

# Building Integration of Solar Energy

A Multifunction Approach

Andreas Fieber

Licentiate Thesis

## Key words

solar energy, building integration, architecture, BIPV, concentration, reflector, sunshade, internal insulation, daylight, active solar heating, passive solar heating, building system, photovoltaic

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# Abstract

This thesis consists of two parts. The first part deals with building integrated solar energy, mainly from an architectural point of view. It is based on a literature review and discusses solar energy, the building as a system, the concept building integration (definition, motives, criteria, examples) and the relation between architecture and solar energy.

The second part presents a novel design of a concentrating, hybrid PV/T system, which uses windows as the media in the integration of building and solar energy system. It is placed inside a window or a glazed facade, where the reflectors are used as moveable sunshades and internal insulation when closed. Since the system is involved in the building's thermal balance and daylight provision, the system is evaluated for its thermal properties and for its daylight obstruction. Measurements show that the window's U-value is reduced from 2.8 for the bare window to 1.2 W/m<sup>2</sup>K with closed reflectors, and simulations indicate a strong redistribution of the daylight with open reflector screens.

The active thermal and photovoltaic performance has been measured for determining the concentrating system's optical efficiency. Long-term measurements of the thermal performance were also made during the summer of 2004. The results were used for creating models, simulating the system's performance, concerning PV/T yield, passive heat gains and thermal loss due to the varying optical performance and U-value of the open or closed reflectors. The simulations were used to provide an indication of a suitable control strategy, i.e. balance between open or closed mode of the reflectors, in respect for a maximal amount of daylight. It was suggested to generally keep the reflectors open at irradiance levels between 10 and 200 W/m<sup>2</sup>, which gives an open window 2800 hours of the year. This control strategy leads to an annual yield of 164 kWh/m<sup>2</sup> of active solar heat and 50 kWh/m<sup>2</sup> of photovoltaic electricity, window area. The annual net thermal transfer through the Solar Window is -78 kWh/m<sup>2</sup>.



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# Foreword

Since the beginning of my architectural training, the use of the sun has been an important inspiration source for my designs of buildings, not only for the obvious reason that our future buildings should contribute to a more sustainable development. This interest, much due to Prof. em. Krister Wiberg, led to an architectural diploma work on the design of a solar house and early sketches of a solar energy system design. The Division of Energy and Building Design gave me the opportunity to develop and deepen my knowledge about this in a licentiate thesis, and for this I am grateful.

I wish to thank my supervisors, Prof. Björn Karlsson and Dr. Helena Bülow-Hübe Dion for support and lessons learned. I thank the staff at the division of Energy and Building Design, especially Håkan Håkansson, Tobias Johansson, Johan Nilsson, Helena Gajbert and Bengt Perers for their contributions to the presented work. I would also like to thank Stefan Larsson and Martin Nilsson for making my ideas take physical shape in actual buildings.

The work of this thesis was financially supported by the Swedish Energy Agency.

Lund, April 2005

A handwritten signature in black ink, reading 'Andreas Fekner'. The signature is fluid and cursive, with the first name 'Andreas' written in a larger, more prominent script than the last name 'Fekner'.



PART I

Building Integration of  
Solar Energy



# 1 Introduction

This thesis discusses the understanding of integrated solar energy technologies in the built environment. This issue deals with a broad range of subjects, from the construction processes to user habits, from brick walls to photovoltaics, from thermodynamics to aesthetics. Therefore, a holistic approach, which deals with this wide range of considerations, is essential for the understanding of the need, benefits and beauty of well-integrated solutions. Hence, the first part of the thesis, in chapters 1 to 5, is focused on discussing the concept of building integrated solar energy from a range of aspects, and the way these aspects could interact. With the need for innovative solutions in mind, an experimental system developed by the author is presented in the second part of the thesis, in chapters 6 to 12.

The first part of the thesis can be read as an introduction to the complex issue of building integrated solar energy. This work is written mainly from an architectural point of view, with an aim to introduce other architects to solar energy, but also to highlight design problems and criteria for the solutions. Hence, the level of technical detail is not very high in this part. It aims to introduce the concept of building integrated solar energy on a broad, architecture orientated perspective. It is also desired to introduce architecturally orientated aspects to players within the field of solar energy, dominated by engineers.

The second part presents a multifunctional hybrid solar energy system, developed by the author in collaboration with colleagues in the division of Energy and Building Design, Lund University. This is presented from perspectives discussed in the first part, and analysed for its functions and performance on a more detailed level. However, the two parts can be read separately.

This chapter continues with a brief background for the research work, followed by a description of the aim and objective of the first study, and a brief description of the methods used. Lastly, an outline of the consecutive chapters of the first part of the thesis is presented.

## 1.1 Background

In view of reports on the ecological risk of using fossil fuels, which causes global warming through the increased green house effect, steps need to be taken to reduce our dependence upon those energy sources (GEO, 2002). Two strategies are dominant in the policies. A transition towards renewable energy sources that allow continued economic growth without further denaturing the planet Earth is of importance. However, it will take a long time before these alternatives are competitive enough to replace non-renewables. Therefore, energy conservation is the other cornerstone for obtaining sustainable development. Reducing energy consumption reduces the need for fossil fuels, and makes it easier for renewables to satisfy the energy demand.

Solar energy technologies can be regarded as representatives of both strategies of renewables and energy conservation (Energiboken, 1995). Energy conservation is here meant to be a strategy for reducing the need for primary energy. As an energy source, solar energy is the basis for almost all other renewable energy sources, plus, on a longer time span, the fossil fuels. By using solar radiation directly for our heating and power needs at the place of “consumption”, building integrated solar energy could be regarded as a primary energy conservation measure. If the system limits are widened, solar-fuelled electric power production is regarded as an energy source with a high exergy output.

For buildings, solar energy has historically been a highly present feature. Thermal mass and south-facing openings for passively providing thermal comfort have been used since ancient civilisations. The architectural revolution of glazed window openings allowed trapping the energy yield from the sun within the building, beside its most important feature: to allow daylight to enter and to obtain communication between inside and outside, without letting wind and rain enter. Daylight is the most important aspect of solar energy in architecture. With the introduction of solar thermal collectors and photovoltaic (PV) panels, architecture has again obtained a new vital element which permits buildings to be redefined: at best, as actual energy producers instead of strict energy users, or, at least, as smaller energy users than at the present. There is a potential for increasing the acceptance of solar energy technologies by making well integrated, informative and aesthetically pleasing designs. This potential might be larger than the quest for single components of greater energy- and cost-effectiveness.

## 1.2 The aim and objective of the study

In order to widen the market share of direct solar energy conversion in the energy mix, building integration is of great importance. However, the concept building integrated solar energy has no clear definition. Therefore, it is necessary to make a comprehensive assessment of the motives, potential, possibilities, obstacles and design criteria of building integration. The aim of this thesis is to make this assessment, by exploring existing and new strategies and approaches which contribute to a widened acceptance of solar energy in the built environment

A resulting list of recommendations for future designs and projects is the desirable outcome of the first part of the study. Definitions of the concept of building integrated solar energy are desired for a common language within the field. The target group for such a result would be architects interested in implementing solar energy systems in their building designs, and solar energy researchers and engineers who want to design systems for building integration.

## 1.3 Theoretical framework

The study of integration of solar energy in buildings is, like all research on architecture, of a complex character that demands a holistic approach (Hestnes, 1999). Solar energy and the system it is to be integrated into, could be regarded as a socio-technical system (Ingelstam, 2002), with both primary, objective and secondary, subjective values to be considered. This combined approach is applicable within system theory, which could be regarded as filling the gap between these two poles (Wallén, 1996). Traditionally, natural science, characterized by measurable facts, has been difficult to study in combination with more subjective features of social or humanistic sciences. System theory can serve as a framework for architectural research, which is “characterized by its study of the system man-building in connection with man’s use and experience of buildings” (Ekholm, 1987). This, together with the holistic quality of system theory (Lundequist, 2000), makes it a suitable theoretical framework for the study. System analysis, a tool within system theory, is also a suitable choice of methodology for the design challenge presented in the second part of the thesis. A system approach applied to the two studies will make it easier to establish a relationship between these.

## 1.4 Scope and limitations

Originally, the work was supposed to deal exclusively with active solar thermal systems. One reason was that the work was to be included in a national research programme on solar thermal systems. Another reason for focusing on this is the overwhelming quantity of material on building integrated photovoltaic systems, (BIPV). There are probably several reasons for the greater interest in PV systems. Its image as a high-tech, futuristic technology probably makes it more interesting for architects, engineers and consumers. Further, integration of PV is technically simpler than integration of solar thermal systems, which also makes it more attractive. The high price of PV systems is another way to justify the greater effort that has been made to integrate PV rather than thermal systems. Passive thermal strategies are in general more interesting for architects, since they often have a determined and positive impact on the design of the entire building. Passive heating represents the opposite to PVs on the high/low tech scale, which has made it attractive for the often nostalgic green building movement. From this regard, active thermal systems have become stuck in between the high tech PV and the low tech passive thermal strategies.

However, this thesis will deal with all strategies, for several reasons. First, the context for any of the systems, the built environment, is the same whatever one chooses. The main criteria for the design; location, orientation, leaning angles et c will generally be the same as will the discussion of the impact on the architectural expression. Second, all strategies are often taken into consideration in successful and interesting reference projects, since they all aim at the same objective; reduction of auxiliary energy demand, where solar energy is one part of the puzzle. Future projects will increasingly implement more than one strategy at the same time. As discussed by Anne Grete Hestnes (1999), future divisions between active thermal, passive thermal and PV installations will make little sense. It will be of greater interest to speak about solar buildings which adapt and make use of the sun in several ways. There is also a growing number of products – both on the commercial market and within the research field – that could be classified as hybrids, combining thermal and photovoltaic or even daylight properties, whereas the individual strategies can no longer be regarded separately. The project presented in the second part of the thesis is a clear example of this. Third, the Swedish market for thermal collectors is well developed, whereas BIPV is a relatively novel and rare concept in Sweden so far. But although thermal systems have been on the market for a long time, the interest in integrating them in buildings has been limited. With the present boom of BIPV on the global market,

it should be fruitful to make use of and apply this knowledge and trends also on thermal systems in order to increase their acceptance.

One should not forget that integrating a solar energy system should be first and foremost part of a primary energy conservation measure for the building system, and therefore an isolated perspective on the single system is useless. An introduction of passive thermal systems, day lighting and photovoltaics is therefore essential for getting the full picture of the potential of solar energy manifestations in the built environment.

Geographically, the study will focus on Swedish conditions. However, interesting concepts and projects to show the state-of-the-art technologies and applications are gathered globally.

## 1.5 Methodology

The first part of the thesis is based on a literature review and will have the character of an introduction and discussion. Facts and trends within the research and building industry spheres are presented.

A system analysis that widens the understanding of the key concepts used (integration, building, solar energy) will be made.

Parametric studies are conducted to discuss design considerations in the integration process, like the dependence on orientation and inclination of collectors or photovoltaic panels. Experiences from some case studies, made for implementation of both active thermal systems and PV installations during the licentiate work are presented.

The second part is a presentation of a design project which deals with issues similar to those in the theoretical part. The design process is described, as well as both the practical parts of hybrid construction and evaluation, and the building integration of the system. This methodology will be described in detail in the introductory chapter of the second part.

## 1.6 Outline of part I

The background section above can serve as a basis for the content. A second background chapter deepens this discussion and presents the two systems that are the objects of integration; the solar system and the building system. The structure of these presentations prepares the way for the discussions in the following chapters. First and foremost, building integrated solar energy is an environmental conservation strategy. Chapter two starts with the environmental background. The mechanisms of the

Sun and the way it has affected biological and cultural life on earth are introduced. The importance of location in time and space for the quality and quantity of solar radiation is presented. The nature of sunlight, and the three main solar energy forms, which are of interest for architectural integration - daylight, heat and electricity - are introduced. Hence the basic systems for capturing and converting the rays of sun to these energy forms are presented: passive solar building design, solar collectors and PV panels. Last, the system where those technologies are to be integrated, the building as a system, is presented.

With the objects defined, a clear definition of the term integration is needed for further discussion. Chapter three deals with this. What do we mean by building integration? What are the motives for integrating solar energy systems into the building system and how should they interact to best correspond to these motives? What aspects have to be considered for a well-made integration? Which aspects are important for increasing the acceptance of solar energy in the built environment? Examples of projects with typical approaches to building integrated solar energy will be presented.

Building integration of solar energy will inevitably affect the architectural expression of the building. Whether we deal with passive strategies or active thermal or PV systems, and irrespective of the degree of integration, some basic design criteria have to exist for a successful solution. Chapter four deals with these criteria.

The final and concluding chapter five attempts to assess lessons learned during the writing of the preceding pages. A discussion related to existing examples will lead to a conclusion with a list of recommendations for future design strategies.

## 2 Background – solar energy systems and the building as a system

All life on Earth and its energy flows derive from the sun. Throughout the natural development of the planet and its inhabitants, the ecological systems have been in balance with the sun as the external energy source. Owing to the use of fossil fuels, which leads to increasing global warming, this balance was changed. Hence, energy conservation and a transition towards renewable energy sources, is essential. Direct use of solar energy is one of the cornerstones in this process. Since the sun is a central part in both global warming and in reducing this increase, this background chapter starts with a brief description of the sun as a life supporting system for earth, and the problems associated with the sun due to human intervention in the energy balance.

The system approach is suitable for the building. A building is a complex system with several clearly defined subsystems and relations to its context and users. The study deals with the way solar energy systems could or should interact with the building system. Within this chapter, the systems concerned will be reviewed, in order to discuss in what sense and to what extent they can interact with each other.

### 2.1 The solar system and environmental problems

The Sun is the source of all life on earth. It has a mass of  $1,989 \cdot 10^{30}$  kg, of which hydrogen represents 71%. A fusion process takes place within its core under extreme temperature ( $16 \cdot 10^6$  K) and pressure. Hydrogen is transformed into helium, the other main constituent (27%), and immense quantities of energy are thus released through its 5 780 K surface

to the outer space. The radiation spreads radially at all directions, hence a diminishing small portion reaches the surface of the earth. Still, this energy exceeds its human inhabitants' energy use by a thousandfold.

The warming of the planet by the sun derives from the shortwave radiation that reaches the atmosphere, at a rate of  $1,37 \text{ kW/m}^2$ . Some 30% of this radiation is reflected or absorbed by the atmosphere. The rest is transmitted towards the Earth's surface as direct or indirect radiation. The direct radiation goes straight from the sun to the surface, and the indirect radiation is diffused by the atmosphere, clouds etc. The radiation activates molecules in the terrestrial material, generating heat, which radiates from the material as infrared long wave radiation towards the sky. The atmospheric gases and clouds let some of this out into space, but they absorb and radiate back a considerable portion of it. This absorption is essential for maintaining the life-keeping thermal balance on Earth. Without it, the temperature on Earth would be around 50 K lower (Karlsson, 2001). Similarities between the thermal properties of the atmosphere and a window are obvious; most of the shortwave radiation is let through, admitting heat to the inside, which is trapped to a large extent by the glass. Hence the expression *greenhouse effect*. The parallel with passively heated buildings, where the wise use of windows is the most essential part of the concept, is clear. The reflecting and absorbing properties of the atmosphere depend on the content of the so-called greenhouse gases, such as  $\text{CO}_2$ , methane (150% increase since 1750),  $\text{N}_2\text{O}$  (17% increase), and CFCs (Blasing, 2005).

The Sun is the engine running the climatic cycles of water, wind and temperature, and the organic cycle of photosynthesis and respiration. The whole creation of water derives from the energy of the sun. In the water, evolution resulted in organisms that could make use of the ultraviolet radiation from the sun to transform it into chemically bound energy in the process called photosynthesis, where water and carbon dioxide are transformed into carbohydrates and oxygen. Thus organisms could evolve, which through metabolism and respiration perform the reverse process of photosynthesis, consuming carbohydrates and oxygen to exhale water and carbon dioxide. With the energy input from the sun and the evolution of species, a stock of biodiversity and biomass constructed the living environment that still surrounds us. The surplus of biomass created by the sun was transformed into fossil material over a time span of millions of years.

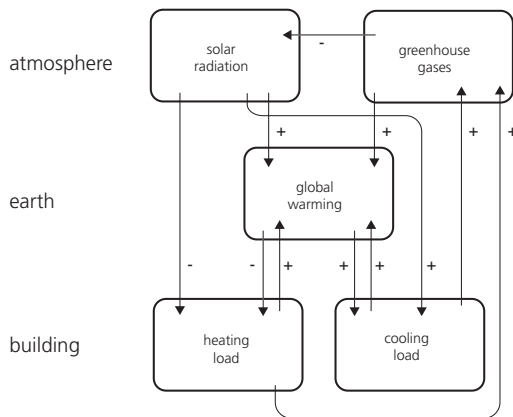
With the introduction of technology as a means to reduce human labour, an alienation from the natural ecological balance started. From only using wood as a fuel for heating and cooking, where reproduction can be in balance with consumption, man started using fossil fuels like coal and oil for more efficient processes of energy conversion towards industrialisation. The drawbacks are that those fuels are consumed in a

time span that is marginal to what it took to create them (hence the classification “non-renewable”), and that this leads to a net release of carbon dioxide into the atmosphere.

The concentration of  $\text{CO}_2$  in the atmosphere has increased by 31% since 1750 (Blasing, 2005). The consequences of this are under discussion, but the vast majority of the research world agrees that this is the main contribution to the increased global warming that is taking place. The increased temperature leads to rising sea levels and increased desert areas, which means less potential cultivation area for an ever-increasing population. Other populations that would not benefit from global warming are numerous plants and animal species; with the current trend of global warming, 15-20% of the Earth’s species are at risk of going extinct by 2050 (Thomas, 2004). Other serious threats derived from the use of fossil fuels are the release of oxides of nitrogen (causing acid rain that endangers forests and lakes) and health threats caused by carbon monoxide in dense urban areas.

Another potential threat to the organisms is the diminution of the ozone layer which filters UV-C, the solar radiation with the shortest wavelength and hence the highest energy content, which can cause cancer and genetic mutations. This is caused by a more aggressive and longer-lasting set of gases, called CFCs. Those are used mainly in cooling devices, such as refrigerators and air conditioners. The use of extensive cooling is often derived from poor building design, where little consideration is given to the environmental context the building has been put into.

The concentration of CFCs is expected to diminish, because of steps taken to reduce their use, but the CFCs released will cause damage for a long time, since they work as catalysts, i.e. they cause the conversion of ozone ( $\text{O}_3$ ) to oxygen ( $\text{O}_2$ ) without being destroyed themselves.



*Figure 2.1  
A systematic description  
of the relation between  
solar radiation, global  
warming and the en-  
ergy use of buildings.  
The arrows indicate  
influence.*

## 2.2 Energy conservation and renewable energy sources

As discussed, solar energy is both essential for life, and has become an ingredient of the greatest global environmental problems that we are facing. The greenhouse effect we are dependent upon derives from the sun. The increasing global warming is caused by the increasing concentration of greenhouse gases. Since we cannot turn down the effect of the sun, we are obliged to deal with the greenhouse gases, mainly CO<sub>2</sub>. Since the net release of CO<sub>2</sub> is directly related to the use of fossil fuels for energy purposes, two solutions are applicable:

- Reduction of the energy demand
- Conversion from fossil fuels to renewable energy sources

Both strategies are essential for sustainability. The high demand for energy, derived from an apparent belief in fossil fuels and nuclear power as endless sources, is the main problem. One kWh that is saved is always the most environmentally friendly. But focusing only on energy conservation entails a risk, since no matter how much energy we can save, the use of fossil fuels for providing this energy will still increase the concentration of greenhouse gases. Therefore, a conversion towards renewable energy sources must take place at the same time. The direct use of solar energy has an essential role in this process. It could be regarded both as an energy conservation measure and a renewable energy source. When integrated into buildings, solar energy systems are a part of the building structure that reduces the demand for domestic hot water, space heating or electricity. A solar plant converting solar radiation to grid connected electric power is obviously regarded as a renewable source of energy. From an exergy point of view it seems wise to make direct use of the energy source that is the mother of almost all other energy sources we are using.

As discussed, solar energy is transformed and stored as carbohydrates in the biomass, which we make use of through eating or burning, besides using wood as a construction material. When this energy source is utilised, whether through our bodies or a burner, the CO<sub>2</sub> released is cycled back to the reproduction of biomass, provided that this reproduction is of the same magnitude as the consumption. Hence, biomass is a flowing, solar fuelled renewable energy source that is not depleted for a very long time. However, responsible harvesting of the forests is not practised globally. Large areas of e.g. rain forests, hosts of a great biodiversity, are damaged by reckless cutting, and the unbalanced burning of wood often takes place without filtering the smoke, which can make biomass one of the most pol-

luting energy sources. In Sweden, the use of biomass represents 16,5% of the energy supply in 2003 (Energimyndigheten, 2004).

The winds created by the rotation of the Earth and the spatial differences in solar radiation on its surface, are an everlasting source of energy, with no polluting emissions. However, the wind turbines made to harvest the wind energy need energy to be produced and are aesthetically polluting to many people, who consider that wind turbines destroy the beauty of the landscapes they are put into. Here is a clear conflict of interest and opinion depending on one's attitude towards environmental issues. People with an environmental concern often have a more positive attitude towards wind turbines, and might even find them aesthetically pleasing. Sweden's share of power supplied by wind turbines is 0,5% (Energimyndigheten, 2004).

The water cycle, describing how water is pumped back and forth between land and sea with the sun as the engine, is another important renewable energy source, not least in Sweden, where it represented 41% of the power production in 2003 (Energimyndigheten, 2004). As with wind energy, the source is pollutant free, but the exploitation of rivers is a serious threat to the biodiversity in the surrounding ecosystems ([www.naturvardsverket.se](http://www.naturvardsverket.se)).

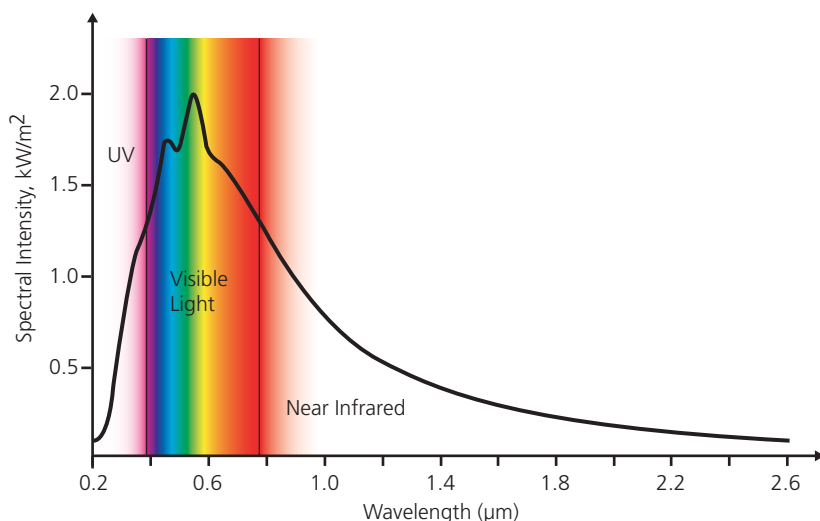
A hybrid energy source between wind and water energy is wave energy that generates power directly from wave movement. Similar to this is the only renewable energy source that is not derived from the sun, tidal water energy.

## 2.3 Solar energy on Earth

As discussed, almost every renewable energy source derives from solar radiation. This also applies for fossil fuels, but the great difference here is the huge discrepancy in time scale between consumption and reproduction, with consequences such as depletion and global warming. In comparison one can observe that the direct use of solar energy is pollutant free (except for the production of the components) and of no harm to its local surroundings, except for the notion that people can find solar collectors or PV panels ugly. A unique feature is the possibility to directly convert both heat and electricity from solar radiation. Drawbacks are cost and the time bound variation of solar radiation.

### 2.3.1 The nature of sunlight

Solar radiation occurs over a wide band of wavelengths, from ultra violet (UV) at 300–400 nm, via visible light (VIS) at 400–700 nm, to infrared (IR) at 700–2500 nm. The energy content proportions of those groups are 3, 53 and 44% respectively. Hence, about half of the sunlight is invisible to the human eye. The infra red radiation from the sun is within the “near infrared” spectrum, which means that it has a relatively short wavelength (compared to true infrared), and hence a high energy content, since energy content as a rule of thumb decreases with increasing wavelength. Hence all solar radiation (except the UV radiation of the shortest wavelength, so far filtered by the ozone layer), can penetrate the atmospheric gases and glass, which makes it possible for us to make use of the solar energy in the shape of light and heat, outdoors and indoors.



*Figure 2.2 The wavelength distribution of solar radiation. The coloured section indicated the visible light, which lies between the ultraviolet and the near infrared spectrums.*

For the building context, the usable forms of direct or converted sunlight can be divided into daylight, heat and electricity. Daylight is perhaps the most important ingredient in architecture, and has been a main characteristic of many enduring monuments and manifests of architectural history, from Egyptian Abu Simbel, via Roman Pantheon, baroque interiors and Le Corbusier's work to Liebeskind's plans for the memorial plaza of the World Trade Centre in New York City.

The total, or global, radiation on a horizontal surface  $I_G$ , can be divided into direct radiation  $I_b$  (b for beam), indirect radiation  $I_d$  (d for diffuse) and ground radiation  $I_g$ .

### 2.3.2 Direct radiation

What comes shining straight from the sun towards Earth's surface without interruption in parallel beams is called direct radiation. The magnitude, provided that there are no interruptions due to clouds or smog, is dependent on the solar angle, i.e. the deviation from a horizontal beam, or a beam running parallel to the tangent of the point of observation. The greater the solar angle (up to  $90^\circ$ ), the higher is the energy content per area of the surface exposed to the radiation. At a higher angle, there is also less atmosphere and other interruptions for the radiation to be reflected on or absorbed into. In figure 2.3, the influence of the solar angle is shown. The spectral irradiance decreases for a larger air mass, which expresses the amount of atmospheric gases that the radiation passes on its way to the surface of the Earth. Air mass 1 means a perpendicular direction towards the surface, i.e. the shortest way possible. Air mass 2 means the double distance, the result of a solar angle of  $\sin^{-1}(1/2) = 30^\circ$ . The solar angle can be calculated from the date, time and latitude, i.e. the radiation is time and space dependent. However, the calculated values are theoretical, since the true radiation depends on the atmospheric conditions. The direct radiation,  $I_{b,n}$  (b for beam – direct radiation, n for normal) can be measured with a pyrheliometer. The direct radiation with the incoming angle  $\theta$  (from zenith) on any inclined surface, can be calculated as  $I_b = I_{b,n} \cos(\theta)$ .

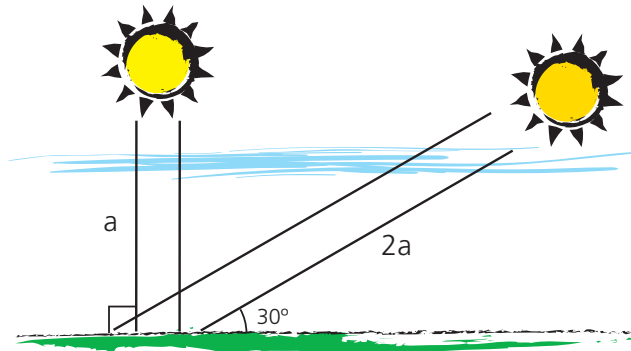


Figure 2.3 *The intensity of direct radiation is dependent on the solar height, due to the exposed area, which grows with increasing deviation from zenith, and the air mass ( $a$ ) which for the solar height  $30^\circ$  is double that for the zenith.*

### 2.3.3 Indirect radiation and ground radiation

The radiation diffused by the atmosphere and the clouds is called indirect radiation. It is the indirect radiation that creates the blue colour of the sky and the spectrum of reds, yellow and purple in the sunset. This radiation is spread in all possible directions and is complicated to calculate properly. It can be divided into three different components; the circumsolar, the horizontal and the isotropic diffuse radiation, see figure 2.4.

