation of indoor air quality in a single-family active house, Indoor Air conference 2014

[146] Pommer, K., Bech, P. (2003) Handbook on Environtal Assessment of Products, Danish Technological Institute.

[147] Rea, M.S. (2000) The IESNA Lighting Handbook: Reference and application, New York: Illuminating Engineering Society of North America.

[148] Reinhart, C., Walkenhorst, O. (2001) Dynamic RADIANCE-Based Daylight Simulations for a Full-Scale Test Office with Outer Venetian Blinds, Energy and Buildings, 33:7, pp. 683-697)

[149] Reinhart, C. (2014) Daylight Handbook I

[150] Reiser, C., David, R., Faigl, M., Baumann, O. (2008) DIN 18599 - Accounting for primary energy – new code requires dynamic symulation, Third National Conference of IBPSAUSA.

[151] Richardson, G., Eick, S., Jones, R. (2005) How is the indoor environment related to asthma?: literature review, Journal of Advanced Nursing, vol. 52, no. 3, pp. 328-339.

[152] Robbins, C. L. (1986) Daylighting Design and Analysis, New York: Van Nostrand Reinhold Company.

[153] Rosen, L. N., Targum, S. D., Terman, M., Bryant, M. J., Hoffman, H., Kasper, S. F., Hamovit, J. R., Docherty, J. P., Welch, B., Rosenthal, N. E. (1990) Prevalence of seasonal affective disorder at four latitudes, Psychiatry Research, vol. 31, no. 2, pp. 131-144.

[154] Schmidt, L. (2003) Ultrafine partikler. Gasteknisk center.

[155] Schweizer, C., Edwards, R. D., Bayer-Oglesby, L., Gauderman, W. J., Ilacqua, V., Jantunen, M. J., Lai, H. K., Nieuwenhuijsen, M., Künzli, M. (2007) Indoor time-microenvironment-activity patterns in seven regions of Europe. Journal of Exposure Science and Environmental Epidemiology, 17(2), 170-181

[156] Seppanen, O., Fisk, W., Lei, Q. H. (2009) Ventilation and performance in office work, Indoor Air, vol. 18, pp. 28-36

[157] Seppanen, O., Fisk, W. J. (2002) Relationship of SBS symptoms and ventilation system type in office buildings. Indoor Air, 12(2), 98–112.

[158] Seppanen, O. Fisk, W. J. (2006) Some quantitative relations between indoor environmental quality and work performance or health, International Journal of HVACandR Research, vol. 12, no. 4, pp. 957-973.

[159] Sloane, P. D., Figueiro, M., Cohen, L. (2008) Light as Therapy for Sleep Disorders and Depression in Older Adults, Clinical Geriatrics, vol. 16, no. 3, pp. 25-31

[160] Smeds, J., Wall, M. (2007) Enhanced energy conservation in houses through high performance design, Energy and Buildings, vol. 39, no. 3, pp. 273-278.

[161] Steiger, S., Roth, J. K., Østergaard, L. (2012) Hybrid ventilation - the ventilation concept in the future school buildings? In AIVC conference Copenhagen 2012

[162] Finlay, S., Pereira, I., Fryer-Smith, E., Charlton, A., Roberts-Hughes, R. (2012) The Way We Live Now, RIBA and Ipsos MORI

[163] Sundell, J., Wickman, M., Pershagen, G., Nordvall, S. L. (1995) Ventilation in homes infested by house-dust mites, Allergy, vol. 50, no. 2, pp. 106-112.

[164] Sundell, J. (1999) Indoor Environment and health, Swedish National Institute of Public Health.

[165] Sundell, J. (2004a) On the history of indoor air quality and health, Indoor Air, vol. 14, no. 7, pp. 51-58.

[166] Sundell, J. (2004b) Varför behöver vi bra ventilation?, Nordbygg.

[167] Tregenza, P., Wilson, M. (2011) Daylighting – Architecture and Lighting Design (page 111)

[168] U.S. Green Building Council (2010) http://www.usgbc.org/ (accessed: 2010-06-04).

[169] Ulrich, R. S., Simons, R. F., Losito, B. D., Fiorito, E., Miles, M. A., Zelson, M. (1991) Stress recovery during exposure to natural and urban environments. Journal of Environmental Psychology, 11(3), 201-230.