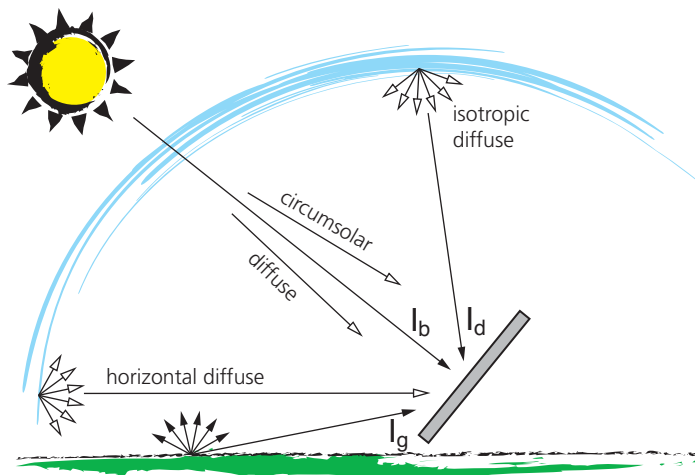
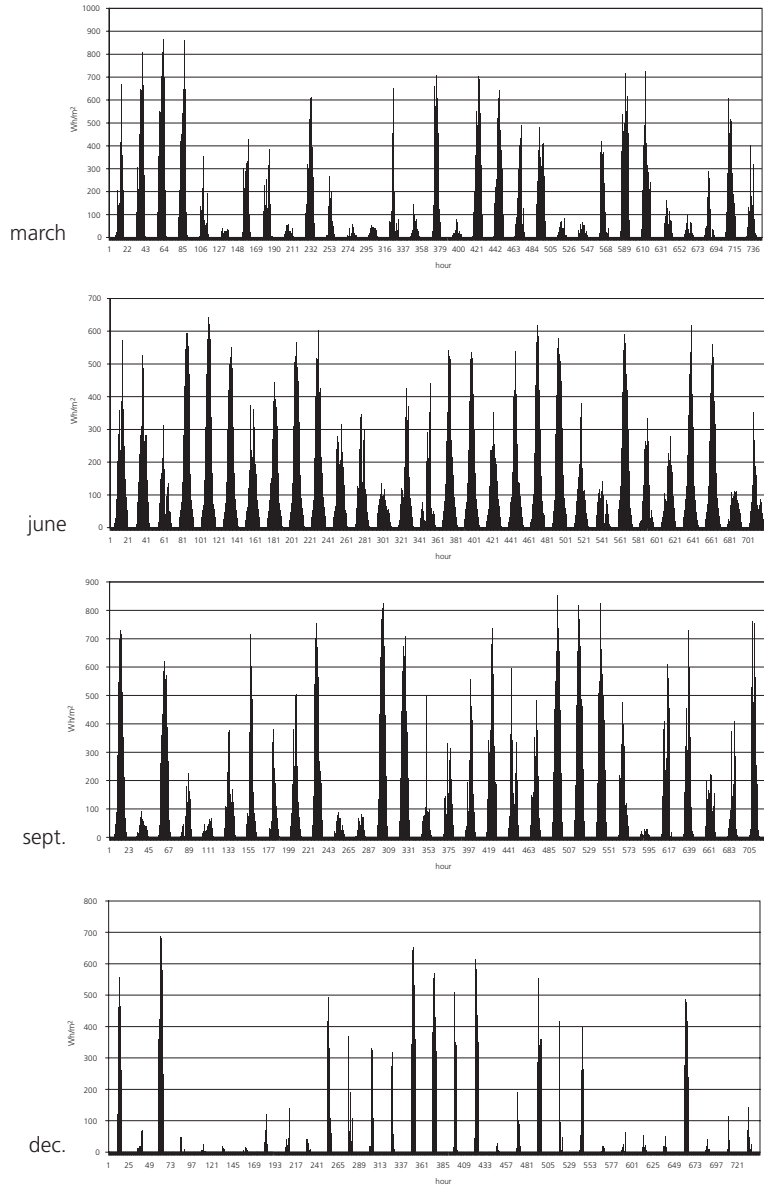


Figure 2.4 Direct radiation, ground radiation, and the different components of diffuse radiation (white arrows).

The radiation reflected from the ground is dependent on the ground reflectance (%) due to material, colour etc. For example, snow has a ground reflectance of 80-95% (Adamson, 1986).

### 2.3.4 Seasonal and spatial variation of sunlight intensity

The time dependence is due to Earth's rotation around the sun (yearly variations) and around its own axis (daily variations). Calculations have been made in the program Meteonorm (Meteotest, 2004) to describe the seasonal and diurnal variations of the solar angle, and hence the intensity of radiation.



*Figure 2.5 Seasonal variation of the global irradiance in Stockholm (lat  $59.4^\circ$ ) towards a vertical surface. Data from Meteornorm.*

The spatial dependence is due to the declination of Earth's rotation axis in relation to the orbit around the sun.

### 2.3.5 Effective solar height

The effective solar height is defined as the angle between the horizontal plane and the projection in the transversal plane of the incoming direct solar radiation. The transversal plane is the plane perpendicular to the plane of the exposed surface. For south-facing surfaces, this plane corresponds to the north-south plane. The effective solar height can in this case also be called the south projection angle. The projection in this plane derives from the aim to divide the vector describing the direct irradiance into two components: one perpendicular to the surface of the device, which will provide all the energy, and one parallel to the surface, which will have no contribution to the power supply, see figure 2.6.

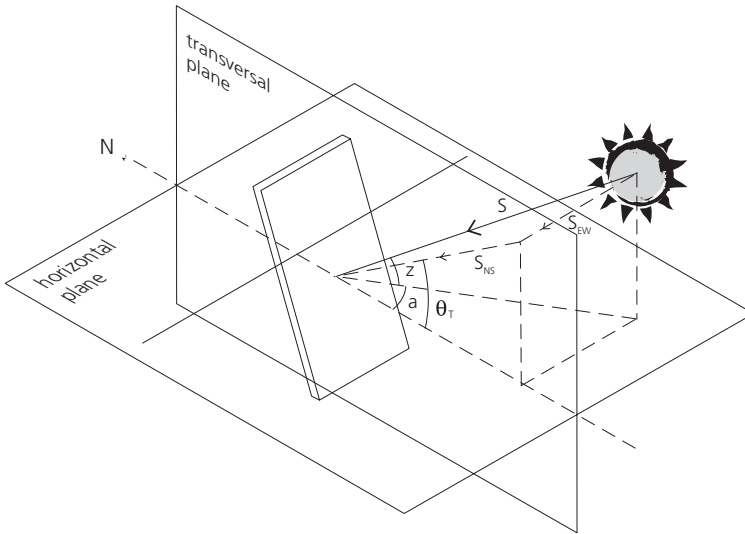


Figure 2.6 The effective solar height,  $\theta_T$  is the solar height projected onto the transversal plane, perpendicular to the plane of the exposed surface.

The relation between the effective solar height  $\theta_T$  and the zenith  $z$  and the azimuth  $a$  is described by equation 2.1:

$$\tan(\theta_T) = \tan(z) / \cos(a) \quad [\text{Eq. 2.1}]$$

From climatic data generated in Meteonorm (Meteotest, 2004), the effective solar height projected towards vertical surfaces with different azimuths for different Swedish locations was analysed. Figure 2.7 shows the annual distribution of the effective solar height.

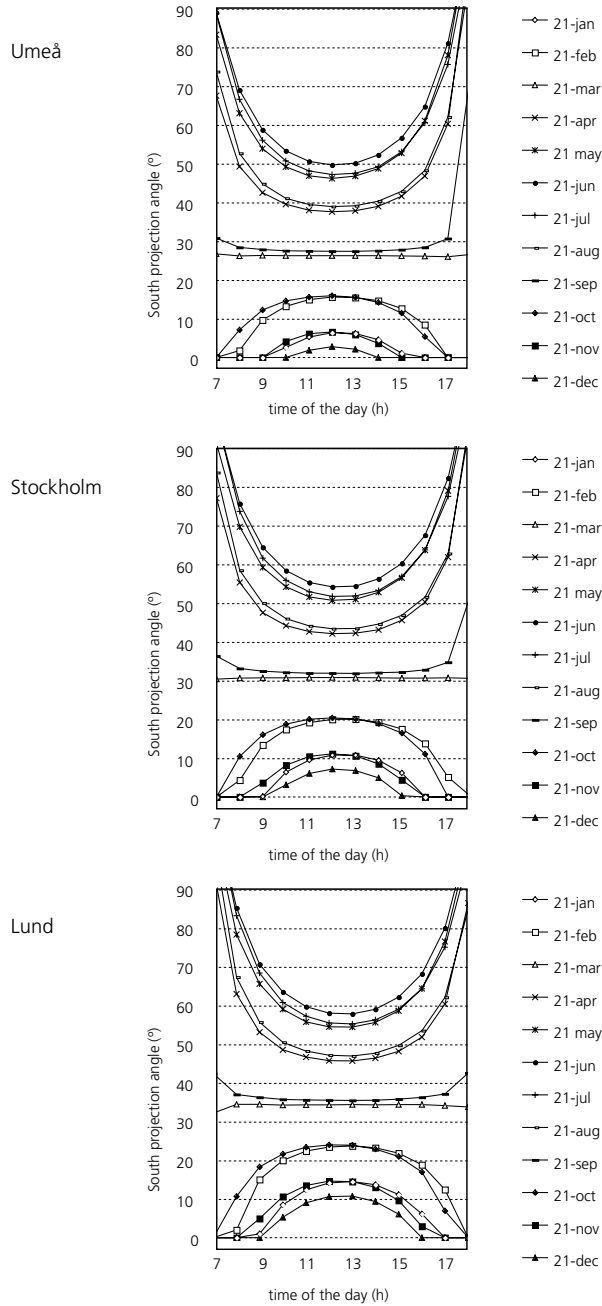


Figure 2.7

The south projection angle,  $\theta_T$ , for Lund (lat  $55.4^\circ$  N), Stockholm, (lat  $59.4^\circ$  N), and Umeå (lat  $63.5^\circ$  N), Sweden, for the 21st of every month of the year.

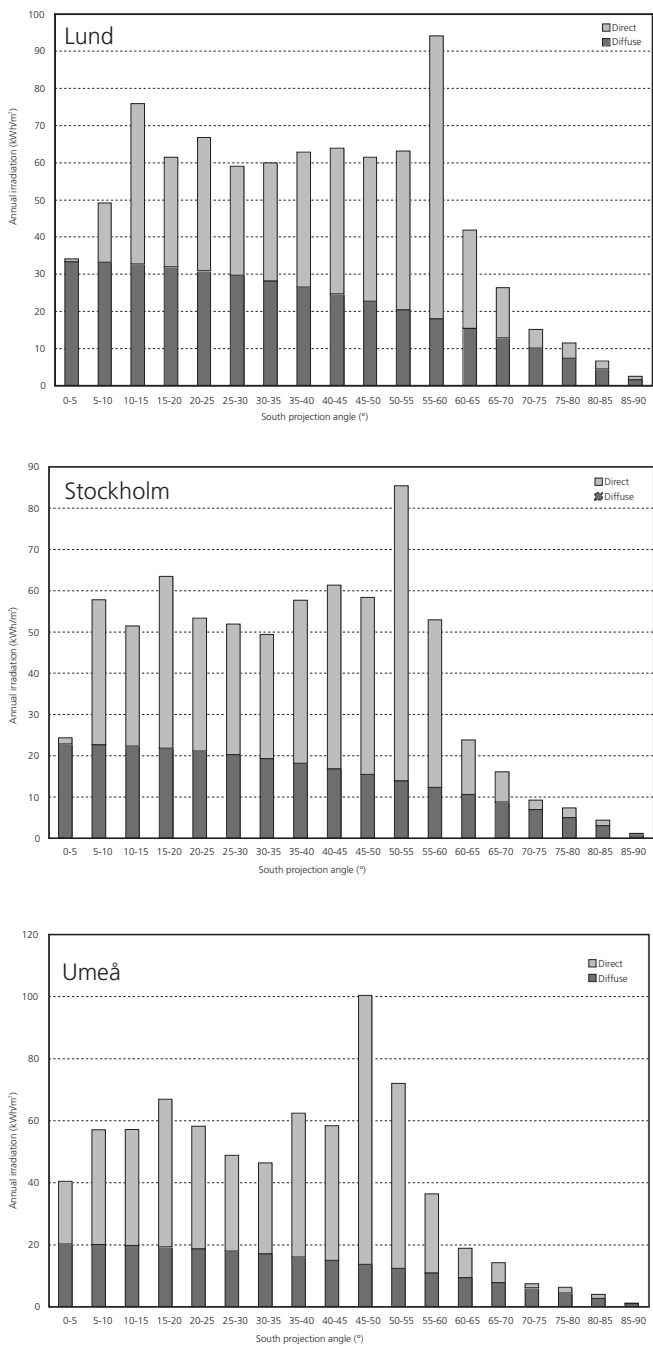


Figure 2.8 Annual direct and diffuse irradiation on a south-facing wall in Lund, Stockholm and Umeå, projected on the north-south vertical plane. Data was generated in Meteonorm (Meteotest, 2004).

## 2.4 Solar energy technologies for the building context

There are three main strategies to directly harvest solar energy in buildings. The most obvious is to make as much use as possible of the solar radiation via the design of the building in order to increase the amount of daylight and to reduce the need for auxiliary heating energy, without an added subsystem. Steps taken to reduce cooling loads due to solar radiation are also included in what is called passive solar house design.

To contribute to the building's energy balance by using a medium such as air, water or oil in an integrated subsystem is called active solar heating. This can be used for preheating ventilation air, for waterborne space heating or for domestic hot water (DHW).

The third strategy is to use photovoltaic panels to directly convert solar radiation into electricity for the activities of the building.

For increasing the efficiency of these systems, some supporting technologies are also worth mentioning. Concentrating systems aim to make more use of the energy converting components and hence to increase cost effectiveness. Hybrid systems combine passive, active and /or PV systems in order to increase efficiency and material resources.

### 2.4.1 Passive solar house design

By adopting wise building design, the energy demand for heating or cooling a building can be satisfied or reduced without the addition of supporting systems. Steps taken to passively reduce the building's energy demand are

- orientating the building wisely
- maximizing the volume to surface ratio
- enhancing window orientation towards the sun
- using thermally heavy materials in the interior
- a high degree of insulation in the building envelope et cetera

These steps should, if possible, be taken before considering additional systems like active thermal or photovoltaics. The building in itself will be standing substantially longer than any supporting system, and the thermal properties of the building will always be superior to these systems and will even determine the design criteria for these. Heat will always be lost, or gained, via the building envelope no matter how well or badly the solar collectors work, and therefore it is essential to make those losses as small, and gains as big, as possible, without jeopardizing the thermal comfort. A minimised heating demand will also be a way to increase the solar fraction,

i.e. the relative contribution from an active solar heating system, which could increase the motivation for installing such a system.

The concept passive solar house has gained much attention recently due to successful extremely low energy houses in e.g. Germany and Sweden. However, as with the term building integration, some confusion has occurred as to what it really means. The German "passivhaus" concept primarily considers it to be a definition of a maximal heating demand figure. This should be less than  $15 \text{ kWh/m}^2\text{a}$ , which should "not be attained at the cost of an increased use of energy for other purposes, like electricity. Furthermore, the combined primary energy use (including household electricity) may not exceed  $120 \text{ kWh/m}^2\text{a}$ " ([www.passiv.de](http://www.passiv.de)). Whether we consider it to be a matter of using the insolation to cover as much of the energy supply as possible, or to use stricter requirements as mentioned above, the common denominator is that the building should be designed with a high ambition to reduce the auxiliary energy demand.

The knowledge of the sun's heating capability has been present since the dawn of life, and cave settlements with a design gaining from the sun have been found from several civilizations. Historically, the Greek mathematician and inventor Archimedes made the first known design of a passive solar house, with south-facing openings and thermal mass inside. The term was used by the movement of designing solar houses in the US during the 1970s, as a response to the emerging oil crisis. The main concept was to maximize solar gain through the windows and to capture it with heavy materials of high thermal capacity. Thus the heat can be stored in the material in order to avoid overheating when the sun shines and to make use of the heat when the materials cool off during night time. In order to avoid overheating during summer, this strategy demands wise solar shading.

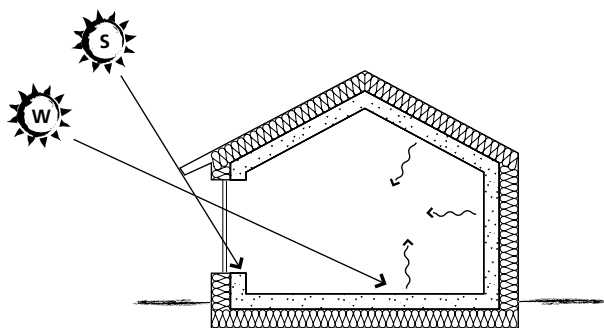
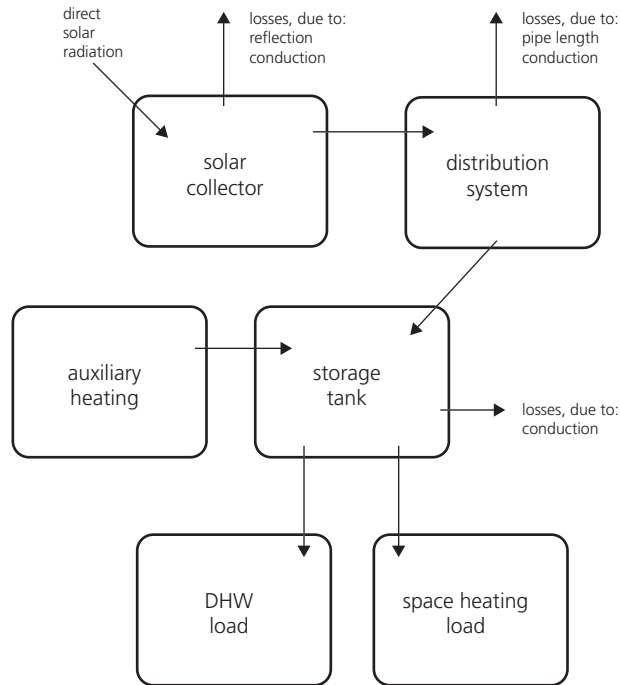


Figure 2.9 *The principle of a passive solar house design. Heavy and insulated thermal mass stores incoming solar heat of low solar heights due to wise solar shading.*

### 2.4.2 Active solar heating systems

An added subsystem to the building which converts solar energy to heat, distributed via air or water to satisfy parts of the ventilation, space heating or DHW energy demand is called active solar heating. These systems can be divided into three main categories; air solar systems, DHW systems and combo-systems, for space heating and DHW. Air systems use channels to preheat incoming ventilation air with the use of the sun. They can also be used as a dynamic insulation, i.e. the heated air is contained as an outer layer in the building envelope to reduce heat losses due to conductivity. Using water or oil as a medium to preheat DHW and/or water for space heating is the most common and cost-effective strategy (Andrén, 1999). A schematic representation of an active solar heating system is shown in figure 2.10.



*Figure 2.10 Schematic representation of a fluid-borne active solar heating system. The arrows indicate energy flows.*

The central component of the system is the solar collector, which converts the solar radiation into heat carried by the fluid medium. The collector consists of a heat absorber, which is heated upon exposure to the sun. The

absorber preferably has a selective coating, which gives an optimised relation between absorbed (maximised) and emitted (minimised) heat, for best thermal performance. In the absorber, the heat is transferred to the fluid, often via a heat-carrying pipe attached to, or integrated in the absorber. To reduce thermal losses from the absorber, two components are used which are in analogy with a building; First, a glass cover to let in the radiation and to trap most of the infrared heat radiation within the collector. Second, insulation to prevent conductive heat losses from the collector. Hence, we have a subsystem within the active solar system with solar radiation as input and thermal delivery and thermal losses as outputs. The goal within this subsystem is to maximise the thermal delivery from the collector by maximising the exposure to radiation and to minimise the thermal losses. Steps taken for this are better glazing with e.g. antireflective coating (to increase transmittance), low energy coating (to reduce emittance), more efficient absorber and selective coating, closer contact between absorber and heat carrying pipe and increased insulation.

The heat carrying subsystem consists of pipes that are insulated in order to reduce heat losses during transit from the collector to the storage subsystem. Heat is the input and output, and to diminish the losses is the only objective. Steps taken for this are shorter distance between collector and storage, and increased insulation thickness.

At the other end of the system is the storage tank, where the interaction with the building's heating and DHW systems takes place. Storage capacity is essential in order to compensate for the seasonal diversity characteristic of solar radiation. The heat from the heat carrying subsystem is transferred to the tank via a heat exchanger (the heat carrying fluid runs in a closed system from the collector), placed in the lower part of the tank. In the upper part, a heat exchanger transfers the heat stored to the space heating or DHW distribution systems. In order to get an effective heat exchange, it is important to have a distinct stratification between the lower part, which should be cold, and the upper part, which should be warm, since the exchange efficiency is dependent upon the contrast in temperature between the exchanging media. The most important reason for having this stratification, is that the top of the tank should keep the proper delivery temperature, in order to avoid auxiliary heating, e.g. from an electric heater. The storage system can collaborate with other supporting systems, such as auxiliary heaters of any energy source (electricity, oil, gas or bio fuel), and thus is the heart of the building's integrated heating systems. Support from other energy sources is essential since the seasonal variation of the solar radiation makes it very hard if not impossible to size the system to fully cover the heating energy demand. A rule of thumb is that a well designed and economically viable combined DHW/space heating system in a single family house under Swedish conditions can satisfy

around 50% of the DHW demand and around 15% of the space heating demand. (Andr  n, 1999) A system like this would need a collector area of around 10 m<sup>2</sup> and a storage tank of around 750 l.

### Flat plate collectors

The most common thermal collector is the flat plate collector, a glazed and conventionally insulated flat box, with flat heat absorbers, see figure 2.12. Dimensions vary between different products, but generally the width is adapted to the modular system of roof constructions, with a 120 cm c-c distance. The depth is approximately 10 cm, and the most variable dimension is the length, from 2-4 m approximately. The covering glass is a flat single pane, sometimes with an antireflective coating, to maximize solar gains. It could also be matte in order to hide the appearance of the underlying heat absorbers. Those are flat, with a width of around 12 cm placed next to each other with a centrally placed heat-carrying pipe. The absorbers are often made of copper with a selective coating. The pipe is either welded to the bottom or integrated in between two sheets. The box is insulated with mineral wool or expanded polystyrene in the bottom and on the sides, and covered in most cases with metal sheets.

The absorbers are normally black for maximal absorptance, although work has been done with alternative colours for wider building integration potential (Tripanagnostopoulos, 2000).

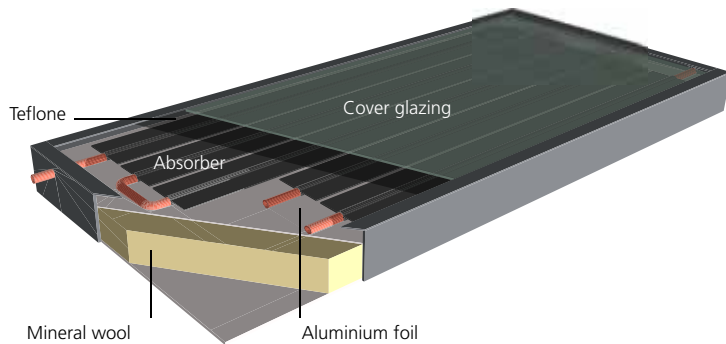


Figure 2.11 The construction of a typical flat plate collector.

### Vacuum collectors

In order to reduce thermal losses in the collector, vacuum is an alternative to conventional insulation. This is realized in so called vacuum tube collectors, where the covering glass is an evacuated tube, containing the absorber, which is flat or tube-shaped. Hence the glass also functions as

insulation, since the vacuum cannot transport any heat. Structurally, the vacuum tube collector can work as flat plate collector with a heat carrying water pipe running through and connecting adjacent tubes. There are also heat pipes, where every tube is a closed system which transports heat to the surrounding media circuit via a small internal heat exchanger. The efficiency of these tubes is even higher.

The performance of vacuum tube collectors is said to be more than twice as efficient as that of flat plate collectors, but a comparison test conducted by SP, the Swedish national testing and research institute, shows a positive difference of less than 50% for the vacuum tube collector. Further, the tubes perform worse during the cold season, due to the colder glass surface of the evacuated tubes, which leads to longer periods of ice, snow or frost cover (Kovács and Pettersson, 2002).

Vacuum tube collectors have a less discreet, but what could be considered a more interesting, modern and “high tech” appearance than conventional flat plate collectors, see figure 2.13. The structure of the assembled tubes, with an adjustable absorber inclination angle (if those are flat), makes them more suitable for vertical (e.g. in façades) mounting than compared to flat plate collectors. Also the transparent appearance of the glass tubes, however with non-transparent absorber inside, makes them interesting for in horizontal sunshades, in front of windows etc.



*Figure 2.12     Roof applied vacuum tube collectors in Stockholm (left), and tube collectors applied on the façade of a multi-family house in Malmö.*

## Air collectors

With air channels exposed to the sun, preheating of inlet ventilation air can be achieved. Many of those systems are directly integrated into the building construction, but a few systems are produced separately, e.g.

the SolarWall system ([www.solarwall.com](http://www.solarwall.com)). Air collectors without a fan can be considered as passive systems. Such highly building integrated systems have been developed by Swedish architect Christer Nordström (Nordström, 1982).

### 2.4.3 Photovoltaic systems

From the discovery by the French physicist Edmund Becquerel in 1839 that solar radiation can generate electric current in electrodes, via the development of semiconductors, one of the most promising technologies for a sustainable future is under continuous development. From being a specialised technology mainly for the space industry, a boom in projects the last decade for building integrated photovoltaics (BIPV) makes solar generated power an increasing feature of our everyday lives. Prices are still far too high (approx. 5 times higher than conventional electricity) to be competitive to conventionally produced electricity. However, learning curves show that prices have dropped and will continue to drop over time, due to technological improvements and larger production volumes.

The central and most costly component of a photovoltaic power system is the solar panel, which is a composition of series connected solar cells. A solar cell is a thin semi conducting silicon wafer, with a positive doped top and negative doped bottom. When exposed to solar radiation, electrons move from the top to the bottom surface, and an electric potential of 0.5 volt occurs in the cell (Green, 2002).

As for solar thermal energy, photovoltaic power has an uneven delivery profile (shifting current at a constant voltage) due to the seasonal diversity of solar radiation, thus storage capacity is essential. The storage can be effected either by batteries or by connection to the central grid, which then serves as an infinite storage and backup resource. This alternative is the most realistic in urban or other dense areas, where there is a grid. Battery backup systems are more suitable where photovoltaic systems are most realistic to implement today, namely in remote areas without grid supplied electric power. An interesting technology for a future boom for photovoltaics is the use of hydrogen for storing the energy. Via electrolysis, an electric current can decompose water molecules into hydrogen and oxygen. The hydrogen can easily be stored without losses, and can, by the reverse process in fuel cells, be converted back to electric power with steam as the only by-product. This technology is of particular interest for the transport sector, which besides being a large contributor to global warming also causes hazardous local pollution in urban areas. Hence, the full or partial use of fuel cells is under development by a number of major car manufacturers. With the storage capacity of hydrogen, the uneven

distribution of solar radiation becomes less problematic, since the need for transport energy can be a backup for overcapacity during summer. Further, the less complicated transport of hydrogen, with reduced losses, makes it possible to harvest solar electricity in large desert areas with high solar intensity.

The direct current (DC) from PV panels normally has to be transformed to ~220 volts alternating current (AC) for normal use in residential, office or commercial situations, either before the connection to the grid, or from the battery backup system. This conversion is made by an AC/DC inverter, which consumes a small portion of the power produced.

The silicon PV cells exist in a range of varieties, differing in composition, appearance, efficiency and price. The original and still most efficient is the monocrystalline cell, cut in a slice of ~0.2 mm from a single piece of silicon. This makes it expensive to produce, but it is also the most efficient cell with a conversion rate of ~16%. A monocrystalline cell is distinguished by its black, homogeneous surface. The cell is commonly square shaped, 10 by 10 cm, with cut rounded corners, which derives from the circular section of the sliced work piece. The other and more commonly used polycrystalline cell is made out of smaller parts of silicon which are easier to derive, e.g. as a residual or recycled product from the electronics industry, and hence has a lower price. However, the conversion rate is a little lower, around 12%. Polycrystalline cells are recognized by their random, camouflage-like surface pattern, most often in a shiny deep blue colour. Other colours are also possible, like red, grey, green or golden yellow, but their drawbacks are lower efficiency (~10%) and higher price. The dimensions are normally the same as those of monocrystalline cells, and the cells are arranged in modules, commonly in a 4 by 9 unit matrix, connected in series to obtain an output of 18 volts. The cells are laminated between a glass front and an opaque back cover. The spacing of approximately 10 mm often gives the modules a heterogeneous surface. For monocrystalline cells, the modules often have a bright background, which makes the surface a graphic pattern, which might be hard to integrate in a building. The polycrystalline modules often have a darker background, but the cells themselves have a rather heterogeneous graphical pattern, which could be disturbing in a sensitive architectural context. For all crystalline cells it is possible to replace the back laminate with a glass, so that a semi-transparent module is obtained, where solar radiation can be let through the glazing. Thus, those panels can be used in conventional façade or roof glazing systems. This has grown popular in more prestigious BIPV projects during the last years.

Perhaps the most promising technologies for the future are the thin film cells that can be produced at lower prices but with lower efficiency, less than 10%. The thin film cells can, like paint, be spread on any substrate

material, like glass or metal sheets, and are more flexible in the structure than the conventional, square-shaped crystalline cells. Hence, many thin film cells are organized in thin strips running along the whole length of the panel. This makes them more tolerant to partial shading compared with the crystalline cells, since a shadow has to cover the whole of one or more cells to break the circuit. The most common thin film cells are made out of amorphous silicon. Architecturally, thin film panels might be more interesting due to their more uniform surface structure, which tends to be black with hardly visible division lines between the individual cells. This is more attractive for covering large, conventional building surfaces such as roofs, where a discreet integration of the modules is prioritised. The lower conversion rate in combination with a lower price per square metre, makes it possible to cover large areas, which might be desired from a strict architectural point of view, without overdimensioning the system due to cost or performance.

Recently an alternative thin film technology has been introduced on the commercial market, truly transparent thin film cells applied onto a glass substrate, so that a combined window/PV module is obtained. The modules have been building integrated as normal façade or roof windows, with a slightly darker surface, similar to a low-E coated window. However, the conversion rate is less than 5% (Volarlux, 2004).

PV panels are marked by their peak power performance ( $\text{kW}_p$ ), which is the power converted at standard conditions, such as a  $1000 \text{ W/m}^2$  irradiance. This unit is also used for describing the size of a PV installation.

The performance of any photovoltaic system is dependent on the solar radiation intensity (weather conditions, shadowing, angle and orientation), the efficiency of the cells (conversion rate, peak power, fill factor and temperature) and losses in the AC/DC inverter and the storage components. Also, the temperature influences the performance of the PV cells, approximately  $0.5\%/K$  (Emery, 1996). From a building integration point of view, angle, orientation, shading risk and cooling are essential design considerations that have to be taken for the energy performance.



*Figure 2.13 A monocrystalline, three coloured polycrystalline PV cells and an amorphous silicon PV module (smaller scale).*

### 2.4.4 Concentration technologies

By using mirrors to focus the solar radiation onto a smaller spot than the collecting area, a more efficient use of the solar radiation can be achieved. This has been explored since ancient times, e.g. when Archimedes is said to have used mirrors to put enemy naval ships on fire. The use of concentration technologies in building integrated systems is however rare. Most concentrating systems are used in solar power plants, with high concentrating lenses in sun-tracking systems.

For all concentrating systems, the concentration efficiency is determined by the optical concentration factor, which is the ratio between the aperture area and the receiver area (see figure 2.14):  $C_g = A_1/A_2$ .

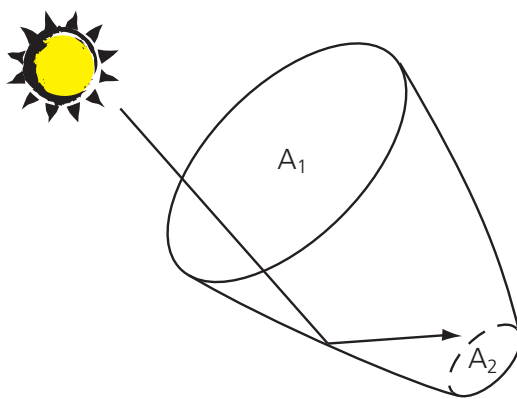


Figure 2.14 The basic principle of a concentrator. The geometrical concentration factor is the ratio between the aperture area and the receiver area,  $A_1/A_2$ .

In theory, a concentrator can be constructed so that it attains a temperature equivalent to the sun's surface temperature. This applies to a three-dimensional system, which can have a maximal concentration factor of 45 000. A two-dimensional system has a theoretical maximal concentration factor of 200 (Brogren, 2004).

Concentrating systems used for energy conversion are in most cases non-imaging, i.e. the system deals with the optimal transfer of a quantity of light between a source distribution and a target distribution, without the demand for distributing the right position of every image point of the light, which is the case for imaging optics (Brogren, 2004). Imaging optics can obtain higher concentration factors, but need to be sun-tracking to function properly.

Non-imaging optics have the advantage of concentrating radiation within an angular region of the sky. For the direct radiation, this applies for solar altitudes within the acceptance angle range that the concentrating system is designed for. The concept of non-imaging optics hence allows for the design of static, low-concentrating systems that can be suitable for building integration (Brogren, 2004).

The simplest way to obtain concentration is to use a flat mirror connected to the module at another angle, see figure 2.15[1]. This is a suitable strategy when solar collectors are rackmounted on a flat surface with a distance between them in order to avoid that one module shades the other. The space between the modules can hence be used for planar reflectors in order to increase radiation intensity and hence reduce the total occupied area for a given heat or electricity load (Brogren, 2004). Planar reflectors can result in an increase of 20-25% of the annual output of PV panels (Rönnelid & Karlsson, 1999). Far more efficient is a curved reflecting area, which can focus the sunrays onto smaller areas. A common two-dimensional reflector design is the CPC, figure 2.15[2], which has the absorber area placed between two curved reflectors. The asymmetric system in figure 2.15[3] has a smaller concentration factor, but is geometrically more suitable for facade integration. This is the principle used by several experimental designs at Vattenfall Utveckling AB (Brogren, 2004), and the design presented in the second part of this thesis.

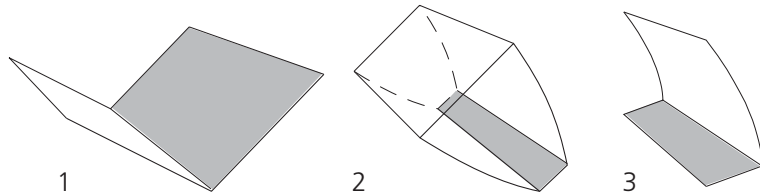
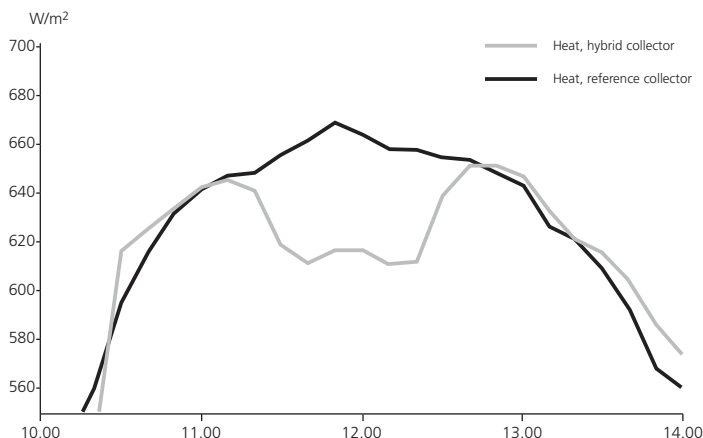


Figure 2.15 Different designs of concentrators. Planar reflector [1], CPC reflector [2] and an asymmetric concentrator [3] for e.g. facade integration. Absorber/PV cell area in grey, reflector area in white.

#### 2.4.5 Hybrid technologies

In a PV cell, ~15% of the irradiance is converted into electricity. The rest becomes heat, some of which heats the cell, some is emitted and lost. Further, concentrated irradiation onto the PV cell generates high local temperatures, which demands cooling. Therefore, a PV/T absorber is designed so as to cool the cell for better performance, and simultaneously

produce hot water for hygienic demands. This active thermal part of the system also contributes to cooling the interior space behind the window. In a PV/T system, the thermal performance of the absorber is reduced by the amount of energy converted by the PV cells. Because of this, the energy output is reduced during the time when the PV cell is utilized. This is illustrated by measurements of a thermal collector and a hybrid PV/T collector, where the PV system was connected, delivering 50 W, between 11.30 and 12.30, see figure 2.16.



*Figure 2.16 A comparison of the performance of a thermal collector with and without PV cells attached to the absorber. The reduction in thermal performance of the hybrid system corresponds to the PV performance, 50 W, produced between 11.30 and 12.30. Measured by Björn Karlsson.*

## 2.5 The building as a system

The building sector represented 39% of the total energy use in Sweden in 2003 (Energimyndigheten, 2004). Around 80% of this is ascribed to maintenance and running posts. This figure could be reduced substantially by designing with knowledge on the surrounding conditions and simple physical laws. A big obstacle to implementing energy-conscious principles is the division into different systems that constitutes the building system, handled by several competences and interests. There is a need for a whole system view on the building system, its subsystems and the way they interact, for obtaining energy efficient buildings. However, energy efficiency is not the primary objective for a building. Like aesthetics, it is

a secondary but important factor that must not interfere with the primary objective, the building function, which is basically provision of shelter, space and comfort for different activities like living, working and interacting. An integral view, where aesthetics, technology and functionality work together for obtaining an environmentally sound architecture should be the objective for all future building projects. This demands knowledge, attitude changes and perhaps a new approach to the process of planning, designing and producing new buildings, as well as restoring existing ones. This section will focus on the system view on buildings. In chapter five the design process will be discussed.

The system view is appropriate for studying the building from an energy perspective. The building could easily be regarded as a system with clear system boundaries, and the integrated subsystems are clearly distinguishable. The interaction with the surrounding systems and the inhabitants is essential for understanding the building system. All those aspects will be categorized in this section in order to attain a holistic approach to the building system the solar energy systems are to be integrated into.

For distinguishing the basic characteristics of the building system, we look upon the essential functions of the building. From there, we look upon the supporting functions that are needed to fulfil the primary functions. Hence, we will have an overview of the systems and the way they interact in the building.

### 2.5.1 Functional aspects

As already discussed, the primary function of a building is to provide shelter for the human being from the surrounding climate, creating appropriate space with comfort to support different activities. This illustrates a relation that is essential for the whole scope of buildings and their role in human culture: human – nature – technology, where the building as an interface between man and nature represents the latter. The building could be regarded as a tool for humans to distinguish themselves from nature, an expression of their independence of nature. This relation escalated during the modern movement in both technological and aesthetic terms, and has now, at least technologically, partly been proven wrong. The technological and energy-intensive solutions for providing comfort have contributed to a poor balance between supply and demand, where man has become dependent upon a continuous devastation of natural resources with little possibility of reproduction. This is of course not only the building sector's responsibility; the relation to the sociological, political, and economical contexts is essential for understanding why our buildings look like they do.

In short, the building system has one primary function: providing appropriate space for human activities in a physical shelter from the natural environment.

Hence we have two interacting systems to be considered:

- The human being
- The natural environment

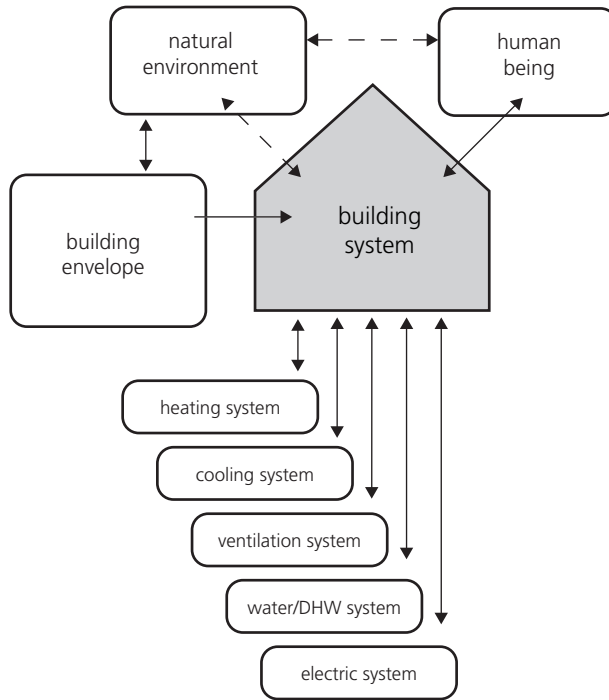
To accomplish this function, the building needs to fulfil several demands, depending on the activities that the building houses. Some demands are however common for all buildings:

- Protection from cold and excess heat
- Protection from wind
- Protection from moisture, rain, snow etc
- Appropriate and appealing space
- Structural support for the shelters and spaces
- Supply of daylight
- Supply of auxiliary heating and cooling
- Supply of fresh air
- Supply of hot and cold water
- Supply of electricity and communication grids

The *building envelope*, i.e. the skin that divides the inner and outer space, satisfies the first six demands. The foundation, the outer walls and the roof are all parts of the building envelope, which is the key element for *passively* achieving energy efficiency within the building system. The latter demands are generally satisfied by the buildings supporting *subsystems*. Those include the heating and cooling systems, the ventilation system, the cold and hot water system, and the electric, telephone and other communication systems. By optimizing those systems we can *actively* obtain energy efficiency within the building system. The division between passive and active systems and approaches is not always that clear or necessary for the full understanding or energy optimisation of the building system. To the contrary, an integrated design approach might promote that some of the active systems become parts of the building envelope, or that the building envelope passively takes over the function of some of the active systems.

## 2.5.2 System overview

From the discussion of the building's functional aspects, a system description of the building can be made. The building is composed of its spatial and constructional structure, surrounded by the environment and housing the human being. For its interaction with those surrounding systems, it is supported by a number of subsystems, see figure 2.17. Each system is described below.



*Figure 2.17 Systematic overview of the building as a system. The building interacts with its natural environment and the human being. The supporting subsystems enhance the interaction.*

### 2.5.2.1 The human being

Space and light and order. Those are the things that men need just as much as they need bread or a place to sleep. (Le Corbusier)

Buildings are built for humans by humans. They exist to house most activities we perform, which includes living, working, trading, production,

amusement et cetera. To be able to work as human beings and conduct all those actions in a consequent and harmonious way, some more or less constant conditions have to exist. The building exists to provide those conditions. It helps us to protect ourselves from hazards, and our property from theft. It gives us shelter from the ever changing climate, which in our part of the world would not be life supporting all year round without this shelter. Hence the building provides the constant thermal comfort, which nature cannot supply. However, the building interacts with humans in more ways than as a shelter. Its outer and inner walls, its floors and its ceilings create spaces that house our activities. These spaces have to be appealing to make us feel good. Scale, proportion and layout of the spaces for a functioning circulation are essential architectural design criteria, which affect our perception and psychological wellbeing. Buildings should also be able to promote communication with the surroundings. Even if a building's primary function is to provide shelter for humans, it could never work if it isolated its inhabitants from the outside. Therefore, visual penetration is an essential feature, which via windows gives the inhabitants daylight and enables them to see what is going on outside. A building also communicates to its surroundings and the humans there. The architectural form of the building tells us something about the inhabitants, the time and situation it was created in et cetera. Hence, the building as a system interacts with the human being in several different ways; technically as a provider of shelter and comfort, functionally as a place suitable for its purpose, aesthetically as a pleasing environment to be in and psychologically as a haven for protection, wellbeing and identity. All these factors have to be considered when designing an architecturally functioning building. Some of these factors, especially the technical ones, are easily quantifiable, while others, like the aesthetic and psychological ones are far more subjective and sometimes a matter of personal preference or taste. For the more technical requirements, like thermal comfort, ventilation rate and warm water temperature, there are building codes that tell us in direct terms what the relation between humans and the building must or should be, which can seldom be compromised. For the functional ones, like floor area, accessibility et cetera, there are some regulations but more often tools for designers or clients to choose appropriate solutions for different situations, based on prior experience on what does or not does work well. However the regulations are often of a more recommending character and those qualities can often be compromised due to cost cuts et cetera. The more subjective values of aesthetic or psychological character have no or a few very general and unclear requirements in the building codes, probably for a good reason. These qualities are ensured by the client's taste and sense for these qualities, the architect's artistic talent and ability to interpret the demands and to synthesize them with the other requirements

into a pleasing whole, and by the craftsmanship of the contractors. These qualities are probably the most vulnerable to reduction or dismissal. Not only because of the common view that these are costly extra features, the first to be compromised, but also because they are so dependent upon a continuous dialogue between the involved partners, since they are not a matter of quantification or regulation, easy to follow. A parallel from what was discussed in the beginning of this chapter; compared with the alarming reports on the ozone hole over the Antarctic, which was easily measurable and hence gave rise to direct actions by banning CFCs, the measures against the greenhouse effect are much harder to implement, since the cause and effect is still only vaguely described and predictable (Karlsson, 2001), and since the probable cause is so closely interlinked with our material standard.

#### 2.5.2.2 The natural environment

A building worth classifying as a piece of architecture always has an awareness of the context it is put into, in one or more ways. Traditionally, in vernacular architecture, the surroundings and what they could offer in materials, terrain and climatic conditions determined the design and orientation of buildings. This was due to the less developed industrial and transport systems, and the lack of supporting subsystems, which would later on make it possible to alienate the building and its requirements from what the surroundings could offer. From this dependence on the surroundings sprang naturally an aesthetic integration between building and landscape, which has been an ever-present feature throughout all architectural history. This awareness has however taken different directions throughout history, as for example with the Baroque movement, with a desire to master nature with strict artificial geometry, or with the modern movement, where the architecture sometimes alienated itself from nature. With the introduction of industrialised subsystems put into the building, often with fossil fuels or electricity as energy source, the building could become totally independent of the surrounding conditions. This also spread to the actual expression of the building during the modern movement's international style, which can be illustrated by the numerous glazed skyscrapers which, judging by their appearance, could be standing anywhere in the world. The passive solar house movement could be described as a reaction to this alienation of architecture from its natural surroundings. Designing the building to take advantage of the natural conditions not only makes the building more technically integrated with its surroundings, but also enhances the possibility of making it more aesthetically connected to the site.

By making the building respond to the shifting characteristics of the surroundings and the climate, a widened integration between man, building and environment can be achieved. What are then the characteristics of the surroundings that could be considered when designing a building? For solar considerations, it is first and foremost the climate characteristics of the site. Irrespective of the unpredictability of the climate, one aspect of it is constant over every yearly cycle, namely the solar angles. Every place on Earth has its unique solar profile, due to the latitude and longitude, affecting the change of solar altitude over the 24 hours and 365 days, as discussed above. This gets slightly more complicated by the altitude, the interruption of a free horizon by the topography, surrounding vegetation and structures. The prevailing solar conditions can relatively easily be calculated on an hourly basis with modern computer tools. Add to this the prevailing climatic conditions, mainly clouds, and the situation gets far more complex and unpredictable. What also affects the thermal balance of a building is mainly the outside temperature and prevailing wind and humidity conditions. In most contemporary calculations of a building's thermal losses and energy balance, the outside temperature is the only condition considered, with adjustments made for solar gains through windows. However, in practice, with clouds, wind and humidity taken into consideration, radiation has not so far really been an object of calculation and prediction, but of experience from measurements from past years. These data can be combined with calculations to make artificial climate profiles for any site in the world, like in the program *Meteonorm* software.

Quantifiable demands for the building's response to external conditions are set in a number of building codes. Perhaps the most important is the energy code that lays down the highest allowed U-value for the building as a whole. The U-value ( $\text{W}/\text{m}^2\text{K}$ ), describes how much thermal power is transmitted through  $1 \text{ m}^2$  of a structure at a temperature difference of 1 K. Traditionally, the energy code had set figures for every building element, such as the walls, the floor and the roof separately (Smeds, 2004). This illustrates a poor integral view, where the parts are considered as separate systems rather than part of a whole building system. By introducing an overall U-value demand, there is higher flexibility to design a building with e.g. walls that better support a passive solar strategy than a traditional lightweight wall, and compensating for the higher U-value with a thicker insulation in the roof. Building codes for energy demand should generally be oriented towards a reduced detail level, in order to enhance an integral view, where different systems are allowed to interact to obtain a desired, low overall energy demand. This trend is facilitated by the numerous simulation programs aiming to calculate the overall energy demand for buildings, which exist mainly within the research field.

### 2.5.2.3 Subsystems

The building system consists of several subsystems that are coordinated to fulfil the characteristics of the building. The division into subsystems can be made in different ways, depending on the aim of the study. The most general description of the building system regards it as being composed of the supporting (as in loadbearing), the enclosing (space-constituting) and the maintaining (support of dynamic resources) system (Ekholm, 1987). For this study, no regard is taken of the supporting system. The enclosing system is represented by the building envelope for its thermal properties. The maintaining systems can be divided into the heating, ventilation, water and power systems.

#### The heating system

The main active subsystem for maintaining the building and providing comfort is the thermal system. During the cold season, auxiliary heating is needed to provide thermal comfort in the building. The heating system can be divided into three main components, the heating source, the distribution system and the space heaters. The space heaters can be radiators, convectors or a grid of pipes or resistance wires integrated into the floor. Floor heating has gained in use during the last decades due to its comfort and flexibility. The sensation of the direct contact with the heating source, can allow the room temperature to be reduced by 1-2°C, with comfort maintained. The flexibility is due to the lack of radiators, which besides being aesthetically disturbing, decreases the flexibility in furnishing the spaces, since they must not be covered if they are to work properly. Floor heating is compatible with active solar heating, since both systems work optimal at low temperatures.

The heating system in a conventional Swedish single family house accounts for 50% or more of its total primary energy demand (Andrén, 1999). The amount depends primarily on the quality of the building envelope and the ventilation.

#### The ventilation system

After temperature, the second factor for achieving comfort is the quality of air. Without ventilation, the air in a populated space gets increasing concentrations of odours and carbon dioxide from respiration. The oxygen level also drops, but it is the CO<sub>2</sub> level that first causes the sensation of poor air quality. The CO<sub>2</sub> level in a room can become poisonous long before the oxygen runs out. In more densely concentrated spaces, like classrooms, concert halls, office spaces etc, it is rather the excess heat

generated by the occupants that makes people feel tired, and needs to be reduced by ventilation.

Ventilation systems are probably the most debated in the low energy building concepts. Some promote all natural ventilation systems, that do not need an electrically powered fan, but these do not recover the heat from the outgoing air, which is performed with an approximate 80% efficiency in balanced ventilation systems incorporating heat exchangers.

### The water system

For hygiene, drinking and cooking, the water grid is an essential part of the standard in a building. Warm water is needed mainly for hygiene, and needs to maintain a minimum temperature of 50°C. A lower temperature increases the risk of illness caused by bacteria like *Legionella*, and a higher temperature poses the risk of skin burns. Energy losses due to the drainage of hot water can be reduced by transferring the heat to the incoming water.

### The power system

The electric grid in a building is essential for artificial lighting and an increasing number of household, working and entertainment devices like washing machines, computers and TV sets. For electrically heated buildings it is also an essential part of the heating and water systems. In extreme passive houses, the “free” heat gains derived from the use of electric devices make a significant contribution to the energy supply. However, energy efficiency for electric equipment is essential due to the higher exergy content of electricity.

### The building envelope

The most essential building system that constitutes the whole boundary between exterior and interior is the building envelope, composed of outer walls (with windows and doors), floor and roof. The composition of the building envelope not only determines the amount of gained and lost thermal energy, but also expresses the building's relation to its context (in the facades). Often, the building envelope also houses the loadbearing system. Hence, the building envelope can be part of all the basic subsystems described above; the supporting, the enclosing and the maintaining system. This makes the building envelope the most complex and the most essential subsystem of the building. In primitive buildings, the building envelope is equivalent to the whole building system. With the addition of new technologies and thus more or less building independent subsystems, the building envelope has lost some of its importance as the main denominator of the building's thermal balance.

Since the building envelope is the part of the building exposed to the exterior, it is desirable to reduce the building's enclosing area in relation to the enclosed volume, i.e. reducing the surface to volume ratio. This is ideally performed by a sphere. However, spherical volumes are hard to construct, inhabit and extend, which is why they have never been adopted on a large scale. The second best alternative in perpendicular terms, is the cube but due to solar movement and spatial organisation, a rectangular plan might be more appropriate. The best way to achieve a low surface to volume ratio is to regard the volume as dwelling volume, and to combine several dwelling volumes into one building volume in attached or multi family houses, so that dwelling spaces, outer walls and slabs are shared by two dwelling spaces, and thus become interior elements in the building volume. This strategy is clearly visible in the low energy attached houses in Lindås, Gothenburg, where deep two story apartments are attached to each other in order to minimize the building envelope, which in this case is also extremely insulated and airtight.

### 2.5.3 Thermal balance

To conclude what has been said about the interacting systems from an energy point of view, an overview of the energy balance of the building can be made. To obtain a thermal balance, all energy related systems within the building systems can be presented, since all energy conversion eventually ends up as waste heat, contributing positively to the thermal balance. For providing a constant temperature, the supplies and the losses need to be in equal amounts. On the plus side are the gains from “free” energy sources, and the primary, bought energy, which we aim to reduce to a minimum. The free gains are direct solar gains and waste heat from occupants, hot water distribution and electrically driven devices. The energy losses are heat losses through the building envelope by conduction, convection and radiation, ventilation losses and losses due to warm water drainage.

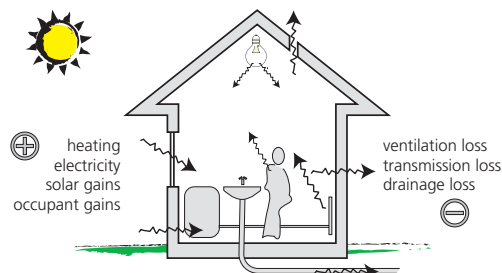


Figure 2.18 Overview of the thermal balance of a building.

## 2.5.4 Windows

Windows in buildings have one primary function, i.e. to provide transparency through the building skin for daylight and view. Windows are often called “the eyes” of the building and are important architectural elements for organizing the structure of the façade, modelling the interior by daylight and providing contact with the outside. Besides the provision of daylight, another effect is a passive gain of solar thermal energy, which makes it unique as a building element. Another characteristic of windows is the higher U-value compared with the surrounding wall area, which means that the gain of passive solar energy will be reduced by the higher loss due to conduction, convection and radiation. Generally, for a temperate climate, windows have a positive thermal balance for south-facing windows over the whole year, a smaller positive or closer to neutral balance for west- and east-facing windows and a negative energy balance for north-facing windows (Adamson, 1986).

### 2.5.4.1 Energy issues

From an energy management perspective, there are two reasons to use windows:

- Passive solar heat gains, reducing the need for auxiliary heating
- Increased amount of daylight indoors, thus reducing the need for artificial lighting

A disadvantage of the extensive use of windows is an increased heat loss due to a higher U-value, i.e. smaller thermal insulation capacity than an opaque wall. Further, comfort demands must be addressed. High passive gains can lead to overheating, and the visual comfort of extensive daylight can be impaired by glare from direct sunlight.

The increasing use of windows demands knowledge of these consequences. The two main problems that might occur is an increased heating and cooling demand. By clever design, these problems can be reduced so that the window e.g. contributes to the heating of the building while not leading to a greater energy demand during the cooling season. In order to avoid thermal losses, a low U-value is preferred. This can be achieved through good design of the window frame (with a minimization of the thermal bridges) and by using low-e coated glass and gas fillings between the panes. In order to reduce the cooling demand and avoid glare, other kinds of glass coatings and/or sunshading devices are common strategies.