[170] Ulrich, R. S. (1984) View through a window may influence recovery from surgery. Science, 224(4647), 420-421.

[171] UNEP (2009) UN Environmental Programme and SETAC – Society of Environmental Toxicology and Chemistry

[172] UNEP (2009) United Nations Environmental Programme Life Cycle Management How business uses it to decrease footprint, create opportunities and make value chains more sustainable.

[173] United States Environmental Protection Agency (1991) Indoor Air Facts No. 4 (revised) Sick Building Syndrome

[174] Van Marken Lichtenbelt, W. D., Vanhommerig, J. W., Smulders, N. M., Drossaerts, J. M. a F. L., Kemerink, G. J., Bouvy, N. D., Teule, G. J. J. (2009) Cold-activated brown adipose tissue in healthy men. The New England Journal of Medicine, 360(15), 1500–8.

[175] Veitch, J. A., and Gifford, R. (1996) Assessing beliefs about lighting effects on health, performance, mood, and social behavior. Environment and Behavior, 28(4), 446-470

[176] Veitch J. A., Slater A.I. (1998) A framework for understanding and promoting lighting quality, Proceedings of the first CIE Symposium on lighting quality, pp. 237-241.

[177] Veitch, J. A., Hine, D. W., and Gifford, R. (1993) End-users' knowledge, beliefs, and preferences for lighting. Journal of Interior Design, 19(2), 15-26

[178] Veitch, J. A., Charles, K. E., Newsham, G. R., Marquardt, C. J. G. and Geerts, J. (2003) Environmental Satisfaction in Open-Plan Environments: 5. Workstation and Physical Condition Effects. IRC Research Report RR-154. Institute for Research in Construction. National Research Council Canada, Ottawa, ONT, K1A 0R6, Canada

[179] Veitch, J. A., Newsham, G. R., Boyce, P. R. and Jones, C. C. (2008) Lighting appraisal, well-being, and performance in open-plan offices: A linked mechanisms approach. Lighting Research and Technology, 40(2), 133-151.

[180] Veitch, J. A. (2002) Principles of Healthy Lighting : Highlights of CIE TC 6-11 ' s, National Research Council Canada.

[181] VELUX Group (2009) VELUX Energy Terminology Guide.

[182] Walch, J. M., Rabin, B. S., Day, R., Williams, J. N., Choi, K., Kang, J. D. (2005) The effect of sunlight on postoperative analgesic medication use: A prospective study of patients undergoing spinal surgery. Psychosomatic Medicine, 67(1):156-163

[183] Walitsky, P. (2002) Sustainable lighting products, Philips.

[184] Wang, N., Boubekri, M. (2010), Investigation of declared seating preference and measured cognitive performance in a sunlit room, Journal of Environmental Psychology, Vol. 30, No. 2, p. 226-238

[185] Wang, N., Boubekri, M. (2011) Design recommendations based on cognitive, mood and preference assessments in a sunlit workplace, Lighting Research and Technology, Vol 43, No. 1, p. 55-77

[186] Wargocki, P., and Wyon, D. (2006) Effects of HVAC On Student Performance. ASHRAE Journal, 48(October), 23–28.

[187] Wargocki P, Sundell J, Bischof W, Brundrett, G., Fanger P. O., Gyntelberg F., Hanssen S. O., Harrison P., Pickering A., Seppänen O., Wouters P. (2002), Ventilation and health in non-industrial indoor environments: report from a European multidisciplinary scientific consensus meeting (EUROVEN), Indoor Air, vol. 12, no. 2, pp. 113-28.

[188] Bornehag, C.G., Blomquist, G., Gyntelberg, F., Järvholm, B., Malmberg, P., Nordvall, L., Nielsen, A., Pershagen, G., Sundell, J. (2001) Dampness in Buildings and Health. Nordic interdisciplinary review of the scientific evidence on associations between exposure to "dampness" in buildings and health effects (NORDDAMP), Indoor Air, vol. 11, no. 2, pp. 72-86.

[189] Wargocki, P., Seppänen, O., Andersson, J., Boerstra, A., Clements-Croome, D., Fitzner, K., and Hanssen, S. O. (2007) Indoor Climate and Productivity in Offices (REHVA Guidebook) REHVA.