### 2.5.4.2 Window physics - the thermal balance of a window.

The window is a unique building element in the sense that it can contribute positively to the building's energy supply, due to the transmitting quality of the window glass.

A window's thermal balance is determined by the net balance between the solar gains and the thermal losses from the warmer inside to the colder outside:

$$Q = I \cdot g - U \cdot (T_{in} - T_{amb}) \quad [\text{Eq. 2.2}]$$

- $I$  is the solar irradiance ( $\text{W/m}^2$ )
- $g$  is the total solar energy transmittance (-)
- $U$  is the thermal transmittance ( $\text{W/m}^2\text{K}$ )
- $T_{in}$  is the indoor temperature
- $T_{amb}$  is the ambient temperature

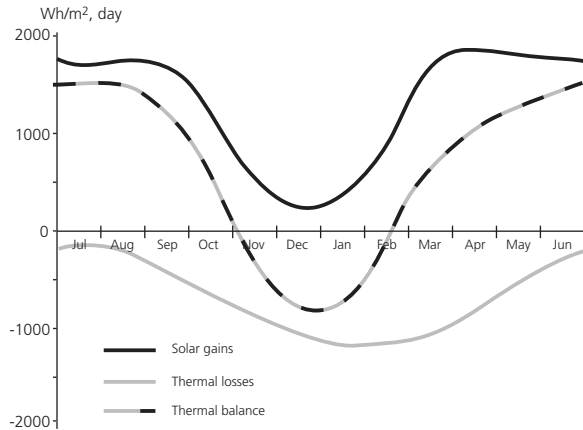


Figure 2.19 The thermal balance of a south-facing window ( $U$ -value  $2 \text{ W/m}^2\text{K}$ ) in Stockholm. Source: Lundqvist, 1980.

The  $U$ -value of the window is a temperature dependent value that defines the thermal losses, and the  $g$ -value describes the solar energy gain.

$I$  and  $T$  are climate dependent, i.e. based on the situation that the window is put into.

The gains depend on the glazing's transmittance (%), absorptance (%) and reflectance (%). These shares make up the total irradiance:

$$t + a + r = 1 \quad [\text{Eq. 2.3}]$$

The transmittance is the percentage of irradiance admitted through the glazing, thus contributing to the interior's thermal balance. The irradiance reaching the interior is hence reduced by the reflectance and absorptance of the glass. The absorptance is the energy absorbed by the glass as heat (%). The reflectance is the share of irradiance which does not pass the glass, nor is converted into heat in the glass, but reflected at the glass surface.

The thermal losses depend on three separate mechanisms: conduction, radiation and convection, as illustrated in figure 2.20. Conduction refers mainly to the energy flow through the solid materials that the window is constructed of. Since the glass panes are separated by air, this mechanism is mainly due to the frame design and the conductivity of the frame materials. The heat transfer, due to conduction ( $\text{W}/\text{m}^2\text{K}$ ) through a solid body is defined by the conductivity of its material,  $\lambda$  ( $\text{W}/\text{mK}$ ) divided by its thickness  $d$  (m). Convection describes heat losses through air movements, due to density variation, which transports warm air towards cold surfaces. Radiation is the heat radiated from a body towards a colder environment.

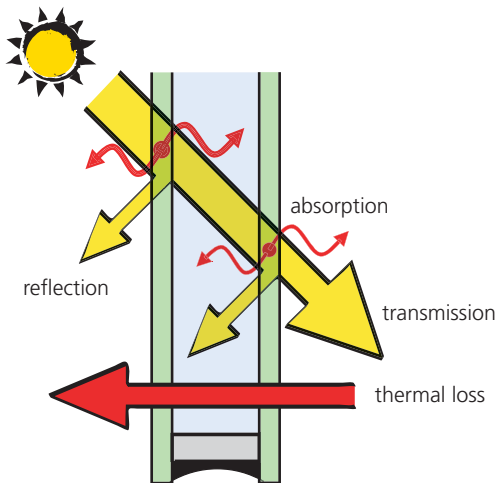


Figure 2.20 The energy flows through a typical window.

In order to calculate the net energy balance of a building for a whole year, one needs to determine whether or not the sun is useful for passive heating. A simplified way of calculating this is suggested by (Roos & Karlsson, 1994). Apart from comfort problems due to overheating, the energy transport through the window is only interesting during the heating season. By determining the length of the heating season, and hence calculating the number of degree hours and the accumulated irradiance during that period. "Karlssons window equation" describes the net energy transport,  $Q$ , through the window as

$$Q = Q_{solar} - Q_{loss} = \bar{g} S(t_b) - UG(t_b) \quad [\text{Eq. 2.4}]$$

- $g$  is the mean value of the total solar energy transport during the heating season (-)
- $S$  is the accumulated irradiance onto the window for the time when the ambient temperature is below the balance temperature of the building ( $\text{Wh/m}^2, \text{yr}$ )
- $U$  is the U-value of the window ( $\text{W/m}^2\text{K}$ )
- $G$  is the accumulated degree hours for the time when the ambient temperature is below the balance temperature of the building ( $^{\circ}\text{Ch/yr}$ ).

The balance temperature of a building can be described as the ambient temperature when the building needs to be neither heated nor cooled. In this method, all solar radiation that occurs at an ambient temperature below the balance temperature is considered useful.

The balance temperature is given by the building's use and design. An office building with a high degree of fenestration and a high activity of people and equipment during daytime, thus with high solar gains and internal loads, has a low balance temperature, i.e. the building needs cooling for a greater part of the year. For a residential building, used mainly during the rest of the day and with a far lower inhabitant density, the balance temperature will be higher, which means the heating season is longer than the cooling season. The better the insulation (i.e. the lower the U-value), the lower is the balance temperature.



## 3 Building integration

### 3.1 Building integration – a matter of definition

Attempts to popularize solar energy by using the term “building integration” have become common in recent years. Building integration is often mentioned as the key to implementing solar energy technologies on a wider scale. However, there seem to be different interpretations of what the term actually means. The “true meaning” of building integration is not always reflected by solar energy applications within the built environment. To be able to discuss the subject further, there is a need to define what we mean by building integration of solar energy. Since the terms *building* and *solar energy* were already discussed in the previous chapter, it is time to have a closer look at the term *integration*.

#### 3.1.1 Integration

The following definition of *integration* is made in the Oxford English Dictionary (2003):

- The action or process of integrating.
- The making up or composition of a whole by adding together or combining the separate parts or elements; combination into an integral whole: a making whole or entire.

When using a systems theory perspective, it is essential to find what integration is considered to mean in this field. Science philosopher Mario Bunge defines a system’s integration as the strength of its connections. Some systems and system parts are more loosely connected to each other than others, i.e. the integration varies between different systems. (Bunge, 1979). Integration should not be confused with coordination. While integration describes the strength of internal connections within a system, coordination describes the interaction of the system’s parts in order to

achieve synergy effects. The coordination of two objects means that they together contribute to the system's integrity.

In this sense, both integration and coordination seem to describe what we want to achieve by building integration of solar energy. However, from a systems theory point of view, the formal meaning of integration is not quite the same as the practical meaning, since it deals with one system internally, and the term building integration deals with the interaction between the building and the energy system.

### 3.1.2 Building integration of solar energy –formal meanings

The expression building integration of solar energy, means to combine the building and the solar energy system. In what sense or to what extent this combination is made is an object for further discussion.

From a systems theory point of view, the systems do not necessarily need to be fused into one system. Rather it is essential to define the systems separately in order to find what they have in common and what they do not have, but could have in common and how they do and could interact. By studying these relations, a basis for integration between the systems can be obtained.

Formally, full integration would mean that the building as a system would not manage if the integrated solar energy system were withdrawn, i.e. the solar energy system is an essential part of the building system. This would certainly be true if the solar fraction were 100%, since the building would then provide no thermal, hygienic or visual comfort without the sun. However, there is no possible way that solar energy could cover the whole energy demand over the whole year (or even day). Hence, the level of integration can be regarded as a function of the solar fraction of the building's energy demand.

If the solar panels or collectors are a part of the building envelope, there is little doubt that the building would sooner or later collapse on the withdrawal of the system. Hence, this criterion could more directly qualify a system to be called integrated.

There is also a danger in calling for integration, if this means that the solar energy system and the hosting building system share different features when combined. The risk of losing flexibility in the overall system is large since the solar energy system most likely has a shorter lifespan than the building (perhaps 20 years compared to the building's 50 or longer).

### 3.1.3 Building integration of solar energy – common definitions

Building integration is now a commonly used term within the research field, mainly for photovoltaics, where there is a commonly used abbreviation; BIPV, short for Building Integrated PhotoVoltaics. Just as common as it is to find texts on building integration, just as hard is it to find a statement on what the author really means with the expression. However, a few attempts have been found:

“During the 1990s, solar energy converters have been increasingly used in cooperation with common construction technology, in what is commonly called building integrated solar energy”. (Lundgren, 2004, my translation)

As described below, the term can have different meanings for different players within the building process:

“The term ‘building integration’ is not well defined. For an architect it is mainly the integration of a solar heating system in the design, for the engineer it is a technology to have the collector as part of a building. For an installer it is a matter of integration with the heating system of the house and the project developer sees building integration more as an aspect of the building process. This can be further explained with some examples. A collector on an existing roof that replaces roofing material is technically, but not aesthetically, integrated. On the other hand an architect may design a collector that is a design feature and not integrated in a building component, but an integral part of the design.” (Bosselaar, 2004)

IEA Task 16 aimed to define what building integrated photovoltaics (BIPV) means.

From a literature review of the sources using the term, building integrated solar energy systems could generally be characterized as follows:

- The system contributes to the building’s energy supply
- The collector or the PV panel is part of the building envelope
- The collector or the PV panel offers new architectural expression

These could be defined as the main *primary* criteria for building integration of solar energy components. Whether any of these criteria are satisfied

in a positive or negative way, is an object for discussion. However, in many cases, one or more of these criteria are not fulfilled at all. For example, there is a nationally well-known example from the Western Harbour area in Malmö, where vacuum tube thermal collectors have been put onto the façade and the roof of a multifamily house. There is little doubt about the architectural impact of these elements, which can be regarded as successful. However, the elements are not truly a part of the building envelope. The building would physically manage without the addition of the vacuum tube collectors. Further, all the active solar thermal installations in the Western Harbour Bo01 exhibition area are connected to a local low-temperature district heating system, owned, together with the solar thermal and PV systems, by the utility Sydkraft. This grid is connected to all the settlements around the area, whether they are carrying solar collectors or not. Hence, the systems are not directly delivering energy to the consuming structure they are *applied* on, since application is the issue here, rather than integration.

### 3.1.4 Integration or application?

As Marja Lundgren points out (Lundgren, 2004), a distinction could be made between building *integration* and building *application*:

“When solar panels or collectors constitute part of the building’s construction or climate shield, it is usually called building *integrated* solar energy. Another common form could be called building *applied* solar energy when the solar panel is an addition outside the building envelope. To distinguish between these two forms is to elucidate two separate architectural strategies.” (Lundgren, 2004, my translation)

Whether the last statement is an objective truth or not can be discussed. However, *application* is a good description on a great deal of installed so-called integrated systems. Except for the quite uncommon phenomenon of the Bo01 area, where the production systems do not deliver energy directly to the structure they are mounted on, what primarily distinguishes an applied system from an integrated system has to do with the installation of the collectors or panels;

- An applied, as opposed to integrated, solar panel/collector is mounted on the outside of the building envelope, so that the envelope could function well without the applied element.

A classical and very common example of applied solar energy is the large number of solar collectors mounted on top of ceramic tiles on the roofs of single family houses. This is an example of a typical “techno-orientated” solution, with all consideration given to the simplest solution possible from an installation and maintenance point of view, at least for an already existing building. The total absence of aesthetic consideration gives little opportunity for greater acceptance of the technology among the wider population, apart from those already convinced.

The “stamp” example does not mean that applied systems are necessarily aesthetically worse than integrated ones. This is a matter of intention. Going back to the better example from the Western Harbour area, some other positive effects of the applied solar energy system are obtained. For example, the vertical vacuum tube collectors serve as windshields for spaces on top of the roof. They also function as windbreaks for the area behind this building, which faces the heavily windy seafront. Criteria like these could be regarded as *secondary* characteristics of building integrated (or applied) solar energy elements:

- Well integrated systems can have a positive impact on the architecture of the exterior.
- The integrated systems can have secondary functions outside the building envelope; i.e. windshields, sunshades, balcony fences et cetera.

The latter corresponds to the philosophy of e.g. English/Swedish architect Ralph Erskine, who often made an effort to attach external elements like balconies, windshields et cetera onto the actual exterior of rather simple building structures, to allow for comfort and social interaction. The flexibility which this approach leads to has also been adopted by many of the pioneers within the so-called High Tech architectural movement. Projects with a High Tech profile are often characterized by exposed circulation and ventilation installations on the exterior, facilitating future maintenance. To apply a system onto rather than within the building envelope, has a bigger advantage of flexibility than the truly integrated system. Not only for the applied system itself, but also for the building it is applied onto. Table 3.1 compares the characteristics as advantages or disadvantages of integration versus application:

Table 3.1 Comparison of characteristics of an applied and an integrated solar energy system.

	Application	Integration
<b>Aesthetics</b>	Commonly negative, due to lack of awareness. Dependent on intentions.	Higher probability of an accepted solution.
<b>Construction</b>	Higher flexibility, due to mutual independence	Higher efficiency due to double functionality
<b>Economy</b>	High investment, with possible long term savings due to flexibility	Saving of construction materials and mounting equipment
<b>Energy</b>	No use of PV generated heat.  More convective exposure for thermal collectors.	Less material, multifunctional insulation  Heat gain potential
<b>Implementation</b>	Fewer limitations. Possible any time.	Motivated only by the time of construction or renovation

### 3.1.5 Building integration – a matter of level

With this new awareness of the difference between integration and application, there is reason to question if this distinction is useful outside the academic field. Since building integration is a rather new concept, with no commonly established meaning, it might be confusing and regarded as tongue-twisting to make the issue even more complex by introducing the term application as an alternative strategy. It might be more useful to classify the system by its *level* of integration, where an applied system is ascribed a low level.

To determine the level of integration of the solar energy system with a building, the following characteristics of the system could be useful. It could also be regarded as a final summary of what building integration is about:

The level of integration can be determined by:

- The level of physical involvement in the building envelope.
- The level of involvement in the building's energy balance, regarding both the number of energy forms and the quantitative fraction of the primary energy use.
- The visual appearance, hence the user's, visitor's or observer's perception of the level of integration.
- The objective of the integration project.
- The impact of the building's architecture on the design and integration of the system and vice versa.

### 3.2 Building integration - a systems approach

The building system and the solar energy systems from chapter two are confronted in order to find out what they have in common and how they can interact.

The level of integration discussed in the previous section can, in accordance with Bunge's characterization of a system integration, also be defined as the strength of the connections between the building structure, its interacting systems and its supporting subsystems, as shown in figure 2.17.

The solar panels or collectors can tie together the natural environment with the building's heating system and electrical system, due to its use of solar energy, which is harvested at the site of the building. If the solar panels are used as shading devices, they are also involved in the buildings' thermal balance by reducing passive solar heating loads that would require cooling. Passive or active solar air systems can also be integrated with the building's ventilation system.

By integrating the panels or collectors into the building envelope, the heating or the electric systems are tied closer to the building structure. Since the building envelope also communicates the building's appearance to the inhabitants of its surroundings, the façade-integrated solar energy elements also contribute to a system integration in this sense. Further, visible solar energy conversion at the place of consumption, enhances a deepened understanding of interdependence between building, humans and the natural environment.

### 3.3 Motives for building integration

What justifies building integration as a strategy? By listing the arguments for the strategy, both objective motives and less quantifiable motives, from theory or from concrete examples, the picture gets clearer of what building integration is and should be about. The primary motive is the obvious objective to harvest renewable solar energy for conversion to usable heat or electricity. In addition to this there are secondary motives, for so-called added value. Hence, the motives can be divided into primary, objective motives, and secondary, subjective motives.

#### 3.3.1 Objective motives

The obvious, measurable motives for building integration could be divided into environmental, energy related, constructional and financial motives. These can be classified as objective, *primary* motives. The aims of those motives can be evaluated by using quantitative methods. Sometimes these motives go hand in hand, and can therefore be repeated, but they are commented on from their own perspectives.

Environmental motives:

- Increased implementation of a renewable energy source.
- Less land use is needed compared with ground mounted systems.
- Less exploitation of natural resources.

The direct harvesting of solar energy is by nature relatively area-consuming. With an ever-increasing population and a decreasing land area for e.g. food production or recreation, a logical solution is to make use of the settlements of people instead of productive land areas, to make the ecological footprint as small as possible. Due to the benefit of material saving, both for the building system and for the solar energy system separately, virgin material resources can be spared for other purposes.

Energy related:

- Energy is made accessible at the place of its use.
- Co-generative effects, mainly thermal, are achievable.
- Less grey energy due to material savings.

Since around 40% of the total energy use takes place in buildings, it is essential to take measures to reduce the energy demand of buildings. By directly converting solar energy to useful forms in the building system, this could be regarded as a measure to improve the energy-efficiency. The short distance between energy source and user makes transportation losses minimal. The need for insulation in a thermal collector gives it a double benefit when inserted into a wall. At the same time the integration into the roof or wall gives the collector a thicker insulation than it would normally get, hence increasing the efficiency. For PV panels, the heat generated during conversion (around 80% of the insolation) could be used if integrated wisely. Generally, a life cycle analysis (LCA) calls for the least possible material use, because of the encapsulated or “grey” energy demand for all steps taken; extraction, refinement, production, transport, mounting, dismantling and finally reuse, recycling or deposition. However, since the energy needed for the running and maintenance of the product is taken into account in an LCA, the material use is not always the most important factor for an environmentally friendly product.

Constructional motives:

- Solar panels or collectors replace conventional outer skin materials of the building envelope, hence they are given additional functions, mainly climate protection.

Solar energy conversion is by nature a matter of exposure to solar radiation. The same goes for the building envelope. Its main function is to deal with the relation between indoor and outdoor climate, so that the interior is given a relatively constant comfort with the least possible energy input. The exposed outer materials in both systems have basically the same characteristics, such as wind, water and, to some extent, impact protection. It is probable that added functions give the system greater interest, trust and acceptance.

Financial motives:

- By saving construction material, the cost of the system is reduced.

Building integration is first and foremost a strategy of cost savings. Cost savings due to the material and energy savings mentioned above, reduce the investment and potentially also the energy bill. The running cost of solar energy is normally based upon the depreciation time, often set to ten

years. However, the system's lifetime is normally expected to be considerably longer, and hence the energy yield after the depreciation time could be considered free.

### 3.3.2 Subjective motives

In spite of all the measurable benefits of building integration, we have to remember the reason for introducing this strategy from the start: solar energy is still not economically competitive. In spite of this, projects like these take place all the time. Except for e.g. governmental funding, there are obviously other motives for investing in solar energy than the directly quantifiable ones. Whether these motives are based on pure idealism and environmental awareness, or just a matter of goodwill that is expected to pay off indirectly in the long run, the effects are hard to quantify. What they have in common is a belief in a non-materialistic or added value. These motives can be classified as subjective, secondary motives. We divide these into idealistic, educational, and image motives.

Idealistic motives:

- Solar energy is a clean and renewable energy source
- Building integrated solar energy makes the building more autonomous

For many, and especially private persons, the extra cost of solar energy systems is worthwhile since the environmental aspect is more important than the economical aspect. Steps taken at an individual level are motivated by the “think globally, act locally” attitude, where individuals try to do what they can to decrease their ecological footprint. Another aspect related to the individualistic approach is the aim to reduce the dependence on centralized systems, which despite high efficiency can show great vulnerability. As opposed to centralized energy systems, like power plants, solar energy converters have a high degree of modularity, i.e. they can be decentralised in small quantities.

Educational motives:

- Solar energy in the built environment is visible
- The exposure can lead to environmental awareness and engagement

Contrary to most other energy sources, solar energy combines modularity with exposure. The converting elements must by definition be exposed to the solar irradiance, and are therefore in most cases highly visible for users and passers-by. Like wind turbines, solar panels and collectors directly give an idea of the conversion of energy. Not as directly as wind turbines, though, since one needs to be aware of what the panels or collectors actually are, i.e. providers of energy, while the wind turbines' rotation more directly shows what is going on, even though one has to be aware that the mechanical rotation is transformed into electricity in a generator. The modularity makes solar energy visually connected to the site of energy use. This gives the solar energy system and its hosting architecture an added intellectual dimension.

The pedagogic dimension of solar architecture is illustrated by many projects which aim to distribute knowledge of solar energy through educational programmes, demonstration objects et cetera. International conferences such as EuroSun2004 in Freiburg dedicate entire sessions to this subject (EuroSun, 2004).

Image motives:

- Solar energy gives a positive image of environmental awareness or modernity

As described in the section above, the visibility of solar energy technologies can also be used for promoting the building owner's or user's image as an environmentally aware and responsible person or company. When asked why a photovoltaic installation was chosen for a company's new headquarters, the manager answered simply: "Because it is ecology made visible" (Green & Brogren, 2003).

Other motives:

- The feeling of "free energy" can psychologically overrule the burden of high investment

The term "free" energy is often used as an argument by the contractors and sellers of solar energy systems. It is true in the sense that the actual source of energy, the sun, is free of charge, but the equipment needed to make use of this energy is cost intensive, so that thermal energy is slightly more expensive and photovoltaic power is ~5 times more expensive than conventional energy. However, an investment like this can be "forgotten"

as the energy bill gets lower. This is not an objective, financial motive, but can function as a motivation for choosing a solar energy system.

### 3.4 The integrated design process

A successful building integration of a solar energy system is dependent upon a successful planning, design and implementation process. This demands that the different actors within the project work as a team, with each competence involved at an early stage.

IEA Task 23 – Optimization of Solar Energy Use in Large Buildings, has been committed to promote the integrated design process as a key strategy for implementing low energy solutions for the built environment ([www.iea-shc.org/task23/](http://www.iea-shc.org/task23/)). As opposed to the conventional, linear building design process, where the environmental managing systems are chosen after the building design is made, the integrated design process promotes an interdisciplinary approach from the beginning of the project, in order to achieve synergy effects.

The integrated design process recognises the fact that changes and improvements of a design are easy to make early in the design process, but become harder to achieve as the process develops. Therefore it is essential to engage all disciplines in the initial design phase, to set goals on performance and to model and simulate designs before they are made permanent.

An integrated design process can be more expensive than a conventional one, as goes for the investment of the final design, but the aim at drastically reducing running and maintenance costs, as well as occupant comfort and productivity (Energy Design Resources, 2005) should make it worthwhile.

The integrated design process promotes a whole system analysis, which is “an evaluative process that treats a building as a series of interacting systems instead of looking at building systems as individual components that function in isolation” (Energy Design Resources, 2005)

The integrated design process is characterized by a “down-stream” thinking, where the function of a space is regarded in first hand, i.e. the relation between building and user is determinant for the design. The supporting systems are a result of the accumulated needs for every space of the building. This might seem obvious, but is not always the case in conventional building design, where poor coordination and communication between different actors within the construction process is common.

## 3.5 Design criteria for solar panels or collectors

From the motives above and the system presentation made in the previous chapter, some design criteria, to be observed when a system for building integrated solar energy is chosen, can be listed. The thermal collectors or PV panels can be judged by their energy performance, daylight performance, construction properties, maintenance properties, economic properties and aesthetic properties.

### 3.5.1 Energy performance

The thermal collector or PV panel is judged by its ability to convert solar radiation to warm water, air or electricity, i.e. its conversion rate, expressed as a percentage. This value is dependent upon orientation and slope, but for comparisons, a reference angle and orientation should be presented. This could be called the collector's active energy performance, which is independent of the level of building integration.

The second energy related parameter that is independent of the level of integration is the encapsulated energy, or grey energy content of the components. The less energy that is used for its production, the shorter the energy payback time, i.e. running time needed for the thermal collector to start producing "free" energy.

Directly related to the building integration is in what sense the insulation of the thermal collector can contribute to the insulation of the building envelope. When it is integrated into the building envelope, it might appear that this contribution is negative – i.e. that the depth of the collector would force a reduction of insulation in e.g. the roof, if they still are regarded as separate elements. If the collector were more closely integrated with the roof, the insulation could be shared between the two and hence serve a double purpose, which is only possible in a warm roof, where the outer skin of the roof is not separated from the insulated ceiling with a ventilated air space. This is an example of the need for a holistic analysis in order to avoid conflicts between functions, which can reduce the credibility of solar energy.

### 3.5.2 Constructional properties

This deals with the potential for the collector system to be integrated at all into the building envelope. First and foremost, demands on air and water tightness must be satisfied when integrating the components. This

can always be achieved by additional work and material, but the component should have the best possible interface for making an air and water tight connection to the adjacent building envelope. It is essential that the component itself is air and water tight.

### 3.5.3 Maintenance properties

Systems should be designed and integrated so that they and the building construction can be easily maintained. Cleaning, repair and replacement of components should not be jeopardized. Generally, applied as opposed to integrated systems are likely to be more appropriate from this point of view, since they are easier to reach or replace. However, they are also likely to be more vulnerable to climate exposure, vandalism or theft. Technically well integrated panels, placed within the building envelope, should not compromise the characteristics of the elements they replace.

### 3.5.4 Financial properties

Price competitiveness is essential for solar energy systems, since they have been and still are relatively expensive compared with conventional energy sources. Hence the collector itself should be of low price. How well integrated the collector can be regarding energy performance and constructional placement in the building envelope, should however be included in the economic analysis. Hence, an expensive collector of higher quality but with better building integration properties can be a better business proposition in the long run.

### 3.5.5 Aesthetic properties

Solar energy systems are partly socio- technical systems, since they are part of the building system, a highly socio-technical system. Therefore, attention has to be paid to the human subjective values, like aesthetics, pedagogy, image. The solar energy systems are exposed, and must therefore be aesthetically appealing to the users and passers-by. They also have a large potential for exposing, and saying something about, energy technology and environmental friendliness. From this, an aesthetic approach to the visible use of solar energy components can be drawn up. First, the components have to look good, so that no one can blame them for being ugly, which is a common comment about e.g. solar collectors today, often for a good reason. Second, they should be designed, and integrated, in order to clearly

show their function. There are several approaches that ignore both these criteria, there are some that highlight one of them and ignore the other, while a few systems consider both. One approach that clearly considers the aesthetics while ignoring the pedagogic motives, is when an attempt is made to integrate the panels or collectors as discreetly as possible. This approach is often wise, since it is often a critical issue to integrate the technology in an architecturally or cultural historically sensitive context. When it comes to implementing the technologies on a large scale, there is a need for systems that look normal. Pedagogic signs should not call for attention everywhere, especially not when the technology has gained enough acceptance to be installed anywhere.

### Colour

For thermal collectors, the acceptance for architectural façade integration has been relatively low. This might be due to the lack of available colours, besides the standard black absorber surface. Further, the plumbing of the collectors is generally visible through the glazing of the collector. Some attempts have recently been made to change the appearance. Glazing which reflects non-usable wavelengths of sunlight, thus reducing the transparency of the collector, has been developed by e.g. SOLABS (Munari-Probst 2004). This consortium has also developed thermal collectors with unglazed colored absorbers, in order to reduce investment cost and to increase architectural acceptance (Solabs, 2004).

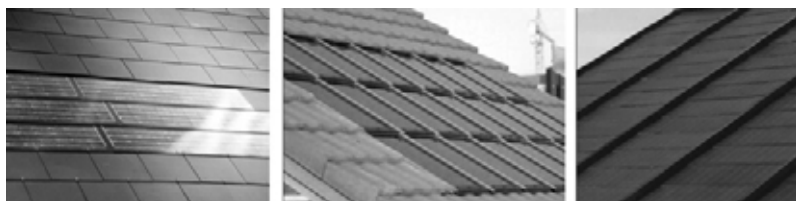
Mono-crystalline and thin film cells are generally black. Poly-crystalline cells are generally blue, due to the anti-reflective coating. Other colors, like grey, yellow, red and green are also available, although more expensive and with lower efficiency (Green, 2002).

### Scale and proportion

As for all exterior elements, it is essential that collectors and panels are harmoniously scaled and proportioned. First, the dimensions should be in harmony with the building's modular grid, not only for constructional reasons but also for aesthetic harmony with the building. Second, the actual solar panels or collectors themselves should have an attractive expression in order to be accepted as architectural elements, especially when they are mounted onto a limited part of the building element surface.

## Design for mimicry

On the growing market of solar energy components for building integration, some producers have recognized the need for elements that can blend in naturally with existing covering structures, such as roof tiles, sheet metal et cetera. Figure 3.1 shows some examples of such products.



*Figure 3.1 Examples of solar panels adapted to existing covering materials. Braas (left) with PV panels similar to flat roof tiles, Newtec (centre) for adaptation to ceramic tiles and UniSolar thin film panels for resemblance of metal sheet roofs.*

## 3.6 Convivial technology

In his thesis on the relation technology – humans – art, for obtaining ecologically sustainable architecture, Michael Edén points out the need for “convivial” technology, i.e. technology that encourages engagement and joy from the user in relation to the technology used. Convivial, a concept introduced by Ivan Illich, literally means sociable, jovial or festive, and was chosen to emphasize joy of work and the aim for fellowship (Edén, 1987). Edén puts conviviality in relation to artistry, and concludes that they have much in common, since convivial technology could hardly be designed without symbolizing caring for nature, joy and fellowship of work. Hence, conviviality postulates an aesthetic intention. The concept derives from the desire to transform technology so as to return it to being something like a servant of mankind instead of being its master.

Could solar energy systems be regarded as a convivial technology? As discussed, it is clear that they can symbolize caring for nature. Their modularity and potential for increased autonomy could also be said to encourage engagement and joy of working with it on an individual basis, since the output directly affects one’s comfort and energy bill. On the other hand, the autonomy hardly encourages fellowship on a societal level, but

so far, the solar energy community is characterized by a common belief in the need and benefits of an increased use of solar energy.

Without aiming to ascribe solar energy systems the quality of conviviality, the concept could be used as a guiding principle in developing new designs for such systems. By aiming to express environmental friendliness and joy as an aesthetic approach, solar energy systems can widen their acceptance on the market. The technology itself already has the first quality, since the energy source it exploits is perhaps the most environmentally friendly. The question is how this could be emphasized in the appearance of the systems. It is not only about what the elements look like, but also how they are integrated into the building.

### 3.7 Concealed or exposed systems?

Aesthetic considerations determine whether the solar energy systems are clearly visible or whether they are incorporated as discreetly as possible within the building envelope. Both approaches can be used for aesthetic reasons, but for different purposes. To make a stereotype categorization, one could say that the concealment approach sets the building in focus, while the exposure approach emphasizes the technology itself. The best examples are perhaps those that manage to emphasize both the building and the supporting solar energy technology. This could be categorized as a mature aesthetic building integration of solar energy. What is typical of many of those projects is the successful process approach of having the integration considerations in mind from the start of the design phase.

### 3.8 Examples of building integration

The Swedish electric power research and development fund Elforsk, financed by the power and building industry, is running a research programme for developing the status of solar power, called SolEl 03-07. In the former programme, SolEl 00-02, an assessment was made of all major grid-connected building integrated PV systems in Sweden (Hedström, 2004). The performance of a large variety of projects has been investigated regarding their AC energy delivery.

The projects differ by building type, orientation, type of PV panels, azimuth, tilt angles and motives for using PVs. Building types include residential buildings, offices, museums, schools and train stations, placed between Malmö (lat 55.3°) and Härnösand (lat 62.7°). The PV panels

used include crystalline cells and amorphous thin film cells, from different manufacturers. The azimuth is generally towards south with small deviations, but some façade-integrated systems face e.g. both south and east or west. The tilt angle varies from vertically mounted façade-panels, to minus (!) four degrees, i.e. facing north. Hence, there is also a great variety in output, not only due to scale. The annual energy output ranges between 12 kWh/m<sup>2</sup> to 102 kWh/m<sup>2</sup>, with an average of 69 kWh/m<sup>2</sup>. The motives for the installations are mainly about demonstration purposes, pedagogic reasons, expression of an ecological profile or simply to widen the organisation's knowledge and experience of implementing PV systems.

For a detailed presentation of the projects in figures, see (Hedström 2004). Here, some of the projects are presented due to features of interest for the discussion on building integration. The actual energy output and cost is here a useful measure for evaluating the consequences of decisions taken in the planning process.

### IKEA head office, Älmhult

The installation on IKEA's head office in Älmhult from 1997 is still the largest PV project in Sweden. Two essentially different systems are installed on the same building, where the first is intended for production and the other for demonstration purposes. The production installation is a rack mounted, 378 m<sup>2</sup> monocrystalline array of 49.5 kW<sub>p</sub>. It delivered 39 MWh in 2003, equivalent to 104 kWh/m<sup>2</sup> or 797 kWh/kW<sub>p</sub>. This is the best performing system among all the investigated projects, which is due to the high-performing cell-type (conversion rate ~16%), and the optimal geometric conditions. The building is orientated directly towards south (azimuth 180°), and the tilt angle (40°) is optimized due to the rack-mounting on the flat roof.

The performance of the demonstration installation was less successful. The intentions were however totally different; to show a new PV technology integrated into the façade. The panels used were 250 m<sup>2</sup> of 10.9 kW<sub>p</sub> amorphous thin film modules ( $\eta$  ~4-7%) of a rather novel product line, which results in mismatch-losses, due to the uneven distribution of outgoing voltage from the individual modules. The vertical placement on the south-facing façades also contributes to the poor performance of 3,7 MWh, equivalent to 15 kWh/m<sup>2</sup> or 343 kWh/kW<sub>p</sub>, in 2003.

This example shows the conflict between performance and demonstration concepts, where the two strategies do not seem to be able to meet. There is a reason to question the value of a demonstration installation that does not meet the expected energy performance, since that is the primary reason for its existence. It is naturally important to be able to make

experimental installations and to introduce novel ways to integrate them into buildings, but there is always a risk that the basic requirements will not be satisfied, which could reduce the promotional effects. However, in the IKEA case, the presence of the other high-performing installation reduces this risk.

### Göteborg Energi

Another example of a mainly demonstrational installation is the 165 m<sup>2</sup>, 6.8 kW<sub>p</sub> façade installation on the south-facing (azimuth 180°) gable of the office building of Göteborg Energi, the Gothenburg municipal energy company, see figure 3.2. The motive for the installation was to acquire the PV technology and to attract the public attention to the company's environmental efforts, by optimal exposure of the modules. The amorphous thin film modules were combined with enamelled sheet metal to obtain a graphic pattern. In addition to the low energy performance, 1.8 MWh, equivalent to 16 kWh/m<sup>2</sup> or 397 kWh/kW<sub>p</sub>, for 2003, the project was made substantially more expensive because of the long distance for bolting into the concrete carcass due to the insulation thickness. Further, the cost of the decorative sheet metal was the same as that of the PV panels. From a technical and energy perspective this was therefore not very successful, but the claimed purpose was fulfilled; the estimated economic value of the medial attention to the project multiplied the investment several times. This is a strong indicator of the potential of implementing solar energy into the built environment for more subjective reasons, such as image, especially for publicly known institutions like this one. This has been recognized in the latest Swedish budget proposition, where a tax reduction of 70% of the cost of photovoltaic installations in official buildings has been proposed (Regeringens proposition 2003/04:100).

The small energy gains are in this case closely related to the so far small number of Swedish BIPV projects. When they become more common, architecturally more convincing and novel examples are needed for this promotional effect. The best result would be an aesthetically pleasing installation that also shows a high energy efficiency.



*Figure 3.2 The southfacing gable of Göteborg Energi with thin film modules.*

### Harmonihus, Western Harbour, Malmö

Another example of a less technically successful but exposed and demonstrative installation, backed up by a hidden system of higher productivity, is clearly visible on top of a multifamily building in Malmö. Here, PV cells are laminated separately between glass panes in a so called semi-transparent module. The panels are placed horizontally, or actually with a slightly negative tilt angle of  $4^\circ$  from the south-facing façade, in a system that allows the tenants to slide them forward to serve as sun and rain shelter for the roof terraces. In order to ensure rain drainage, there was a need to tilt the panels in this direction, which must be regarded as a failure in the synthesis between functionality and energy performance. The loss due to this would be approximately 4% compared with a horizontal position, and 7% compared with a positive angle of the same magnitude. This installation delivered 6 MWh, or  $50 \text{ kWh/m}^2$ , during its best year. There is also a more conventional roof installation behind the terrace roof panels. This is divided into two parts, one of  $20 \text{ m}^2$  with a  $60^\circ$  tilt angle, and one of 10

m<sup>2</sup> at 30°. However, these installations had not been put into operation before the assessment due to unsolved ownership conditions.



*Figure 3.3 A sliding photovoltaic roof for the terraces of a multifamily house in Malmö.*

For the same reason, the apartments have not been sold, and hence there is little knowledge of the performance of the solar shading function of the movable semitransparent modules. From my own experience, semitransparent modules in façade systems do not protect effectively from glare (although they reduce the overall amount of daylight), since the space between the opaque cells is fully transparent. In this case, the solar shading function ought to work better since it mainly protects the tenants from hazardous UV radiation and heat due to direct exposure from the sun when they are outside, rather than provides glare protection. The portion of PV cells should also be enough to have a substantial cooling effect in combination with the natural ventilation of an outdoor space, especially in this case, at the fourth floor in a windy area. To use this kind of modules as a shading strategy for indoor spaces has from my personal experience been found to be insufficient from a thermal point of view.

Another interesting aspect of these installations is the ownership. The installations are owned and maintained by the utility Sydkraft, with the required surface put at their disposal by the building proprietor. The power from the roof installation is directly connected to the building while the semitransparent modules deliver directly to Sydkraft's grid. These panels have been mounted on a frame, which is independent of the building structure, most likely for legal reasons.

## Härnösand

One interesting example of an aesthetically pleasing installation on a brick façade is the regional museum of Härnösand in northern Sweden. Instead of trying to make the PV modules part of the brick-clad building envelope, the monocrystalline cells have been arranged in long narrow strips at a distance, both from the façade behind and from each other. This harmonizes well with the building's architectural language, expressed in the proportions of the windows and other exterior elements.



*Figure 3.4      The façade installation of the regional museum in Härnösand.  
Courtesy of Carl Michael Johannesson.*

The PV system (and the solar collectors on the roof) were not intended in the initial design, but were a compromise with the architect. An earlier integration in the design process might have ended up in a different, in this case perhaps a less aesthetically interesting solution. Additionally, the distance between the modules and the bricks allows ventilation behind the modules, which can have a positive impact on their performance.

The 34 m<sup>2</sup>, 4 kW<sub>p</sub> installation delivered 1.7 MWh in 2003, equivalent to 49 kWh/m<sup>2</sup> or 415 kWh/kW<sub>p</sub>, about two thirds of the expected outcome. This is mainly due to the afternoon shading effect of a group of trees which were in an unfortunate position, to the west in front of the south-facing façade. Some of the trees were cut down after a compromise with the neighbours, but apparently not enough to diminish the shading effect. It is questionable to cut down trees that are of public interest, in order to install a low-performing PV system on façades. Compromises

like this one can be even more risky, since they have a negative effect on both the promotional image and the performance of the PV installation. Again, it is worth pointing out the importance of integrating solar energy strategies early in the building design process.

### Kristianstad

One of the most successful façade integrated systems is installed in two similar multifamily buildings in Kristianstad, southern Sweden (figure 3.5). The two identical systems cover 50 m<sup>2</sup> each, with a 11.8 kW<sub>p</sub> capacity, and delivered 8.3 MWh in 2003, equivalent to 83 kWh/ m<sup>2</sup> or 704 kWh/kW<sub>p</sub>. The installations are equally divided on the façade and on an adjacent roof with a tilt of 30°. The performance of the wall and roof modules has not been measured separately, but theoretically, they should account for 43 and 57% respectively.

Like in Härnösand, the modules are mounted with an air space behind them to allow for cooling for better performance, although this is not architecturally expressed.

The array of the panels, with the inclined panels placed right below the façade panels, is interesting since they probably help each other by reflection. It is interesting to note that for direct radiation, this phenomenon only accounts for one surface reflecting towards the other, depending on whether the solar altitude is larger or smaller than the roof's inclination, see figure 3.6.



*Figure 3.5 The façade installation of a renovated multi family house in Kristianstad. Courtesy of Carl Michael Johannesson.*

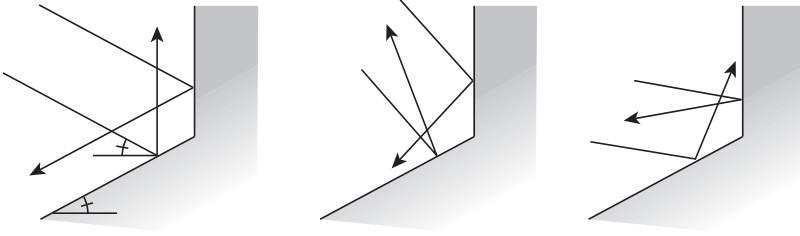


Figure 3.6 The reflecting effect of mounting two panels with different inclinations next to each other, as is the case at the residential buildings in Kristianstad.

This means that the reflectance occurs simultaneously with the most advantageous solar angle for each surface, which rather strengthens the effect of the changing radiation intensity over time. However, a combination of installations on a low sloping roof and a façade helps to level out the contrast in performance over the year. This is visible in figure 3.5, which shows the monthly output distribution for this installation, compared with the distribution of a roof installation of a similar magnitude. We can also note that a façade installation has a more even performance than a roof installation, due to the less efficient use of intense summer radiation and more efficient use of less intense fall/spring radiation.

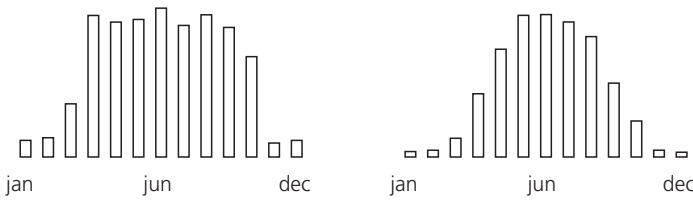


Figure 3.5 Diagrams comparing the monthly distribution of the annual performance in kWh of the combined façade-roof installation in Kristianstad, and the roof installation in Malmö. The former shows a more even distribution of performance over the year, due to smaller exposure to the summer sun and greater exposure to lower spring and summer sun.

Another interesting aspect of the Kristianstad installations is the exposed digital display on top of the façade, where spectators can directly see the amount of momentary power conversion and hence get a notion of the function and see that it actually works. This can contribute to give architecture a new, intellectual dimension. However, as in the case of using signs for orientation, it is desirable that the architecture itself should aim to be sufficient for this kind of information. This is a promising challenge and opportunity for new expressions when solar energy technologies are integrated into the built environment.



## 4 Architecture and solar energy

When solar energy elements are integrated in buildings, a dual influence relation occurs. The building design sets limitations for the possible integration strategies of the solar elements, and the building's appearance will be influenced by these elements. The earlier in the design process considerations are given to integration, the better. What the consequences are and how to deal with them, is discussed in this chapter. When conflicts occur, it is also of importance to know what to prioritize in order to make the right choices to achieve low energy use.

### 4.1 Architectural expression of solar energy

#### 4.1.1 The potential of expressing supporting systems

In his book "The architectural expression of environmental control systems", George Baird discusses the architectural quality of expressing the systems that provide the building with energy and comfort, i.e. the supporting subsystems discussed in chapter 2. By referring to the expression of passive systems in the buildings of pre-industrial man, he explores the potential of expressing environmental control systems, be they active or passive, in contemporary buildings, which can result in "a very strong architectural imagery" (Baird, 2001).

The expression can also be categorized by its level of building systems integration. Baird mentions Rush's categorization of the building's four main systems (structure, envelope, mechanical and interior), and five levels of visual expression of building integration (quoted from Baird, 2001):

- Level 1: Not visible, no change. The system or subsystem in question is not in view to the building user, and therefore modifications of its form are aesthetically irrelevant.
- Level 2: Visible, no change. The system is exposed to public view but not altered or improved in any way from what the purely functional application requires.
- Level 3: Visible, surface change. The system is visible to the building's occupants and has had only surface alterations made to it, with its other physical aspects remaining unchanged.
- Level 4: Visible, with size or shape change. The system is visible to the user of the building and has been given a size and/or shape other than what is simplest and most economical. The surface treatment and position may remain unchanged.
- Level 5: Visible, with location or orientation change. The system is exposed to the view of the occupants of the building, but its position has been altered from what is functionally optimal. The shape or surface, however, may remain unchanged.

Regarding building integrated solar energy systems, we have witnessed a slow transition from level 2, where e.g. a thermal collector simply has been rack-mounted on top of the roof, via level 3 and 4, where solar energy systems, like semi-transparent PV modules, have been designed specifically for building integration, to level 5, where effort has been made to adjust the integration of the systems also to satisfy more subjective values and motives, mentioned in 3.3.2.

Rush's classification can also be put in relation to the levels of integration discussed in 3.1.5. If the system described above also would apply for the building as a system, a more holistic approach towards the integration could be described by level 3 to 5; that the architecture itself can alter due to the introduction of solar energy systems.

#### 4.1.2 The history of expressing environmental control systems

Before the development of separate environmental management systems, the view on the building as an object was dominant. The building itself was the climatic shield and the differentiator between the outer climate and the man-made interior climate. But already from the start in the history of construction, man has made himself dependent on external systems for providing comfort in the interior. By using biofuels to heat the interior, man added a system for satisfying the comfort demands, besides the shelter

that the building provided. The fireplace had a central position in early building types, with very simple solutions for the combustion. Initially, an open fire was the heating and light source, with a hole in the roof for letting out the smoke and to let in daylight. The fireplace gradually evolved into a structural part of the building, for heating and baking, made out of masonry. The chimney became a visible architectural element telling us how the building was provided with heat. The tiled stove was a more refined system that increased the heating efficiency by 40%, and integrated the heating source with natural ventilation. Increased refinement with the introduction of the distribution system led to the moving of the heating source towards the basement, with radiators left in the room:

“Thereby is the heat source gone from ‘the system (called) the dwelling’. From there, it is not a long step to remove it from the building. Dependence on it does not disappear, even if the distance to it can be long enough in space. District heating systems are large, not to mention the electric grid.”  
(My translation, Edén, 1987).

This increased distance between the energy source and the place of its use can be part of the explanation of the alienation of modern architecture from its natural context. The introduction of air condition, promoted as "manufactured weather", made it possible to design buildings without any concern to the building design's response to its surrounding climate (Tsung Leong, 2001). The high tech movement, manifested by Piano and Rogers' Centre Pompidou in Paris, made a big contribution to the expression of environmental control systems, although with a high degree of "machine aesthetic". The same architects have however driven this architectural language towards a more environmentally concerned "eco tech" style. With the introduction of solar energy, a possibility has emerged to reintroduce the energy source in the building, moreover with a large potential for expressing it architecturally, and connecting the building to its physical surrounding.

#### 4.1.3 The potential of expressing solar energy

Among the many subsystems within the building, solar energy has a rather unique position in its potential of expression. First, solar energy elements must be exposed to the sun in the building exterior, thus a conscious design of its architectural integration is necessary. Second, the solar energy converted by the system is used directly in the building, and an expression of the system is therefore even more motivated. As functionalism expresses what the building is used for, and as structuralism expresses how the

building is constructed, solar architecture can express how the building is provided with energy.

The exterior organization of the solar collectors primarily demands a reasonable orientation towards the sun. Further, they have to be placed so that no shading occurs during the productive part of the day and year. Aesthetically, the collectors are exterior elements that should be consciously proportioned and positioned, corresponding to the overall aesthetic. A comparison to the expression of windows is close at hand. In theory, they both represent an idea of the building being penetrated by solar rays for the comfort of the user. Technically and aesthetically, they both contain glass with a frame which gives similar effects, like a darker, reflecting surface, at least during daylight.

Expressing the partial energy supply for the use of the building is an architectural quality that deserves further exploration. By giving the solar energy technology architectural meaning, both fields can benefit: architecture has in general had a somewhat confusing development during the last decades, with different styles expressing different theories derived from philosophy, art, et cetera. With an aim of a more meaningful architectural language connected to its function, like in early modernism, the competitiveness of solar energy can be increased. However, there is also a risk of the reverse situation: less successful examples of building integrated solar energy run the risk of reducing the potential of solar energy as a tool for architects, and conversely of making buildings less interesting for the solar industry.

## 4.2 Architectural limitations for solar energy elements

Building orientation, angles of inclination of building surfaces and shading, place obvious limitations on the ability to integrate solar energy in any building. Shading from neighbouring structures reduces the potential surface area. To this comes the architectural expression and intentions in general, which can turn out to be less suitable for solar energy elements. This is especially obvious for the integration into existing buildings, but also often for new buildings, since the introduction of the solar energy system might enter too late in the design process.

#### 4.2.1 Orientation and inclination

Orientation towards south is the most profitable because of the perpendicular orientation towards the sun when it is at its highest zenith of the day, and because a south orientated surface is exposed to the sun during the longest part of the day, nearly from dawn to dusk. However, the difference in overall exposure is not very dramatic within the south-east to south-west span. A deviation of  $\pm 45^\circ$  from south gives approximately a 10% reduction in total irradiation, which rises to at least 20% for a surface facing east or west.

Even though surfaces facing directions other than south might not lead to a substantial decrease in performance, the pedagogical value of an optimal design promotes the understanding of the mechanisms of solar energy. Further, these elements can contribute to facilitate orientation for passers-by, provided that most people are aware of the fact that solar collectors should face south.

The inclination of the surface is another essential parameter determined by the building design. Due to the variation of direct solar radiation intensity, related to the air mass resistance, discussed in 2.3.2, the exposed surfaces should have an inclination in order to be as perpendicular as possible to the prevailing direct radiation. This can be easily calculated in different simulation programs, such as the solar heating simulation software Polysun (SPF Solartechnik, 2004), which indicates an optimal inclination for a given azimuth, but only for a maximum annual output. If one wants to receive more radiation during e.g. the spring and autumn seasons, at the expense of the summer season, a more vertically orientated surface would be desirable. However, in most cases where integration into a sloping roof is the most suitable, the inclination is fixed. Even if the building is planned at the same stage as the solar energy system, there are other considerations than the solar energy output that contribute to determining the slope of the roof, like building regulations for example in the city plan, considerations to prevailing architectural form in the surrounding area or general aesthetic considerations for the building as a whole.

The smaller the inclination, i.e. the deviation from the horizontal plane, the smaller is the sensitivity of the azimuth. Figure 4.1 shows dependence of direct, diffuse and total irradiation on orientation and inclination for a surface placed in Stockholm. The data was generated in Polysun. Diffuse radiation is more evenly distributed across the sky vault than direct radiation. Hence, the reception of diffuse radiation is less dependent on azimuth and inclination. Since photovoltaic cells make more use of diffuse radiation than active solar collectors, they become less dependent on these parameters.

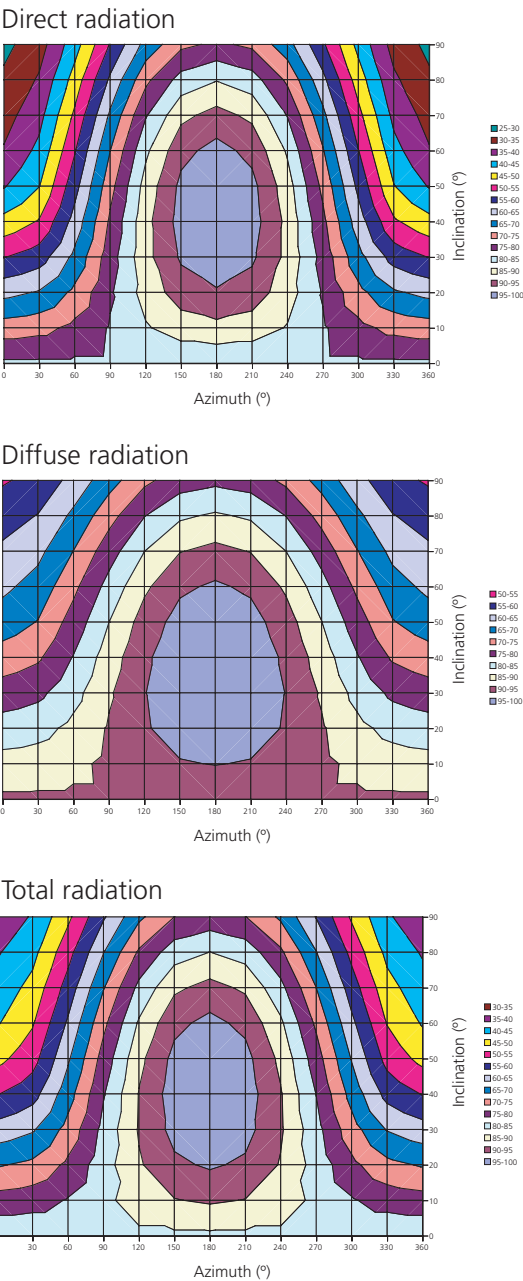


Figure 4.1 The dependence of direct, diffuse and total annual irradiance on different azimuth and inclination angles for Stockholm (lat 59.4°) based on the reference year 1995. The azimuth 180° indicates south. Values were obtained in Polysun.

### 4.2.2 Shading

The building density, the profile of the horizon or the existence of vegetation or other permanent structures that can cause shading, are essential limitations to the location of solar energy elements. For solar thermal elements, the effect of partial shading from direct radiation is smaller than for photovoltaics, where partial shading can cut off the voltage from one single cell or more, and hence the panel as a whole (Green, 2002). This problem is however reduced in most new systems, with diodes disconnecting the affected group of cells. Still the performance from these cells is reduced from the overall output, and therefore shading of solar panels should be avoided at all times. For passive solar house designs, it might be advisable to make use of deciduous trees, which will give shadow during the warm season and let the sun shine through the windows during the heating season.

Building density probably has the largest influence on shading. Façade integration of solar energy elements is out of the question on buildings surrounded by taller, or even equally tall ones in dense areas. Consideration can be given to this aspect in strategic planning and the urban layout of new buildings. This is helped by the general aim to provide maximum daylight for houses and work places, a basic design consideration for all qualitative architecture. As building integration of solar energy will be a more common feature, legislative measures for providing “sun-rights” might be an important tool for implementing solar aspects in the planning process. This will be further discussed in the following chapter.

An advantage for the implementation of solar energy in the built environment is the complexity and multiple use of solar radiation. Irrespective of whether solar energy technologies are to be adopted in a new settlement, the wish for maximum daylight access is or should be a guiding principle for all architectural design, since it affects psychological wellbeing (Küller, 2001). Hence, the most basic design criterion for building integrated solar energy is fulfilled: that the building is “visible” for the sun. Figure 4.2 shows schematically the relation between building height, distance and solar height.

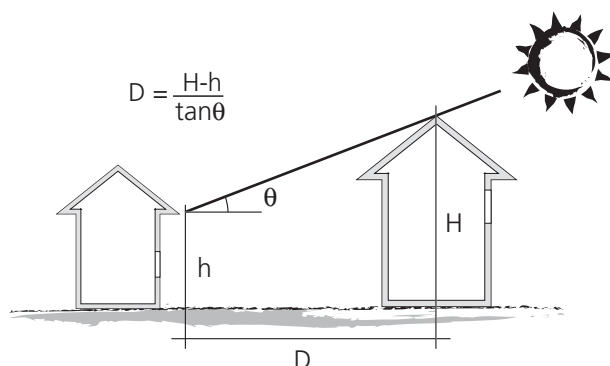


Figure 4.2 The relation between building height ( $h$ ), obstacle height ( $H$ ), distance ( $D$ ) and solar height ( $\theta$ ) for exposure to direct radiation.