[190] Wargocki, P., Alexandre, N., and Da, F. (2012) Use of CO_2 feedback as a retrofit solution for improving air quality in naturally ventilated classrooms. In Proceedings of Healthy Buildings 2012.

[191] Wargocki, P. (2011) Does condensation on a window pane contribute to poor indoor climate? Technical University of Denmark

[192] Webb, A. (2006) Considerations for lighting in the built environment: Non-visual effects of light, Energy and Buildings, vol. 38, no. 7, pp. 721-727.

[193] WHO (2000) The right to healthy indoor air.

[194] WHO (2009) Night Noise Guidelines for Europe. http://www.euro.who.int/en/health-topics/environment-and-health/noise/publications/2009/night-noise-guidelines-for-europe (accessed: 2014-09-19).

[195] WHO (2013) Health effects of particulate matter. Policy implications for countries in eastern Europe, Caucasus and Central Asia.

[196] Wikipedia (2014) http://en.wikipedia.org/wiki/Passive_cooling (accessed: 2014-11-07).

[197] Wirz-Justice, A., Fournier, C. (2010) Light , Health and Wellbeing : Implications from chronobiology for architectural design, World Health Design, vol. 3.

[198] Wirz-Justice, A., Graw, P., Krauchi, K., Sarrafzadeh, A., English, J., Arendt, J., Sand, L. (1996) 'Natural' light treatment of seasonal affective disorder. Journal of Affective Disorders, 37(2-3), 109-1

[199] Wotton, E., Barkow, B. (1983) An Investigation of the Effects of Windows and Lighting in Offices, International Daylighting Conference: General Procedings, pp. 405-411.

[200] Öie, L., Nafstad, F., Botten, G., Magnus, P., Jaakkola, J. K. (1999) Ventilation in Homes and Bronchial Obstruction in Young Children, Epidemiology, vol. 10, no. 3, pp. 294-299.

[201] ÖNORM (2006) B 8115-2: Schallschutz und Raumakustik im Hochbau - Teil 2: Anforderungen an den Schallschutz

Glossary

Glossary

Airing
A short period of time with high ventilation rate caused by open windows.

Building assessments
Assessment schemes where different parameters are evaluated for their environmental impact. The different building assessment schemes take different parameters into account.

Candela (cd)
Unit of luminous intensity, equal to one lumen per steradian (lm/sr).

Carbon footprint
CO_2 emissions in tons or kg CO_2-equivalent of a specific process or product.

Chronobiology
Chronobiology is the science of biological rhythms, more specifically the impact of 24-hour light-dark cycle and seasonal changes in day length on biochemistry, physiology and behaviour in living organisms.

Circadian rhythms
A biological cycle with a period of approximately 24 hours (from the Latin circa = about, dies = day). Circadian rhythms can be found in almost all life forms – animals and plants. Not only the essential functions of the entire organism but almost every individual organ, and even every individual cell, have their own genetically predefined circadian rhythm.

CLO
Clothing level. The clothing insulation level. [1 CLO = 0.155 m^2K/W].

Comfort range
A range with a minimum and maximum value within which comfort is assumed.

Cradle to cradle
An assessment model that follows a different philosophy than LCA and founded on three different principles, one of which is that we cannot live on the earth if we do not reduce the amount of waste.

D
Heat degree hours per year. The sum of temperature differences between indoor and outdoor air temperatures throughout a year.

Daylight autonomy (DA)
The DA is defined as the percentage of time – over a year – for which daylight can provide a specific intensity of light (e.g. 500 lux) in interiors.

Dayligt factor (DF)
The DF expresses – as a percentage – the amount of daylight available indoors compared to the amount of unobstructed daylight available outdoors under standard CIE sky conditions.

dB(A)
Sometimes decibel is annotated in dB(A) rather than dB. The (A) indicates that it refers to a total sound level (consisting of many individual frequencies) that is "A-weighted" and thereby equals human subjective perception of sound.

Decibel (dB)
Decibel is the unit used to measure sound level and is a logarithmic unit used to describe a ratio.

Draught
Unwanted local cooling caused by air movements. Typically occurs with air velocities higher than 0.15 – 0.30 m/s.

Dynamic simulation
A computer calculation that runs for a period of time with time steps, typically 1 hour. Examples are VELUX Energy and Indoor Climate Visualizer.