Methods for maximizing solar access for building structures at an urban scale have been developed throughout history. In ancient Greek civilization, “sun rights” were proclaimed for buildings. Hence any construction blocking access to south was considered illegal (Pearson, 1998). In “The ten books on architecture”, the Roman architect Vitruvius promotes planning for maximal access to the sun (Vitruvius, 1960). Schemes for optimal daylight access were also of great interest for the modernist movement, with Le Corbusier as the front figure (Le Corbusier, 1976). Although these schemes are often associated with high-rise structures in non-attractive settings, there are several arguments for planning for solar access. Even if the active harvesting of solar energy is not on the agenda of the buildings to be erected, future additions of these systems as well as passive gains and daylight access are bonus features. Further, the concern for solar access might indirectly lead to low-density urban design schemes, which generally are preferred as living environments (Rådberg, 1997), in comparison with the high-rise structure scheme, which will inevitably have a considerable negative effect on neighbouring structures concerning solar access.

The term “solar envelope” has been introduced in the research field by Ralph B. Knowles, for examining the optimal urban layout for maximal solar access. The solar envelope is defined as “a construct of space and time: the physical boundaries of surrounding properties and the period of their assured access to sunshine. These two measures, when combined, determine the envelope’s final size and shape”. The space constraint can be illustrated by figure 4.2, where  $h$  represents what is referred to as the

“shadow fence”, i.e. a designated boundary for acceptable shadows from the solar envelope, in figure 4.4 represented by H. The time constraint can determine the borders of the solar envelope with “cut-off times”. This constraint can be represented by the solar height in figure 4.2. By saying that the solar envelope shall not cast off-site shadows above the shadow fences between the cut-off times, the volume of the solar envelope is limited. The wider the span between the cut-off times, the lower the solar angle, and the smaller is the solar envelope. Student projects initiated by Knowles on an urban scale, which were designed with these rules in mind propose sloping block structures of varying height, dependent on the geographical situation. These designs indicate that the prevailing orthogonal structures we are used to might not be the obvious choice when designing for solar gains (Knowles, 2003).

### 4.3 Solar energy in building renovation

To further increase the competitiveness of solar energy systems, there is a large potential to use these elements for retrofit in existing buildings, which are the objects of renovation, besides exchanging old windows for more energy efficient ones (Dalenbäck, 1996). Architecturally sensitive buildings might be inappropriate for the introduction of solar energy elements, but several modern structures might gain from such additions. Sweden has a large stock of multi-family buildings from the 1960s and 1970s which were constructed during the so-called “record years”. The government decided that the large problem of shortage of dwellings should be solved by building one million apartments in ten years (Rörby, 1996). These buildings, which in many cases have gained a bad reputation due to large scale planning and a lack of articulation in façades and surrounding yards, are the objects of renovation during the next decades. Attempts have been made to make some of these less successfully articulated buildings more attractive by (intentionally) adding decorative façade elements, porticoes etc., with a lack of understanding of the original architectural language. Here is a large potential for the implementation of solar energy additions, since the rather box-like buildings can gain from additions, which can reduce the large-scale character. Another common step taken on buildings from this era with flat roofs is to add a pitched roof, in order to change the character towards a more traditional architecture, and to avoid drainage problems which are common on flat roofs. If this change is to be made, whether suitable or not, an integration of solar collectors in these roofs can further increase the motivation for such a step. An architecturally and technically successful example can be found in Gårdsten outside

Gothenburg, where two buildings each were given a pitched roof to house a 220 m<sup>2</sup> large thermal collector, connected to a 20 m<sup>3</sup> water tank, besides air-collectors integrated into the added, non-glazed, double-skin façades and greenhouses, see figure 4.3 (Nordström, 1999).



Figure 4.3 *Aerial photograph and section of the converted multi family houses in Gårdsten, Gothenburg. Courtesy of Christer Nordström Arkitektkontor AB.*

As discussed above, implementation of solar energy technologies in existing buildings is often problematic, due to the building's fixed parameters such as orientation, roof inclination et cetera. The architectural expression, which is often sensitive to modern additions such as thermal collectors or PV panels, must be taken into account. There is a potential conflict between conserving energy and conserving our cultural heritage.

## 4.4 Hidden roof installations

Solar energy elements which are clearly exposed in the exterior, will have an impact on the building's architectural expression. This can be for good or for bad. However, external exposure does not necessarily mean that the elements for harvesting solar energy are highly visible to a passer-by on e.g. street level. Putting low profile elements on a low-sloping roof, with a distance from the roof's edge, can make the additions more or less invisible from street level. This is a matter of distance between the building and the spectator, and the height of the building. From these parameters, a "free triangle" is created on top of the roof, within which the elements can be put without being seen from ground level. The permissible height of the elements is then dependent on the distance from the roof's visible edge,

from zero by the edge, to a maximum at the centre of the roof. For analysing what dimension and distance are necessary for avoiding exposure on roofs, simple graphic and mathematical tools can be used, see figure 4.3.

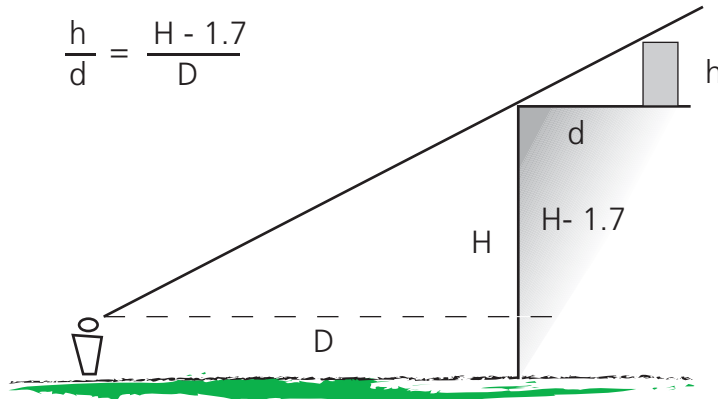


Figure 4.3 The relation between distance between spectator and building, height of the building and collector and the distance from the roof's edge, in order to avoid exposure of the collector.

As described in 3.5.5, several manufacturers, especially within the PV industry, have developed components that have shapes and dimensions similar to e.g. roof shingles and ceramic tiles, in order to adapt to the existing building they are to be integrated into. This might be suitable in projects that have a demanding and culturally sensitive architecture. However, it is questionable whether this should be the way to introduce these technologies in the building sector, or whether they should have the chance to contribute to the evolution of architecture by their own means. The answer is probably that there is enough space for all strategies. Whether we speak about solar houses or the importance of expressing energy supply, it might be useless to speak about a solar architecture in its own terms. The primary target of a building is not to make use of the sun. Rather, this is a way to reduce its primary energy use and to promote the use of renewable energy. Solar harvesting is not an aim in itself for any building, except for maybe a building incorporated in a solar energy plant.

## 4.5 Internal shading

Placing freestanding solar collectors or PV panels on roofs is often the most suitable solution for the vast number of flat roofs, dominating in industrial real estate. Even for other structures, it might be more suitable to use freestanding, rack mounted components, both for technical and aesthetic reasons. However, one must be careful so that there is a minimum distance between the rows facing the sun, in order to avoid that the elements cast shadows on each other, thus reducing the energy output. This distance depends on the lowest allowed solar angle, the tilt and thus the height of the elements, and the inclination of the roof. If the roof is flat the solar angle and the height determines the distance, see figure 4.4[a]. If the roof is inclined in the same direction as the elements are facing, this distance can be shortened, see figure 4.4 [b]. Rack mounted collectors or panels have the advantage that they can also be placed on roofs inclined in the opposite direction. However, this requires a larger distance between the rows, see figure 4.4[c].

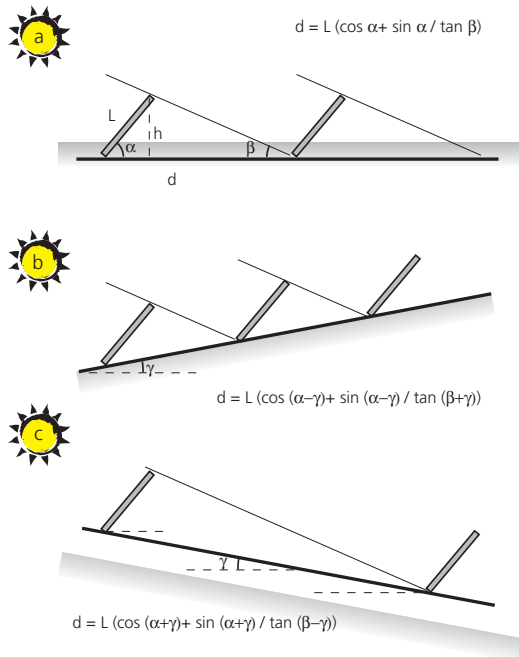


Figure 4.4 The relation between rack mounted collector height and roof angle for avoiding internal shading, for a flat roof (a), a sun-facing roof (b) and a non sun-facing roof (c).

The lowest allowed solar angle is a matter of judgement from case to case, especially in projects with rack-mounted elements. If a higher solar angle is allowed, more rows of solar collectors can fit on the roof surface. It might not make sense to make use of the lowest angles of the year in northern areas, since the winter sun gives very little energy. A balance between shading, number of collectors or panels, their output and cost should be found.

Another example of internal shading is when e.g. vacuum tube collectors intended for inclined roofs are mounted in a vertical position, so that the absorbers placed within the tubes get shaded by the ones above. This happens in the residential building Tegelborgen in the Western Harbour area of Malmö, which otherwise shows an interesting way to architecturally integrate vacuum tube collectors vertically in façade and roof. The collectors run up along the brick façade and continue above the roof, and then continue behind in a row of vertical elements, simultaneously functioning as wind shields. In order to avoid this kind of shading, the tubes can either be separated (which deviates from the product standard), or turned (when flat absorbers are used inside the vacuum tube), so that the absorbers are more vertically oriented. However, this tends to reduce the radiation exposure, thus reducing the energy output from the collectors. With this in mind, vacuum tube collectors have the potential of being in a vertical position, with the absorbers at an optimal tilt angle towards the sun, as long as the distance between the tubes is large enough.

## 4.7 The impact of solar energy on architecture

As discussed, the architectural context affects the way a solar energy system can be integrated and how effective its performance will be. The other way round, one could say that the introduction of solar energy technologies into the planned building might dictate the conditions and the final design of the building or the plan it is to be put into, according to design criteria discussed in the previous sections.

The visual appearance of the solar energy systems, mainly from the visual parts like the collectors or PV panels, will also most conspicuously affect the architecture of the building. Since these elements need to be exposed to the sun, often they will also be highly visible to the surroundings. Whether the impressions of these elements are positive or negative, they are still new elements that will attract attention. The conception of this will be dependent on how successful the architectural integration has been.

As discussed earlier, there are examples of how the integration has been made in a discreet way, with the collectors or panels made more or less invisible. This can be achieved *architecturally* by integrating the elements in a way that geometrically harmonises with the building, e.g. using the roof slope for integration. Further, one can avoid the appearance of having put an alien “stamp” on the roof by using a whole section of the roof instead of putting it centrally, surrounded by other materials (see figure 4.5[a]). If possible, a dedication of a whole, separate roof or façade area for the solar modules might lead to higher architectural quality, with a simultaneous possibility for an elaborate expression of the technology. On a more detailed construction level, the “stamp” impression can be further reduced by putting the top of the collector at the same level as the adjoining elements (see figure 4.5[b]). However, this strategy might pose the risk of interfering with the demands for little maintenance and risk of leakage et cetera. Using elements that are designed to resemble conventional building elements also facilitates a discreet integration.

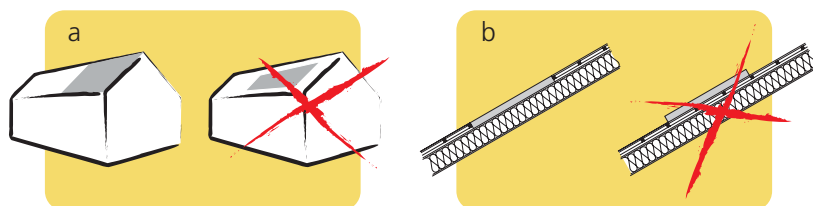


Figure 4.5 Two examples on how to avoid a too conspicuous appearance of the solar collector. The use of a whole surface (a) and putting the top of the collector at the same level as adjoining surfaces (b).

Even though a discreet integration might be the most viable in a majority of buildings, in particular in existing ones, there are other approaches that can express just as successful an integration. The methods described above might interfere with the basic design criteria, i.e. energy efficiency. If the roof is orientated too far from south, it might not be worthwhile to integrate panels along the roof.

## 4.8 System requirements

Apart from the collectors, other parts of the solar energy system might have influence on the architectural context. This is most obvious for solar

thermal systems, where the storage and the desire for short piping can be limiting. For a solar thermal system a storage capacity of 100-150 l/m<sup>2</sup> is recommended, which for a normal DHW solar system results in a tank of 500-800 l, which needs space. Further, it is recommended to have the shortest possible distance between collector and storage tank, in order to minimize distribution losses and to avoid extensive insulation thickness for the pipes.



## 5 Discussion and conclusions - a process proposal

### 5.1 A brief handbook as a conclusion

During the time this text was written, work was made on different preliminary studies for the integration of different solar energy systems into existing buildings (Fieber, 2003, Fieber and Nilsson, 2005). The most valuable experience from those projects, was the development of a methodology for structuring the work. In combination with conclusions from the previous chapters, a suggestion on the process of planning a building integration of a solar energy system closes this part of the thesis. Hopefully this pragmatic approach makes the reading of the conclusions slightly more joyful, and simultaneously this could be seen as a sketch for a possible future handbook in Swedish, which was originally discussed for this thesis work.

### 5.2 Organisation and integrated process

The whole project group should be formed early in the process with mixed competencies. It is important that every actor within the process is interested in achieving a satisfactory result, and therefore early involvement is essential. Each actor should be able to communicate the essence and the criteria of their competence for the project, in order inspire and make ground for co-generative effects from the teamwork.

Like in any building project, the architect plays a key role here, since the integration of solar energy elements highly affects the design of the building. The systems approach, crucial for an integrated design process, is commonly used in most architectural design work.

## 5.3 Defining objectives

The first step is to identify the objective of the integration. What approach is taken to the project? This relates to the discussion in 3.1 and 3.2. The motives for integrating a solar energy system should be identified and discussed within the project group.

It is quite likely that different actors within the project group have different objectives for the project, which should be the case, since each actor must promote their own competence and its role in the project. The group should discuss their own and the common motives for the project, in order to reach a successful, holistic result.

The motives described in 3.3 could be used as a starting point for this discussion. A successful integration project should be motivated from both the more pragmatic, objective perspectives such as energy and cost savings, and the "softer", subjective perspectives, such as aesthetics, promotional effects et cetera. While the solar engineer focuses on e.g. the cost savings in order to reduce investment cost and hence justify the system itself, the architect might focus more on the aesthetical potential of the system for contributing to the architectural expression. The proprietor hopefully sees the financial potential in both those perspectives. All motives should be discussed and synthesized to a common objective of the project.

## 5.4 Building analysis

Presumed that the building, existing or not, has been chosen for the integration project, its properties and its potential for housing a solar energy system must be thoroughly analysed. Some basic criteria such as freedom from shade and surfaces with good orientation and inclination should be fulfilled in order to even consider integrating a solar energy system with a particular building. An assessment of the building's energy system and its consumption of heat and/or electricity are also crucial for dimensioning the system.

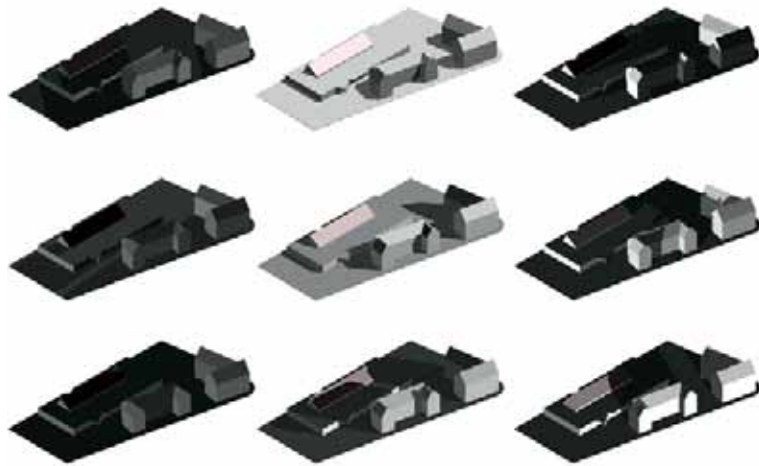
The building's architectural value and the appropriateness for introducing solar collectors in its exterior should be analysed by the architect, in collaboration with the proprietor and perhaps also with authorities in respect to building codes. The architect should also determine whether there is enough space for e.g. storage of water tanks at a short distance from the collector area, in case of a solar thermal system.

The constructional engineer should examine the prerequisites of the construction for the technical integration of the solar system. How can

e.g. the collectors be attached to, or replace, the building skin materials, and does the structural framework allow for the added weight of the elements?

The maintenance and management of the system should also be considered by the designing architects and engineers in dialogue with the property manager.

The risk of shading on the selected surface can be analysed with the help from a 3D CAD program, which can simulate the position of the sun for any place, anytime. This can generate still pictures or animations, which show the movement of the shadows during a whole day. Figure 5.1 shows a series of model pictures of the public art gallery in Malmö, Sweden, whose large roof lanternine is considered to be equipped with a large photovoltaic installation.



*Figure 5.1 Series of CAD model pictures for analysing the shading effects of surrounding buildings onto a roof subject to PV integration.*

## 5.5 Appropriate systems and integration parameters

Depending on what the analysis of the building shows, a suitable solar energy system that meets those prerequisites must be found. Simultaneously the integration parameters are set; how is the integration to be made? Is a simple application on top of the roof the most suitable, or is there a roof with a fair orientation and inclination, large enough to carry a system that

meets the targeted energy conversion? Perhaps PV panels as sunshades is the most suitable, if the largest electrical load is due to space cooling. Or a vertical application is perhaps to prefer, if the loads and the pedagogic impacts are low during summer time?

The level of integration, discussed in 3.1.5, also determines the choice of system. Should the solar panels replace other facade materials, or could they be placed as e.g. louvres in front of windows? Should solar energy contribute to both the heating and DHW demand, or even the electricity demand? And to what extent? Should the appearance of the solar collectors be expressive for demonstrative or aesthetic reasons, or should they be discreetly integrated?

From these criteria, the choice from a wide and fast growing range of solar energy products for building integration, categorized in 2.4, is made.

## 5.6 System simulation and analysis of consequences

By determining the available area, orientation, inclination and other system parameters from the producers of the system, a simulation in a computer program can be made, primarily to determine the energy yield of the system. There are several tools for simulating solar energy systems, but some require separate files with climatic data, which can either be bought from meteorological institutes or generated in programs such as Meteonorm. If alternatives are at hand, the energy yield can be compared in relation to other parameters, such as visual appearance and cost. One simple way to compare the success of integration if different locations for the system are at hand, is to calculate the ratio between the annual energy yield and the installed peak capacity (standard value for PV systems, as described in 2.4.3). With knowledge of the system investment cost (reduced by cut costs due to possible building material replacement), the final solar energy cost or pay off time can be calculated.

Other consequences from the integration project can be analysed by using other tools. For example, the visual effect of adding solar panels to an existing building can be analysed by making a photomontage using an image processing tool, as shown in figure 5.2.



*Figure 5.2 By making a photomontage, the visual impact of integrating a solar energy system to an existing building can easily be illustrated, as in the case of this nursing institution in Malmö, where PV panels are planned to be integrated into the balcony parapets.*

## 5.7 Implementation and follow-up

No matter how well planned and integrated the design process is, the implementation on site determines the final result. A professionally made installation in regard to both appearance and performance is crucial if solar energy systems are to gain a wider acceptance in the built environment.

Finally, monitoring of the system's performance is essential in order to gain experience of consequences of the decisions made in the design process. This can also be useful for demonstration purposes, which emphasizes the pedagogic dimension of solar energy systems.



# PART II

## The Solar Window



## 6 The Solar Window project

### 6.1 Background

Research has been made in Sweden for some time on development of low-concentrating solar energy systems for building integration. Vattenfall utveckling AB in collaboration with Ångström Laboratories, Uppsala University and the department of Construction and Architecture, Lund University, have developed and examined the design and potential of e.g. the so-called MaReCo (Maximum Reflection Concentration) collector, which is a trough-shaped reflector with a centrally placed absorber element (Karlsson et al, 2001). This is a free-standing element for ground-mounting or placement on top of flat roofs. Variations of this concept have been developed into wall-applications for building integration, for both thermal and hybrid PV/T collectors (Brogren, 2004). The Solar Window is a development of this design, introducing windows as the glazing for the collector.

By concentration, expensive thermal absorber and PV cell area can be used more effectively and thereby partly replaced by substantially cheaper reflector material (Brogren, 2004). Designed as building elements, the collectors can be even more cost-efficient through replacement of other building skin materials, besides the added values of building integration, discussed in chapter 3.

The geometry of low-concentrating components is suitable for vertical façade integration. It has a potential to be incorporated within large scale glazing systems, which are popular in modern office buildings. Modern residential houses are also objects for a larger extent of glazed area, often merely as an aesthetic consideration rather than for thermal or visual comfort. Hence, vertically placed solar collectors with their glazed surfaces have a potential to become an increasing feature in modern architecture.

## 6.2 Objective

This project has two purposes. First, to develop a system that in a novel way shows how a low-concentrating PV/T system with added functions can be architecturally integrated and to analyse the energy performance. Second, to try to highlight some of the issues discussed in the former part of this thesis in a tangible design.

## 6.3 Methodology

The project originated from an experimental design process, which was part of a diploma work at the School of Architecture, Lund University. This work also contained the design of a single-family house project in Älvkarleby, Sweden, which was later realized. The Solar Window system is to be integrated into this building. In this phase, the idea of integrating a low-concentrating hybrid PV/T system into a window was introduced.

The study and development of the system has been carried out in several different ways and from different perspectives. The different approaches are here briefly described as parts of the process, and are described in detail in each respective chapter, see the outline below.

The daylight obstruction of the system with open reflectors was simulated with a three-dimensional computer model.

Further refinement in the design led to the construction of a full-scale prototype of the system of approximately one square meter. This has been object for measurements of its U-value as a part of the building skin, and as a thermal collector.

The active thermal performance was monitored on the full-scale prototype by outdoor measurements.

The PV-efficiency was monitored on a smaller prototype.

In order to determine a suitable control strategy, which balances energy performance with user comfort demands, a simulation tool based on TRANSYS code was developed. It simulates all of the system's energy conversing functions simultaneously. The design parameters are fixed, and the building integration parameters, such as control strategy depending on irradiance intensity, are input data.

## 6.4 Outline

The next chapter describes the design concept, the process behind it and the discussion on building integrated solar energy, assessed in part one of this thesis, which partly makes a background for this project. The project is in a high degree focused on integrating all useable forms of solar energy into the building envelope in a highly expressive way, which aims at making the user aware of and engaged in the building's energy supply. The system design and its functions are described in detail, and the parameters that are objects for parametric studies and future adjustments are highlighted. The technological background for the concentration and hybrid properties of the system is also described.

Chapter 8 focuses on the thermal transmittance of the Solar Window. The performance of the Solar Window as a building element are examined, mainly its solar transmittance, its U-value and its solar shading properties.

Chapter 9 discusses the Solar Window's visual properties, like view, glare and daylight. The system works as a daylight redirecting device in the open mode, but leads to obstruction of view and daylight compared to an ordinary window.

Chapter 10 focuses on the PV/T function and performance of the system, based on a combination of measurements and computer simulations.

In chapter 11, different control strategies for the system are discussed. A model of the system, made in TRNSYS, is described, and the method and outcome of the parametric studies from this model is described.

Based on the results, chapter 12 discusses possible future alternative designs and applications. For example, it might be interesting to adjust the reflecting geometry or to reduce PV cell area in relation to the reflector in order to increase cost efficiency. Also, another application is examined, i.e. an integration of the system into a glazed office façade, without the insulation function.



## 7 Design and construction of the Solar Window

### 7.1 Design concept

From the study on building integration, one important conclusion was that full integration means a fruitful combination of architectural, technical and functional integration, i.e. the aesthetic, technical and human perspectives must all be considered.

As an answer to the search for truly building integrated solar energy systems, an experimental design was proposed, which combines all usable forms of solar energy into one system; active and passive heating, PV electricity and daylight, see figure 7.1.

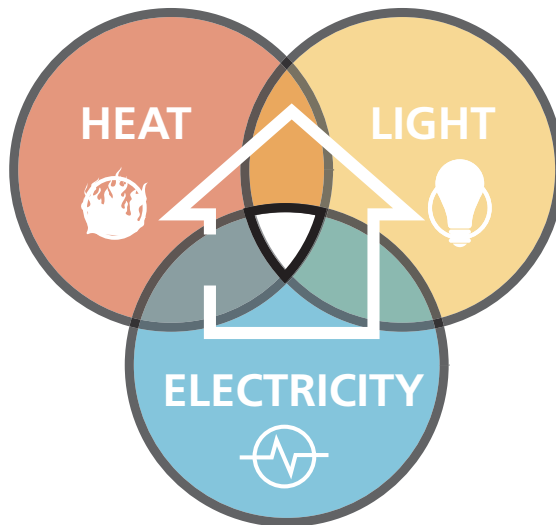


Figure 7.1

*The Solar Window aims to building integrate all forms of energy which can be derived from the sun, in such a way that it is exposed to view.*

It was desired to find an element that serves both an architectural and an energy conversion function. Aesthetically, the system should aim to broaden the understanding of the solar contribution to the building's energy balance, by exposing the system and making it aesthetically pleasing. Hence, it can increase the acceptance of solar energy technologies. From the performance point of view, it was suggested that the element should contribute positively to the thermal balance of the building itself, and not only serve as an active solar collector or solar panel. The life cycle aspect is also taken into account, by using the same element for several purposes.

## 7.2 The Solar Window

In the beginning of the design process, a functional analysis of a solar thermal collector was made, where the desired outputs were compared to the elements in a conventional thermal collector. Since low-concentrating systems have the quality of separating the absorbers or PV cells, there was a desire to explore the potential to make the intermediate reflectors in some way transparent, in order to make the system work as a daylight provider as well. The glazing of a thermal collector, necessary to trap the absorbed heat, is already there, and in a building, the window has the same characteristic.

By using hybrid absorbers and pivoted reflectors behind the window, a multifunctional and responding building skin is achieved. The basic concept of building integration is hence changed from the notion of the solar energy system being part of the building envelope, to the idea of the building envelope being part of the solar energy system.

From an architectural point of view, a window might be a more suitable element for integrating solar energy, since it has a more open, penetrable, collecting and transparent character than i.e. the roof. The roof is otherwise the most common element for building integration, and has a more protective, shielding character, see figure 7.2. To use the roof as a collector for solar energy can hence architecturally seem like a paradox (Nordström, 2003).

Based on these criteria, a design was suggested where the window is the covering glass of the solar collector. The design could also be regarded as a development and variation of the so-called Wall-MaReCo, presented in section 2.2.4. In the Solar Window, the reflecting geometry of the concentrating mirrors was transformed into pivoted shading screens that can be either closed in order to work as concentrating elements, or opened in order to let sunshine into the interior, see figure 7.3. By laminating PV cells on top of the thermal absorber, a hybrid PV/T system is achieved.

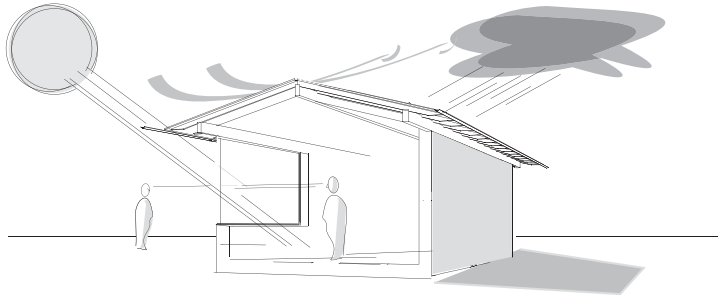


Figure 7.2 *A conceptual comparison between the roof and the wall for the architectural appropriateness for housing solar energy elements.*



Figure 7.3 *Section of the Solar Window with the concentrating reflector screens in a closed, concentrating mode (top) and an open mode (bottom).*

The collecting part of the system consists of three main components: the window, the reflector and the hybrid absorber, see figure 7.4. The combination is intended to give synergy effects by ascribing the components multiple functions. Each component is presented in detail in 7.3 to 7.5.