Electromagnetic spectrum
A continuum of electric and magnetic radiation encompassing all wavelengths.

Energy balance
The balance between heat loss and solar gain for a window.

Energy consumption
The energy consumed to supply the energy demand.

Energy demand
The required energy.

Energy Performance
The total energy demand of a building - including heating, cooling, hot water, electric light and other electrical equipment.

Experienced temperature
A temperature calculated from the PMV value to illustrate what temperature it would be equivalent to.

Forest certification schemes
Certification schemes that promote sustainable forest management. FSC and PEFC are the most important and they are evaluated by an independent, third-party certification body.

Glare
Glare is a sensation caused by an uncomfortably bright light source or reflection in the field of view that can cause annoyance, discomfort, or loss in performance and visibility.

I
Usable solar gain reaching a window in kWh/m^2.

Illuminance
Illuminance is the measure of the amount of light received on a surface. It is typically expressed in lux.

Indoor air quality (IAQ).
The characteristics of the indoor climate of a building, including gaseous composition, temperature, relative humidity and airborne contaminant levels.

Infiltration
Uncontrolled ventilation through leaks in the building envelope.

Infrared (IR)
Electromagnatic radiation with a wavelength longer than that of visible light.

kWh
An energy unit. Commonly used to quantify used energy, for instance for pricing energy.

kWh/m^2 floor area
The total energy demand for the building per m^2 heated floor area.

kWh/m^2 window area
Unit of the energy balance of windows.

Life cycle assessment (LCA)
A model used to assess the environmental impact of a specific process or product.

Luminance
Luminance is the measure of the amount of light reflected or emitted from a surface. It is typically expressed in cd/m^2.

Lux (lx)
Unit of illuminance. One lux is one lumen per square metre (lm/m^2).

Mean radiant temperature
The area weighted mean temperature of all surrounding surfaces.

Melatonin
Melatonin is the most important hormone secreted by the pineal gland and can be described as the body’s signal for the nightly dark phase. It promotes sleep in humans and activity in nocturnal animals.

MET
Activity level of the occupants. Measured in MET, short for metabolism.
[1 MET = 58.2 W/m^2]

Operative temperature
A temperature that describes the total thermal environment and can be compared across cases.

Particulate matter (PM)
Small airborne particles (x = dimension of the aerodynamic diameter).

Parts per million (ppm)
An expression used a.o. to quantify the concentration n of a specific gas (for example CO_2) in atmospheric air. 1 ppm = 1 mL in 1 m^3 (1000 L)

Predicted Mean Vote (PMV)
An index that predicts the mean votes of a large group of people regarding thermal comfort. 0 is neutral, +3 is too warm and -3 is too cold.

Predicted Percentage Dissatisfied (PPD)
A quantitative prediction of the percentage of people dissatisfied with the thermal environment.

Renewable energy
Energy produced by renewable sources, such as the sun, wind or biomass.

Running mean
A weighted average over a period of time. The most recent period has the largest weight.

R_w
The sound insulation value, R_w expresses the ability to reduce noise from outside to inside the building. Sound insulation is expressed in dB.

Seasonal Affective Disorder (SAD)
Also called winter depression. A mood disorder caused by low light levels in winter.

Sick Building Syndrome (SBS).
Term sometimes used to describe situations in which building occupants experience acute health and/or comfort effects that appear to be linked to time spent in a particular building, but where no specific illness or cause can be identified.

Sound Pressure Level (SPL)
Sound pressure level is a logarithmic measure of the effective sound pressure. Sound pressure level is expressed in dB.

Stack effect
Also called chimney effect. Ventilation principle that uses buoyancy of warm air.

Surface reflectance
A figure showing how much light is reflected from a surface.

Ultraviolet (UV)
Electromagnatic radiation with a wavelength shorter than that of visible light.

VELUX ACTIVE Climate Control
A sensor-based system for controlling internal and/or external shading products. Part of a dynamic window system.

VELUX Energy Balance control
A time schedule for controlling internal and/or external shading products. Part of a dynamic window system.

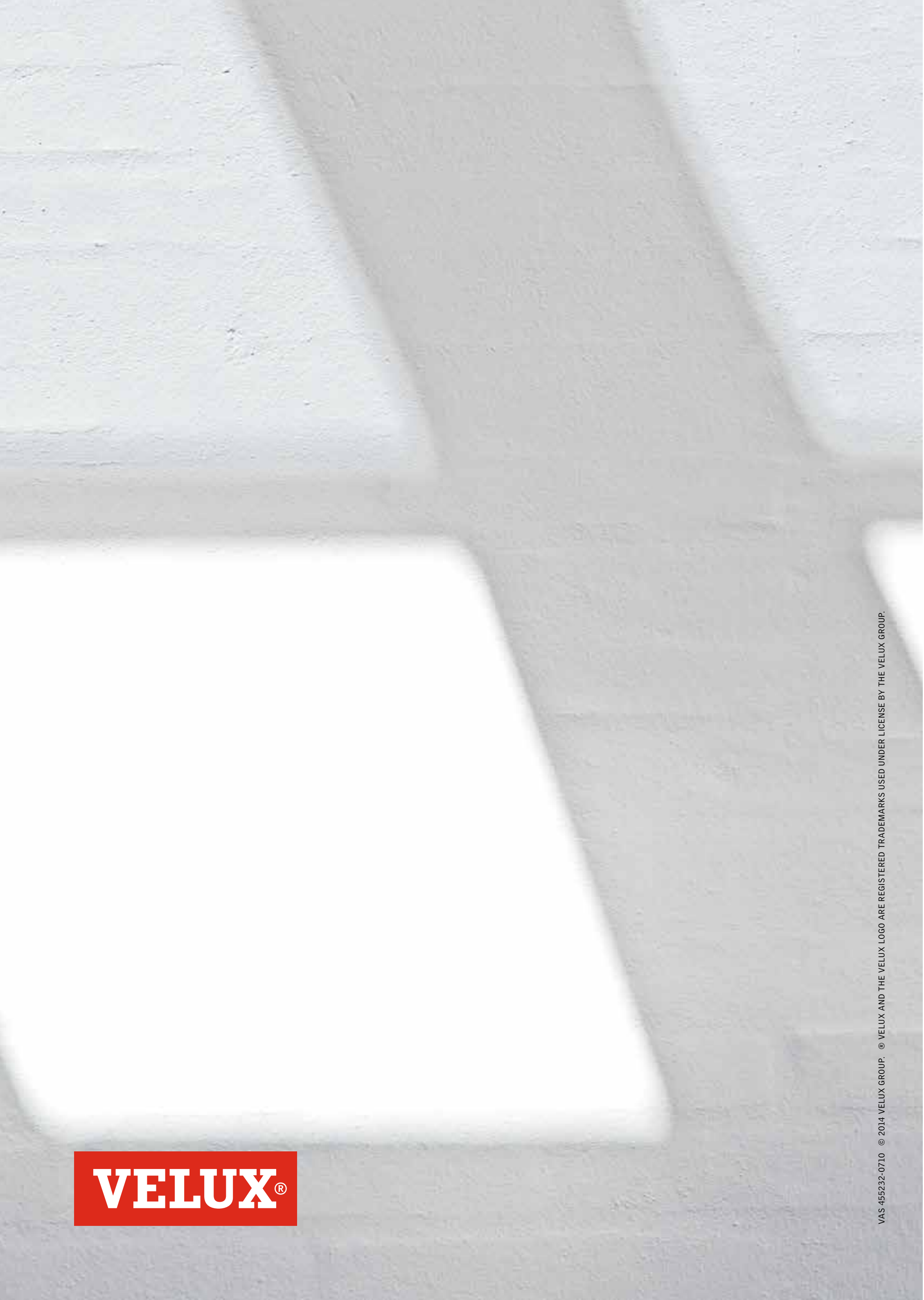
Ventilation rate
An expression of how many times the air in a room is changed per hour. Does not give any information about the efficiency of the ventilation.

Visible transmittance (τ_v)
The amount of daylight coming through a window is referred to as the visible transmittance (τ_v) and is dependent on the composition of the window pane.

Volatile organic compounds (VOCs)
Compounds that evaporate from the many housekeeping, maintenance, and building products made with organic chemicals.

Watt (W)
An energy unit. Often used to express how much energy a component uses. E.g. a 60 W light bulb or a 200 W heat pump.

Window system
A window system is a window and its accessories as a combined unit.
Accessories are shading devices or other devices that change the parameters of the window as a whole.



VELUX®