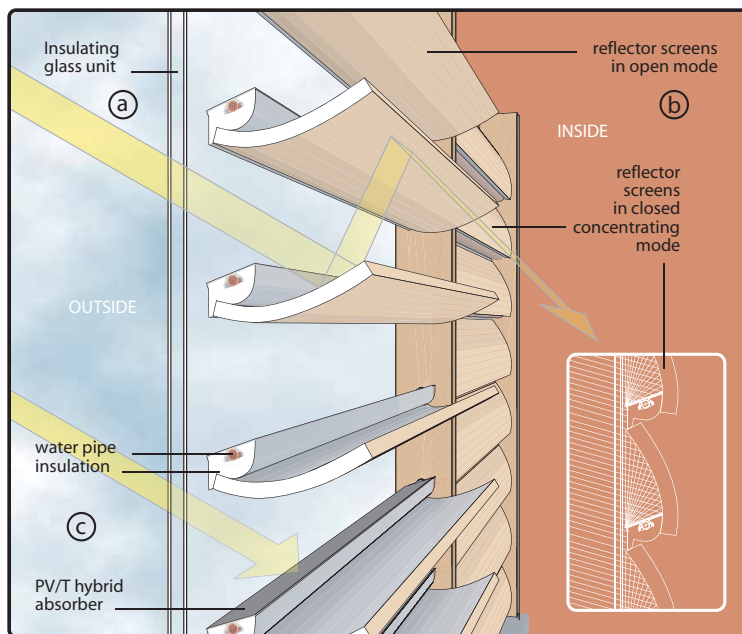


Figure 7.4 Perspective view of the Solar Window and its three main components: the insulating glass unit window (a), the reflector screen (b) and the hybrid PV/T absorber (c).

### 7.2.1 Exposure and aesthetics

As discussed in chapter 4, the exposure of environmental management systems can have several benefits, for pedagogical and architectural reasons. By using windows for the integration, the system will be highly visible from both the exterior and the interior. Functionally, the window speaks the same language as the collector; harvesting the solar energy for the comfort of the interior.

Other aesthetic considerations are mainly due to the reflectors. The curved concentrating geometry can be considered as decorative and expresses the capturing nature of a solar energy system. The rear face towards the interior can be covered with any surface material suitable for the interior context. The modular nature of the reflectors, with no con-

nection to the energy distribution, makes it possible to exchange them for alternative surfaces, thicknesses or reflecting geometries. The concave front facing the window will be highly visible from the exterior, and the mirror like surface might be the most critical aesthetic property for wider acceptance. However, the curved mirror can generate interesting optical expressions in the façade. The extruded picture of the PV/T absorber is visible when the spectator is within the optical acceptance angle range, which means that the impression of the individual modules will differ much depending on height at a short distance. The overall impression of the façade will hence change when approaching it. The flexibility of the reflectors also contributes to a dynamic façade expression.



*Figure 7.5 A rendering of the Solar Window's highly expressive character and its potential for a varying interior and façade expression.*

### 7.2.2 Integration into a single-family house

The system is initially intended for experimental integration into a low energy, single-family house, designed simultaneously with the concept for the solar window, see figure 7.6. This house has an 18 m<sup>2</sup> south facing window structure prepared for the integration of the Solar Window system. The house is constructed with an EPS module system with integrated load bearing wooden studs, with no thermal bridges. A central brick wall and a

ceramic clad concrete floor absorb passive gains. The solar heating system is complemented by a pellet burner. The PV system is both grid-connected and connected to a local DC circuit, which is installed in order to reduce magnetic fields and eliminating losses in battery eliminators, used for DC powered devices, see figure 7.7.



*Figure 7.6 Ground floor plan, section and south façade of the single family house in Älvkarleby, Sweden, where the Solar Window is to be integrated.*

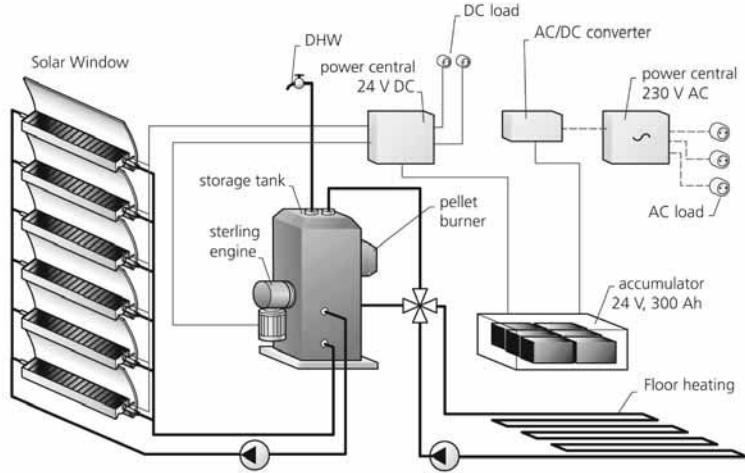


Figure 7.7 Scheme of the heating and power system for the single family house in Älvkarleby, Sweden, where the Solar Window is to be integrated. Courtesy of Claes-Göran Andersson, *Energi & Miljö*, no 11/2002.

### 7.3 The window component

The window is part of the climate shield and serves as the solar radiation transmitter for the system. After the solar radiation is transmitted through the window, it is distributed as daylight, passive or active heating, or as PV electricity, in proportions depending on the arrangement between the closed or open modes. For maximal input for the PV/T absorber through a vertical surface, the transmittance through the window needs to be maximized. Therefore, a highly transparent glass, i.e. low-iron glass with anti-reflective coating is used. Due to the overheating protection provided by the solar shading and the cooling effect of the absorber, a higher transmittance of the glazing can be tolerated.

Since the window is constructed for maximum transmittance, the U-value becomes high ( $\sim 2.8 \text{ W/m}^2$ ) compared with modern Swedish low-energy windows (down to  $1.0 \text{ W/m}^2$ ), which is due to the missing low-e coating, that reduces the emittance of the inner glass. The thermal losses are instead reduced by EPS insulation attached to the back of the reflectors.

Using anti-reflective coatings can to some extent improve the energy performance for a normal window (Rosencrantz and Bülow-Hübe, 2004). The window was constructed as an insulating glass unit (IGU) with two panes of 3 mm glass with anti-reflective coatings, and a 14 mm air gap .

## 7.4 The reflector component

### 7.4.1 The functions of the reflector

The reflector screens are primarily intended for concentration of the solar radiation onto the hybrid absorber. Thus, the need for expensive absorber and PV cell area is reduced, as it is largely replaced by substantially cheaper reflecting material. The resulting distance between the fixed absorbers thus makes it possible to achieve transparency between them when the reflectors are of little use. Hence, daylight may filter through the structure, which also gives passive thermal gains. However, passive solar house designs with large south facing window areas run the risk of overheating the interior. The reflectors are intended to reduce this problem, by serving as internal sunshades during daytime. During night time they reduce thermal losses, since they serve as added insulation.

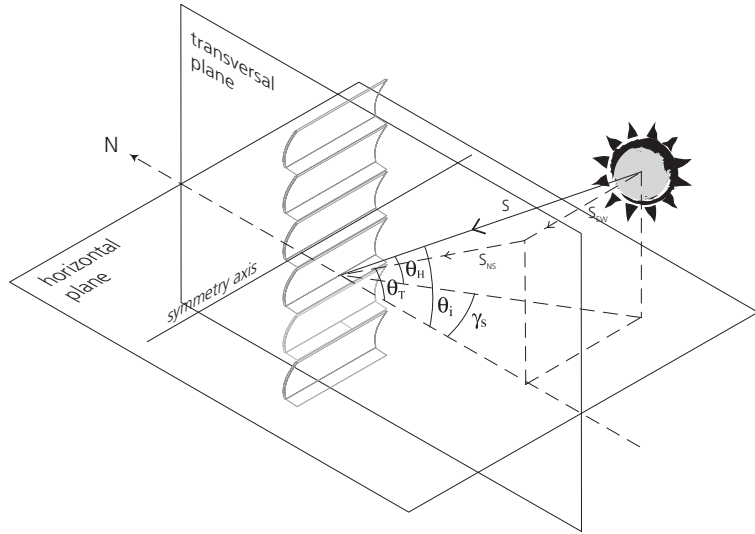
### 7.4.2 The south projection angle and effective solar height

Like all solar energy systems, the Solar Window is aimed to be directed in the most favourable direction towards the sun, i.e. for the northern hemisphere facing south.

The reflector of the Solar Window is designed for concentration of light within a range of solar heights. The optimal choice of this range is dependent upon the irradiance conditions for the specific site, especially due to the latitude.

In order to determine the acceptance angles, the effective solar height is introduced as a means to evaluate the concentrating properties of the reflector. By analysing the energy content of the irradiance for different effective solar heights, guidelines for a proper design of the reflectors' acceptance angles are achieved.

The effective solar height is defined as the angle between the horizontal plane and the projection in the transversal plane of the incoming direct solar radiation. The transversal (or meridian) plane is the plane perpendicular to the plane of the collector. For south-facing surfaces, this plane corresponds to the north-south plane. The effective solar height can in this case also be called the south projection angle. The projection in this plane derives from the aim to divide the vector describing the direct irradiance into two components: one perpendicular to the surface of the device, which will provide all the energy, and one parallel to the surface, which will have no contribution to the power supply, see figure 7.8.



*Figure 7.8 Definition of solar angles in relation to the orientation of the Solar Window. The solar irradiance vector  $S$ , which has an azimuth deviation of  $\gamma_s$  from south, can be divided into components in the north-south direction ( $S_{NS}$ ), and the east-west direction ( $S_{EW}$ ). The effective solar height  $\theta_T$  is the solar height  $\theta_H$  projected in the transversal plane, which is perpendicular to the plane of the collector.*

For maximising irradiation exposure, the diagrams in figure 2.9 indicate that it seems wise to make use of the irradiation coming from solar heights at least between  $10^\circ$  and  $60^\circ$ . However, solar heights around  $10^\circ$  are of little use in the built environment, since this demands an almost free horizon. For example, a southern neighbouring building of 5 m height needs to be at a distance of  $5 / \tan 10^\circ = 28$  m for such a solar height. Hence, it is recommended to prioritise higher solar angles at the expense of lower ones. A minimum acceptance angle of  $\sim 15^\circ$  might be more appropriate.

### 7.4.3 Reflector geometry

The reflector used in the Solar Window is a non-imaging, line focusing, two-dimensional parabolic concentrator. The reflecting geometry is described by the equation  $y = x^2$ , or  $r = P/\cos^2(\theta/2)$ , see figure 7.9 (1). If the curve is tilted  $90^\circ$ ,  $A$  corresponds to the glazed aperture area.  $P$  is the area corresponding to the distance between origo and the focal point  $p$ . In this situation (2), the aperture area is twice as large as the area in focus. For a minimum acceptance angle of  $15^\circ$ , the symmetry axis of the curve, i.e. the  $y$  axis in figure 7.9, is tilted  $15^\circ$  upwards from the horizontal plane. This

leads to the relation  $A=2,7P$ , according to figure 7.9(3). With a 70 mm wide absorber put into the system, represented by [a] in figure 7.9 (4), the size of the aperture area can be calculated, and hence the geometrical concentration factor,  $\eta_g$ , as the ratio between the absorber area and the aperture area. For this geometry,  $\eta_g$  is 2,45.

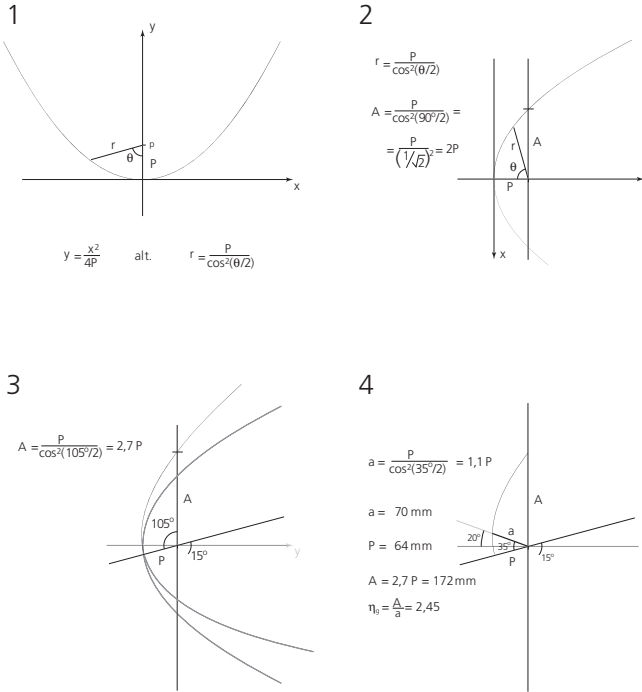
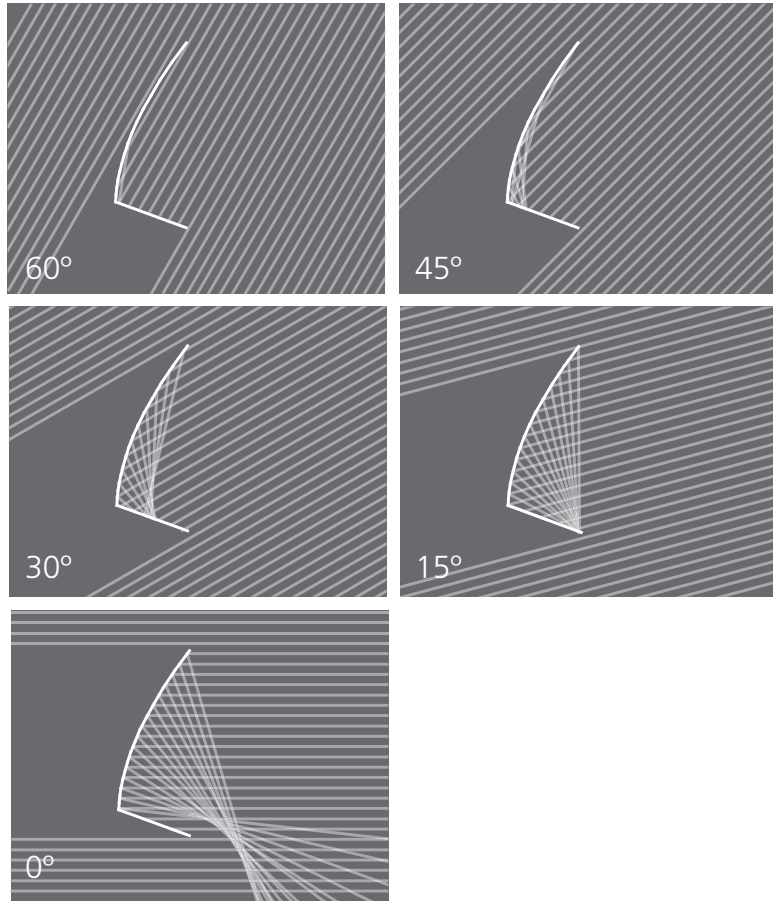


Figure 7.9 The reflecting geometry of the Solar Window. The parabolic curve's symmetry axis is tilted from the horizontal plane according to the lower acceptance angle. With an absorber inserted at an inclination of  $20^\circ$ , the geometrical concentration factor is 2,45.

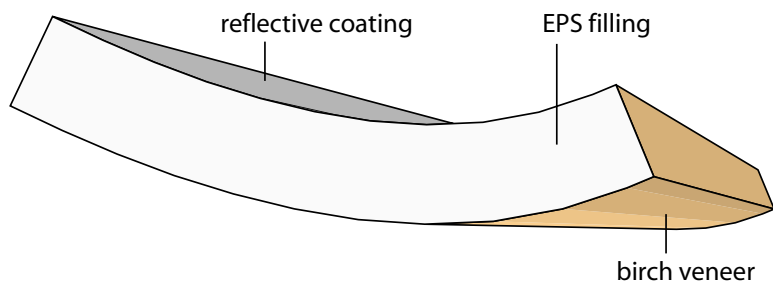
#### 7.4.4 Reflector construction

Figure 7.10 shows the reflecting effect for solar heights between  $60^\circ$  and  $0^\circ$ , by ray-tracing made manually in a CAD program. It is clear that the reflector is of no use for angles above  $60^\circ$  and below  $15^\circ$ , where the focus is on the tip of the absorber. The angles between  $15^\circ$  and  $60^\circ$  are hence called the acceptance angles for the reflector. However, the absorber is reached by irradiation at solar heights up to  $90^\circ$ . Hence, the system's acceptance angles are  $15^\circ$ - $90^\circ$ .



*Figure 7.10 Ray-tracing showing the concentrating effect of the reflecting geometry. The solar height varies from  $60^\circ$ , above which the reflector is not exposed, in  $15^\circ$  intervals down to  $0^\circ$ , where all radiation is reflected outside the absorber. At  $15^\circ$ , which corresponds to the tilt of the optical axis, the focus is on the outer edge of the absorber.*

The fixed absorber has a tilt angle of  $20^\circ$  to the horizontal plane. Hence, the geometrical concentration factor, i.e. the ratio between the glazed opening and the absorber area, can be calculated to 2.45. The curve is extruded horizontally as a trough, and the reflector is constructed as a sandwich composition with a 35 mm EPS core between the reflective film on the concave side and a birch veneer on the convex side, see figure 7.11.



*Figure 7.11 The reflector component is a sandwich construction with EPS between the reflective coating on the concave side and a birch veneer on the convex side.*

## 7.5 The PV/T absorber component

The hybrid absorber is fixed at an angle of  $20^\circ$  to the horizontal plane. An advantage of the reflecting geometry is that it can be said to be sun tracking in the sense that it gathers all incoming irradiation between the acceptance angles onto the absorber. However, the absorber itself should be tilted at an optimal angle, in order to work maximal, especially without the reflectors closed. The advantage of keeping the absorber fixed is that flexible connections for water and electricity would make the system more complex and fragile.

A 2 mm thick aluminium absorber has polycrystalline PV cells laminated on the upper side. The thickness reduces movements due to temperature differences, which otherwise puts the PV cells at risk of cracking. The aluminium profile is taken from a double profile with double water pipes, which was developed for a MaReCo hybrid collector (Helgesson et al, 2003). Water pipes are attached to the bottom for distributing active solar gains and for cooling the PV cells and the cavity between the window surface and the reflectors. They also serve as a supporting structure for the absorbers and the reflectors, and as the pivot for the reflectors. EPS insulation around the pipes also makes endings for the rotation of the reflectors, and connects the insulation of the reflectors into a continuous convection shield. The absorber is shown in figure 7.12.

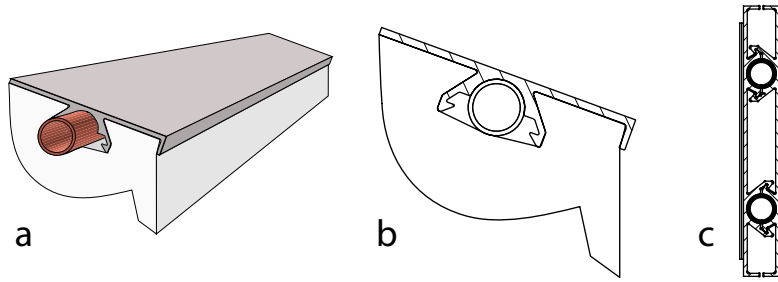


Figure 7.12 The PV/T absorber in perspective (a), section in scale 1:2 (b), and the original profile which the aluminium absorber derives from (c).

## 7.6 The design and construction of a prototype

A full scale prototype was constructed at the Älvkarleby laboratories of Vattenfall Utveckling AB, see figure 7.13. It is made with an IGU of 1.2 by 1.2 m and with five reflectors and absorbers. The window consists of six serieconnected black painted absorbers of a length of 1140 mm. The absorbers in this prototype have no PV cells, hence only the thermal properties can be measured.

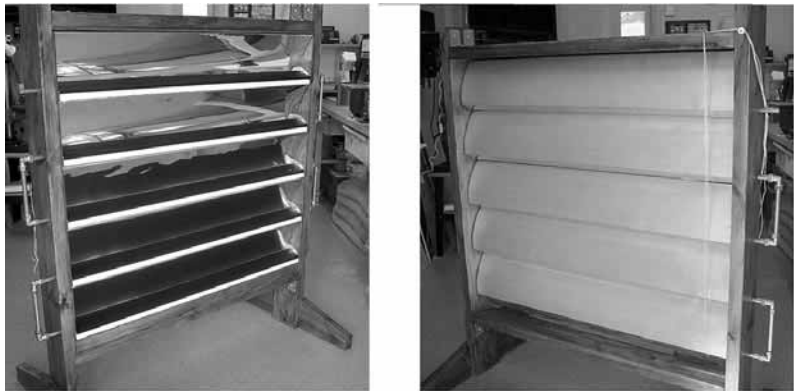


Figure 7.13 The full scale prototype of the Solar Window: front, opened (left) and back, closed.



## 8 Evaluation of the solar and thermal transmittance

A main characteristic of the Solar Window is to dynamically respond to the outer climate by maximising the usable solar gains and minimising the thermal losses. The Solar Window is in this chapter evaluated for its properties as a building component. From this perspective, it can be regarded as a normal window with added features, where the reflectors act both as solar shading and as internal insulation. This chapter discusses the estimation of the Solar Window's g-value, i.e. the total solar energy transmittance, and its U-value, i.e. a measure of the thermal losses one can expect from the interior towards the exterior. In chapter 11, the effect of these properties on the thermal balance of the Solar Window is analysed after introducing different control strategies for the reflectors' modes.

### 8.1 Simulation of the solar energy transmittance

The window consists of a double-pane insulating glass unit (IGU). The panes are proposed to have anti-reflective (AR) coatings in order to increase the active thermal and PV performance for a vertically orientated element. The insulating and solar-shading properties of the reflectors and the anti-reflective coatings are objects for evaluation. The g-value of a window determines the amount of irradiance let through the window, due to transmittance and absorptance. The transmittance (-) tells how much of the irradiance is directly transmitted through the glass, and the absorptance (-) tells how much of the irradiance is absorbed in the glass panes. The g-value is the sum of the transmittance and the share of the absorptance which is transmitted to the room, according to eq. 8.1 (Kvist, 2004).

$$g = (T_P + T_S) / I \quad [\text{Eq. 8.1}]$$

- $T_P$  is the primary transmittance, i.e. the ratio between what is directly transmitted through the glass and the insolation
- $T_S$  is the secondary transmittance, i.e. the ratio between the heat absorbed in the glass, which then reaches the room, and the insolation.

The g-value of the IGU with iron-free glass with AR coatings, used for the Solar Window, was simulated in the window/sunshade energy simulation program ParaSol (Kvist, 2004). The following parameters were used:

Glass emittance (front/back): 84%

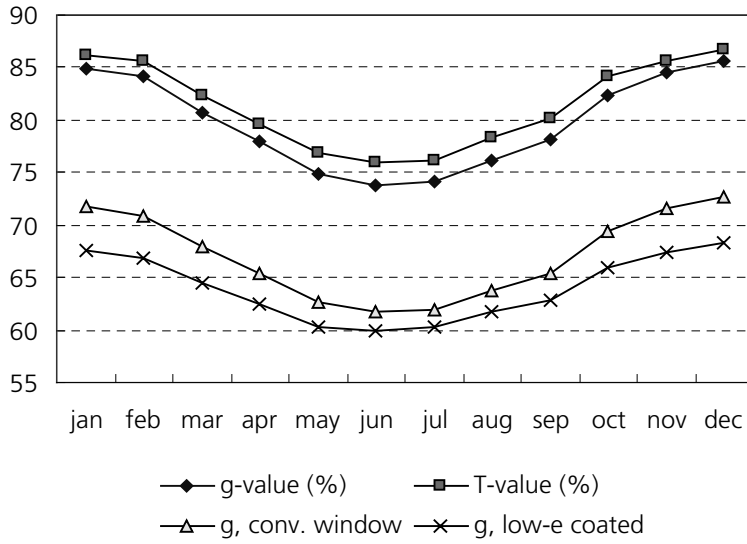
Glass transmittance: 94%

Glass reflectance: 2% for one surface (4% for non AR-coated glass)

Air gap: 12 mm

According to ParaSol, this results in a window U-value of 2.88, without any frame taken into account.

A simulation was made in order to determine the g-value for every month of the year. This is made by calculating the energy demand for the geometry into which the window has been put. One calculation is made with no sun taken into account, and one is made with the sun. The g-value is then calculated as the ratio of the difference between those results, and the irradiance. Due to reflectance and absorptance, the g-value varies with varying angle of incidence. Therefore, summer months with higher solar heights and a larger angle of incidence result in a lower g-value, and winter months with low solar heights and a smaller angle of incidence, give higher g-values. The simulation was made for Stockholm (lat 59.2°) with a south-facing window. Figure 8.1 shows how the mean g-value and T-value vary for every month. The annual mean values for g and T are 75.3 and 73.6% respectively. For comparison, the g-values of a conventional two-pane window with clear glass (U-value 2.88 W/m<sup>2</sup>K) and a window with a low-e coating of 10% emittance (U-value 1.66 W/m<sup>2</sup>K) were also simulated. The secondary transmittance is a small part of the total transmittance, approximately 3% in winter and 2% in summer.



*Figure 8.1 Monthly mean values of g and T for an AR coated IGU, compared with mean g-values for a clear glass and a low-e ( $e=10\%$ ) double pane window. The g-values are used in order to simulate the thermal performance of the Solar Window in chapter 11.*

ParaSol also has the ability to calculate the g- and T-values of a window combined with common solar shading systems available on the Swedish market. This could be used for simulating the solar shading properties of the Solar Window components, and hence the overall g-value for the system. However, it is problematic to translate the properties and geometry of the Solar Window to the input parameters used in ParaSol's user interface. Therefore, this has not been made. Instead, the thermal transmittance properties of the whole system has been modelled in a TRNSYS tool in order to simulate the combined performance of the Solar Window, see chapter 11. This model is based on the g-value simulated above, and on the U-values determined below.

## 8.2 Measurements of thermal transmittance

### 8.2.1 Background - Reflectors as internal insulation

Internal, temporary insulation of the windows is an added function of the reflectors. What one wants to achieve is to trap the solar heat gained through the window due to the transmittance, by reducing the conductive losses during night time through the relatively poorly insulated window. Demands for transparency are not important for an added insulation, since the most important properties of the window, daylight transmittance and view, are uninteresting during night time. Opaque insulation might rather be an advantage, since it prevents view inside, towards an artificially illuminated interior, which is more dominant during night time.

The thermal insulating property of a building element is described by its U-value ( $\text{W}/\text{m}^2\text{K}$ ), which describes the heat transmitted through  $1 \text{ m}^2$  of the element at a temperature difference of 1 K (or  $^\circ\text{C}$ ), according to equation 8.2:

$$P = U \cdot A \cdot (T_{\text{indoors}} - T_{\text{ambient}}) \quad [\text{Eq. 8.2}]$$

The U-value is the inverse of the sum of the thermal resistances (R) of every component in the element, and the heat transfer coefficients of the inner and outer surfaces ( $R_{\text{si}} + R_{\text{se}}$ ) of the element. For a homogenous material, R ( $\text{m}^2\text{K}/\text{W}$ ) is calculated as the material thickness, d (m), divided by its conductivity,  $\lambda$  ( $\text{W}/\text{mK}$ ), according to eq. 8.3:

$$R = d / \lambda \quad [\text{Eq. 8.3}]$$

Internal insulation used during night time can save considerable amounts of energy. An addition of an element with  $R = 1 \text{ m}^2\text{K}/\text{W}$  (equivalent to less than 40 mm of EPS) behind a two pane window can save 60, 66 and 85  $\text{kWh}/\text{m}^2$  window area annually in Malmö, Stockholm and Luleå respectively, provided that the added insulation is airtight and used every day between 8 p.m. and 6 a.m. between October and April (Adamson, 1986).

However, the insulation elements need to be practical in order to be easily applied and removed on a daily basis. Otherwise, the technique runs the risk of not being used at all, and hence becoming an investment of no use. However, the demands of flexibility and comfort might lead

to advanced and expensive solutions, which might diminish the intended energy gain, or substantially lengthen the payback time. Another great risk is the possible occurrence of condensation on the inside of the window, due to the cooling of the window resulting from its insulation from the interior. Hence the colder inner surface might not be able to carry the higher relative humidity.

In the Solar Window, the added internal insulation has other functions, such as solar shading and concentration of irradiance for the PV/T system. Hence, the added cost is low for this function. However, the technical integration of insulation material and the demand for airtightness contribute to making the system technically more complex.

### 8.2.2 Guarded hotbox measurements

With the reflectors closed, convection will occur between the window and the reflector and absorber. This makes it very complicated to calculate the U-value of the Solar Window theoretically. Hence, measurements of the thermal flow through the constructed prototype were made according to the hotbox method, described in the standard (ISO 8990, 1994). It describes a method for calculating the total heat transfer from one side of the object to another for a given temperature difference, by measuring temperatures in the hotbox, which can be calibrated or guarded. A guarded hotbox, which was chosen for the measurements, consists of two adjacent spaces, one hot and one cold space. The hot space consists of a measuring box, surrounded by a guarding box. A wall between the hot and cold space holds the object of measurement.

The work was carried out as a diploma work for a M Sc by Tobias Johansson. Here follows a brief summary of the work dealing with the U-value. For further details, see (Johansson, 2004).

The full scale prototype, described in 7.6, was put into a square shaped hole in the wall between the twin chambers at the laboratory of Energy and Building Design, see figure 8.2. The twin chambers are 21.6 m<sup>3</sup> each. The hot space contains a guarded measuring box, covering the hole and the heating coil, which was placed at the bottom of the measuring box. By keeping the same temperature in the measuring box and in the guarding box, all the thermal exchange will take place between the measuring box and the cold space, i.e. through the Solar Window. Hence, this exchange will correspond to the heat provided by the heating coil, which can be easily measured, due to the electricity source.

Thermocouples used for measuring the temperature at a specific point and thermopiles, used for measuring the temperature difference between two adjacent points, were placed on the prototype and on the surrounding

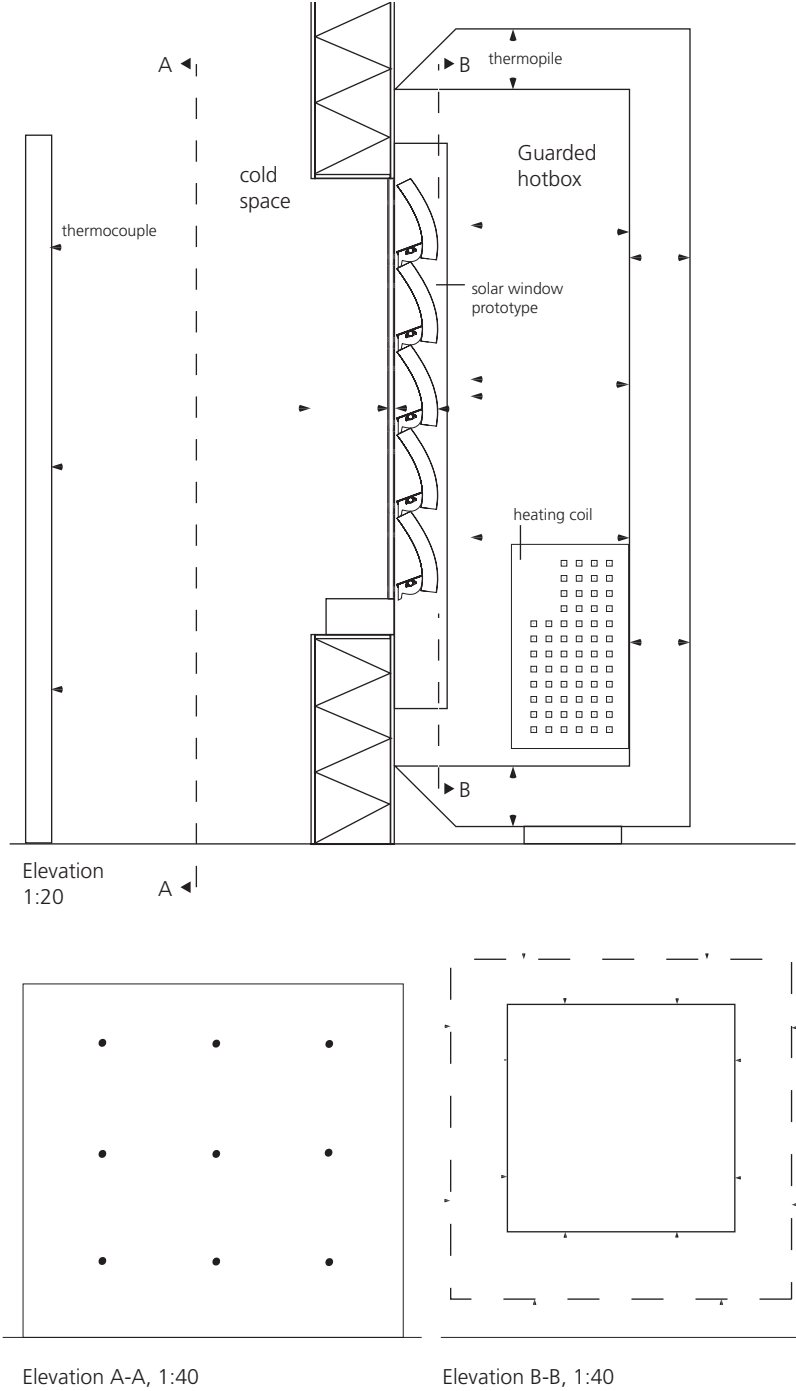


Figure 8.2 Elevation of the guarded hot-box used for U-value measurements according to ISO 8990.

walls according to figure 8.2. Measurements were made with thermocouples on the inner surface of the measuring box and on the surface of a screen in the cold space, facing the prototype, in order to determine the radiant temperature. Thermocouples were also used for the surface temperature of the window and the reflectors, and for measuring the air temperature in both spaces. Thermopiles were placed along the hole surrounding the prototype for calculating the heat flow through the frame, along the border of the measuring box for calculating the heat flow from this box to the guarding box, and finally in the wall of the measuring box in order to calculate the heat flow towards the guarding box. These calculations are used for compensating for these heat flows, when calculating the thermal flow through the prototype.

Calibration measurements were made in order to determine the thermal flow through the wall surrounding the prototype. For all measurements, constant temperatures of 5°C for the cold space and 21°C for the warm space have been kept. The lower temperature was achieved by using cooling fans, covered by screens in order to avoid disturbance to the measurements. Other fans have been used in order to simulate true climatic conditions.

The U-value is calculated according to Eq. 8.4:

$$U = \frac{Q_{win}}{A_{win}(T_{n2} - T_{n1})} \quad [\text{Eq. 8.4}]$$

$Q_{win}$  is the thermal flow through the window

$A_{win}$  is the area of the window (1.29 m<sup>2</sup>)

$T_{n1}$  is the environmental temperature in the cold space

$T_{n2}$  is the environmental temperature in the hot space

$Q_{win}$  is calculated according to Eq. 8.5:

$$Q_{win} = Q - G_{surr} \cdot \Delta T_1 - G_{box} \cdot \Delta T_2 - 3 \cdot Q_{2D} - Q_{1D} \quad [\text{Eq. 8.5}]$$

$Q$  is the power provided by the heating coil [W]

$G_{surr}$  is the conductance of the surrounding wall [0.45 W/K]

$G_{box}$  is the conductance of the measuring box [1.41 W/K]

$\Delta T_1$  is the air temperature difference between hot and cold space [K]

$\Delta T_2$  is the surface temperature difference between the inner and outer surface of the measuring box [K]

$Q_{2D}$  = two-dimensional thermal flow [W]

$Q_{1D}$  = one-dimensional thermal flow [W]

For details of these parameters, see (Johansson, 2004).

$T_n$  is calculated according to Eq. 8.6:

$$T_n = \frac{T_a \frac{Q_{win}}{A_{win}} + Eh_T (T_a - T_r) T_s}{\frac{Q_{win}}{A_{win}} + Eh_T (T_a - T_r)} \quad [\text{Eq. 8.6}]$$

$T_a$  is the air temperature [K]

$T_r$  is the radiant temperature [K]

$T_s$  is the surface temperature of the measured object [K]

$Q_{win}$  is the thermal flow through the window [W]

$A_{win}$  is the area of the window [1.29 m<sup>2</sup>]

$Eh_T$  is a coefficient [-], calculated according to Eq. 8.7:

$$Eh_T = \frac{\sigma (T_r^2 + T_s^2) \cdot (T_r + T_s)}{\frac{1}{\varepsilon_1} + \frac{1}{\varepsilon_2} - 1} \quad [\text{Eq. 8.7}]$$

$\sigma$  is the Stefan-Boltzmann constant =  $5.67 \cdot 10^{-8}$  [W/m<sup>2</sup>K<sup>4</sup>]

$\varepsilon_1$  is the emittance of the measuring box [-]

$\varepsilon_2$  is the emittance of the glass in the cold space [-]

For details of the parameters, see (Johansson 2004).

Tests were made for the window separately and with the solar window components attached with the reflectors in six different positions, with four intermediate opening angles between the fixed open or closed modes.

## 8.2.4 Results

Table 8.1 shows the results for the different measurements. The first measurement concerns the single double-pane window. Number 2 shows the result with the reflectors open, and 3 with the reflectors closed. In 4, gaps between the reflectors, due to a non-perfect prototype construction, have been sealed, and in 5 the gaps between absorber and window have also been sealed. In measurements 6 to 9, intermediate opening angles, shown in figure 8.3, have been used.

The prototype construction was not made sufficiently airtight, and some compensation was therefore made for this by sealing the gaps in its closed position. One measurement was made with the reflectors closed and sealed towards the absorber insulation, and another one also with added sealing between absorber insulation and window, in order to reduce the channel of cold downdraught to one individual module. These two steps made the U-value drop from 1.33 to 1.22 and 1.17 W/m<sup>2</sup>K respectively. Airtightness is hence an important criterion for further design studies.

Table 8.1 Results from the measurements, calculated according to Eq. 8.4. The area has a constant value of 1.29 m<sup>2</sup>.

	Angle	Q <sub>win</sub> (W)	T <sub>n1</sub> (°C)	T <sub>n2</sub> (°C)	U-value (W/m <sup>2</sup> K)
<b>1</b>	-	57,72	4,95	20,87	<b>2,82</b>
<b>2</b>	95°	51,82	4,86	21,40	<b>2,43</b>
<b>3</b>	0°	28,93	4,75	21,58	<b>1,33</b>
<b>4</b>	0°	26,20	4,80	21,53	<b>1,22</b>
<b>5</b>	0°	25,19	4,87	21,56	<b>1,17</b>
<b>6</b>	37°	37,33	4,96	21,74	<b>1,73</b>
<b>7</b>	47°	40,38	4,96	21,81	<b>1,86</b>
<b>8</b>	56°	44,97	4,83	21,68	<b>2,07</b>
<b>9</b>	66°	48,74	4,83	21,65	<b>2,25</b>

The double pane window separately represents a U-value of 2.82 W/m<sup>2</sup>K. It is interesting to note that the U-value is reduced by the addition of the reflectors and absorbers even when they are fully opened. This effect derives from the reduced convection due to interruption of cold downdraught. Hence, the effect of the open reflectors could be regarded as an added internal thermal resistance, which varies with the opening angle. As seen in figure 8.3, the U-value increases with increasing opening angle.

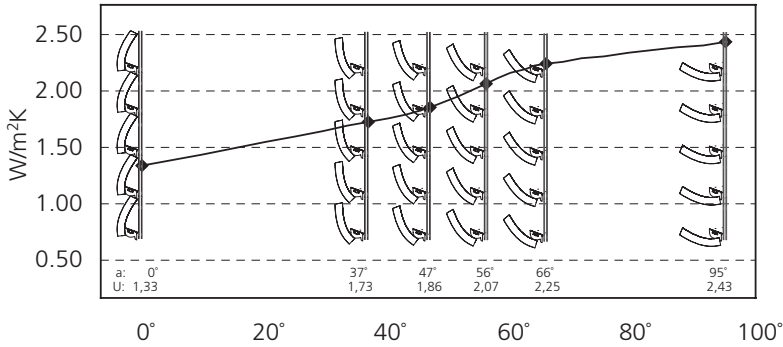


Figure 8.3 Measured U-values for different opening angles of the Solar Window. The U-value of the single window is 2.82 W/m²K.

### 8.2.5 U-value partitioning

In chapter 14, the passive thermal gains of the Solar Window will be discussed. Depending on whether the reflectors are open or closed, different ratios of the transmitted irradiance will reach the room. When the reflectors are closed during daytime, heat will be gathered in the air space between the glass and the reflector and absorber. When the temperature in these cavities exceeds the surrounding outer and inner temperatures, heat will be transported through the window and the reflector and absorber. In order to determine the ratio of incoming heat absorbed by the reflector and absorber that is transported backwards into the interior, the U-value of the reflector and absorber,  $U_{R,A}$  is needed. The U-value of the Solar Window is 1.2 W/m²K and the U-value of the window alone is 2.8 W/m²K. The thermal resistance of the Solar Window,  $R_{SW}$ , is the sum of the thermal resistance of the window,  $R_W$ , and of the reflector and absorber,  $R_{R,A}$ . Hence,  $U_{R,A}$  can be calculated as 2.0 W/m²K, according to figure 8.4.

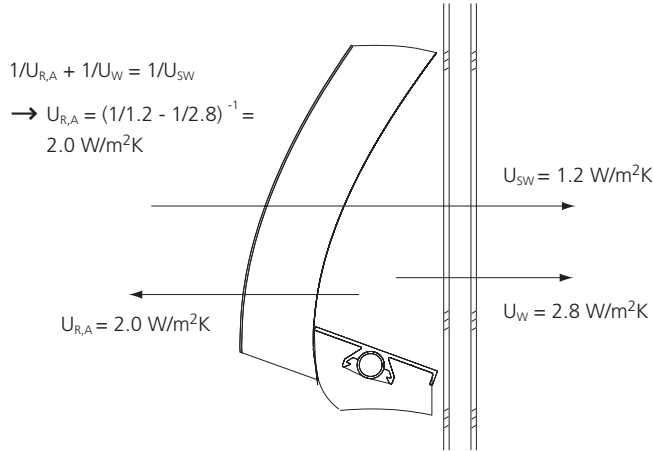


Figure 8.4 In order to determine how much of the absorbed heat goes into the room, the U-value through the reflector and absorber,  $U_{R,A}$ , was calculated as described above.

## 8.2.6 Discussion

The desire for maximal transmittance is achieved by AR coatings, at the expense of a higher U-value for the window. A low-e coated window has a considerably lower U-value, but also a lower transmittance. Hence, the gains of a high transmittance for the PV/T system must be weighed against the thermal losses caused by a high U-value. In this project, the PV and active heating performance have been prioritised in the design of the system. However, the high degree of building integration of the system demands that the overall energy performance, including passive gains and thermal losses, is maximal, so that the gain from the active systems is not reduced by losses due to a poor insulation.

Adding EPS insulation to the reflector screens has a considerable impact on the window's U-value. However, the Solar Window would benefit from an even lower U-value. In chapter 14, the effect of the U-value in relation to the solar gains is analysed. Since the window should have maximal transmittance, steps for a lower U-value should be taken in the design of the reflector screens. The measurements of the prototype showed a decrease in the U-value from 2,8 for the bare window to 1.2 with the reflectors closed and sealed. However, the reflectors in the prototype are connected to the absorber with thick aluminium sides, which make a considerable thermal bridge. Hence, the U-value can be expected to become lower with a more refined design of the connection between reflector and absorber. Regarding

the main geometry between the window and the interior, the reflector with the absorber can in theory have a U-value as low as  $(d/\lambda + R_{si} + R_{se})^{-1} = (0.036/0.035 + 0.17)^{-1} \sim 0.83 \text{ W/m}^2\text{K}$ . As discussed in the previous section, the actual U-value is more than twice as high in practice.

By using soft silicon tube profiles along the borders between reflectors and absorbers, and between absorbers and windows, airtightness is achieved in a vertical section of the Solar Window, see figure 8.5. The airtightness between reflectors and adjacent vertical studs is more difficult to achieve, and depends on the structure that the system is to be integrated into. For the house in Älvkarleby, with wooden studs, it is suggested that an element with a shape corresponding to the inner profile of the reflector, with a soft silicon tube profile attached, is fixed to the stud, as shown in figure 8.5.

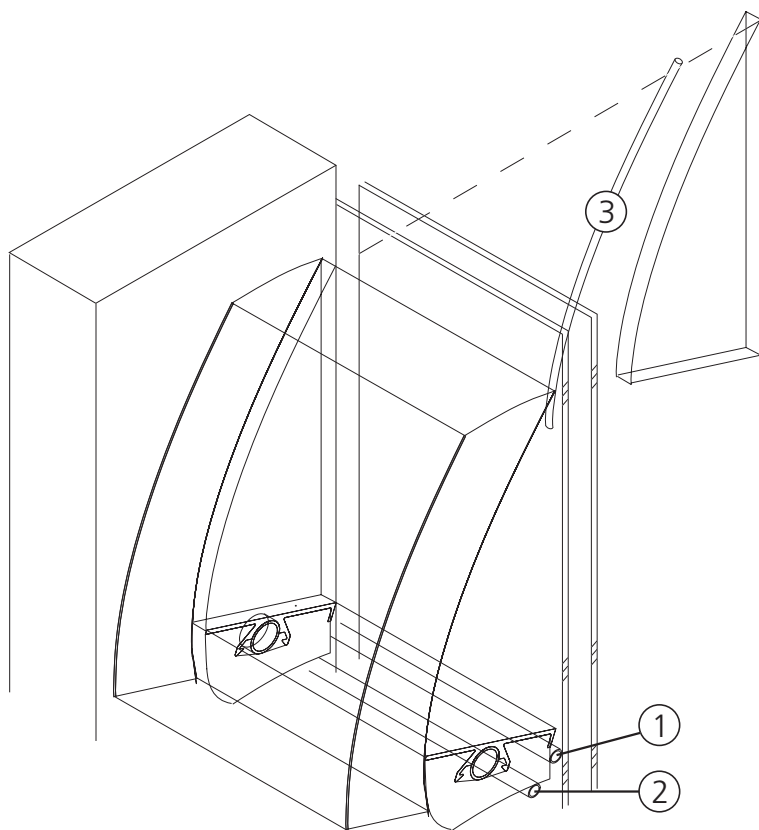


Figure 8.5 Illustration of how to achieve airtightness between window and absorber (1), reflector and absorber (2) and reflector and adjacent vertical stud (3) in order to achieve a low U-value.

## 9 Daylight and view

One important characteristic of the Solar Window is the idea to integrate daylight as a third form of solar energy into a PV/T system. Although this feature is included in the design and integration of semi-transparent PV panels, where the PV cells are mounted between two glass panes to allow daylight to enter in between, the Solar Window allows more control due to the possibility to close the reflectors. However, there can be a conflict between the desire for on one hand daylight and view and on the other hand optimal energy conversion for the PV/T system.

The Solar Window is examined for its visual obstruction of the view, the risk of glare from concentrated daylight towards the interior and the effect on the daylight factor on the room it is installed in.

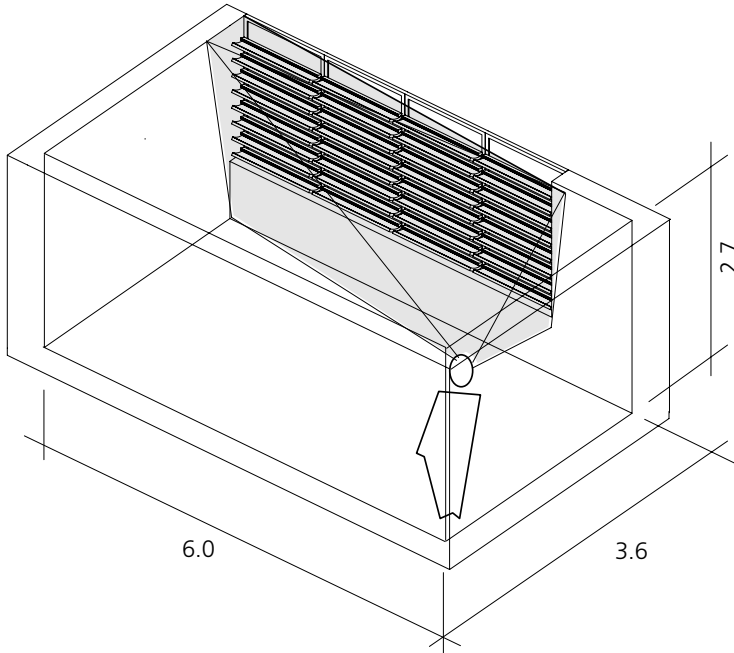
### 9.1 View obstruction

The presence of the absorbers and reflectors behind the window will obstruct the view towards the ambience, whether open or closed. For determining this visual impact, CAD and picture processing tools were used. A three-dimensional CAD model has been used to generate perspective views from the interior. This gives a good impression of how the system affects the view through the window.

#### 9.1.1 Method

A simplified 3D model of the living room of the single family house in Älvkarleby was made in a CAD program. Since this space has a rather complex shape within an open plan, and an opening in the slab towards the upper floor, the room was simplified to a box with the width 6.0, depth 3.6 and height 2.7 m. The Solar Window wall covers 4.8 m of the width and starts at the height 0.6 m, see figure 9.1.

The Solar Window system was modelled with the reflectors in the open mode for the interior perspectives. The perspectives were taken with the spectator's positions according to figure 9.1. As a reference, a rendering (i.e. a computer generated realistic image) was made with normal window openings, and a background picture simulating the view outside.



*Figure 9.1* Size of the room studied for the view obstruction of the Solar Window, and position of the spectator. The grey area indicates the picture plane in the renderings below.

### 9.1.2 Results

Figure 9.2 shows a comparison among the normal window opening, the open Solar Window and a standard internal Venetian blind with 25 mm slats in a horizontal position with the distance 22 mm for the different perspective points, in order to get a comprehensive impression of the visual impact.



*Figure 9.2 Three renderings for the same view to show the visual impact of the Solar Window system (middle). A Venetian blind with horizontal slats (below) is shown for comparison.*

The impression of the view outside is based on subjective judgement, depending on light quantities, the motive outside, and the amount of transparent area. The latter is the most objective and obvious criteria, and it can be quantified as a ratio of the unobstructed area to the area of the normal window. This was made in an image processing program, by reducing the rendered images depth to black and white, where white represents the view outside, see figure 9.3. Photoshop can then in a histogram calculate the number of black pixels, which makes it possible to calculate the ratio of the obstructing reflectors' area to the open window area. For the view presented, this ratio is 47%, which means that the transparent area as defined above is 53%.



Figure 9.3      *Simplified pictures of the renderings in figure 9.2 for estimation of the obstructing area.*

### 9.1.3 Discussion

The visual obstruction of the view through the Solar Window is either total or close to 50%. Compared to traditional solar shading devices, like e.g. Venetian blinds shown above, this is a high value. Whether this is acceptable for a window is a subjective matter, but with the other functions of the Solar Window taken into account, the obstruction might be considered as acceptable. However, the Solar Window is not intended for totally replacing ordinary windows, which are essential for providing proper view.

## 9.2 Estimation of glare

When turned down to the open mode, the reflectors function as a daylight redirecting device. The direct irradiance is reflected upwards, mainly onto the backside of the next reflector above, and then spread downwards. However, at low solar heights, there is a risk that the reflected light passes the reflector above and hence can hit the eye of a spectator standing close to the window.

### 9.2.1 Method

In order to determine how the reflecting geometry treats the daylight, a similar approach to the one used to determine the optical efficiency was used. A two-dimensional ray-tracing analysis was made by hand in a CAD program. Normals to the reflecting curve were drawn, by drawing a line outside the curve which for the other end snaps to the curve when being in the position of the normal. The normal then functions as the mirroring axis for the incoming radiation beams, since the incoming angle equals the outgoing (see figure 9.4). These normals were drawn for a large number of points along the curve, in order to mirror an even distribution of beams to see how they are distributed after the reflection. Two cases with the solar heights  $30^\circ$  and  $20^\circ$  were analysed to determine the critical solar height, under which the reflected, focused radiation will pass by the adjacent reflector.

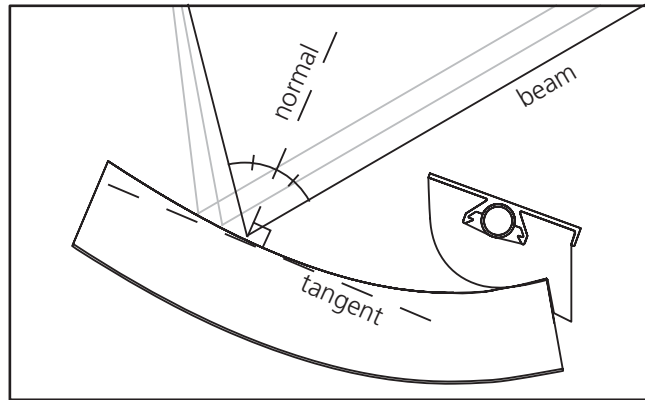


Figure 9.4 Method for manual ray-tracing in a CAD program. A normal is drawn towards the reflecting curve. This is the mirroring axis for the incoming beam.

### 9.2.2 Result

Figure 9.5 shows that all of the reflected irradiance of solar heights above  $30^\circ$  is distributed upwards to the next element above and then diffused. For solar angles at  $20^\circ$  and lower, there is a small risk of glare from the concentrated daylight. Figure 9.6 shows the effect of rotating the reflector  $5^\circ$  less downwards. This results in an approximately  $10^\circ$  lower solar height for direct light to pass by the reflector above, towards the ceiling. Figure 9.7 shows the optical performance of a set of three open reflectors. These

ray-tracing images were made from simulations in ZEMAX (ZEMAX Development Corporation, 2005), by Johan Nilsson, EBD.

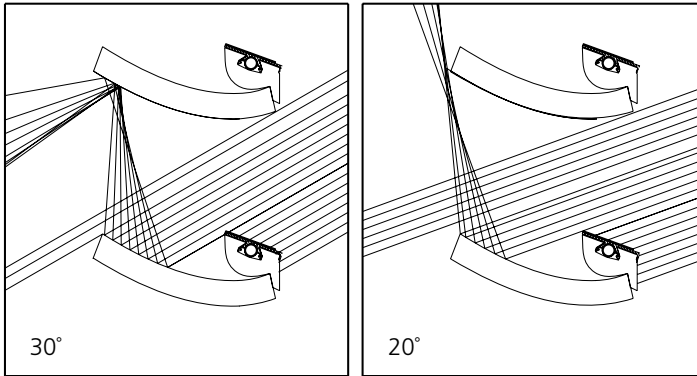


Figure 9.5 Ray-tracing image illustrating the distribution of direct radiation with the reflectors opened at a solar height of 30° and 20°.

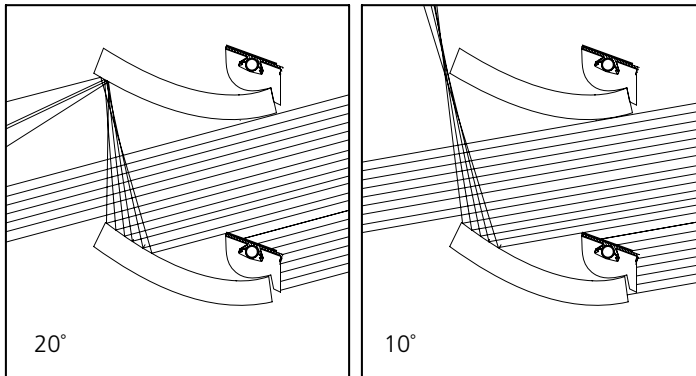
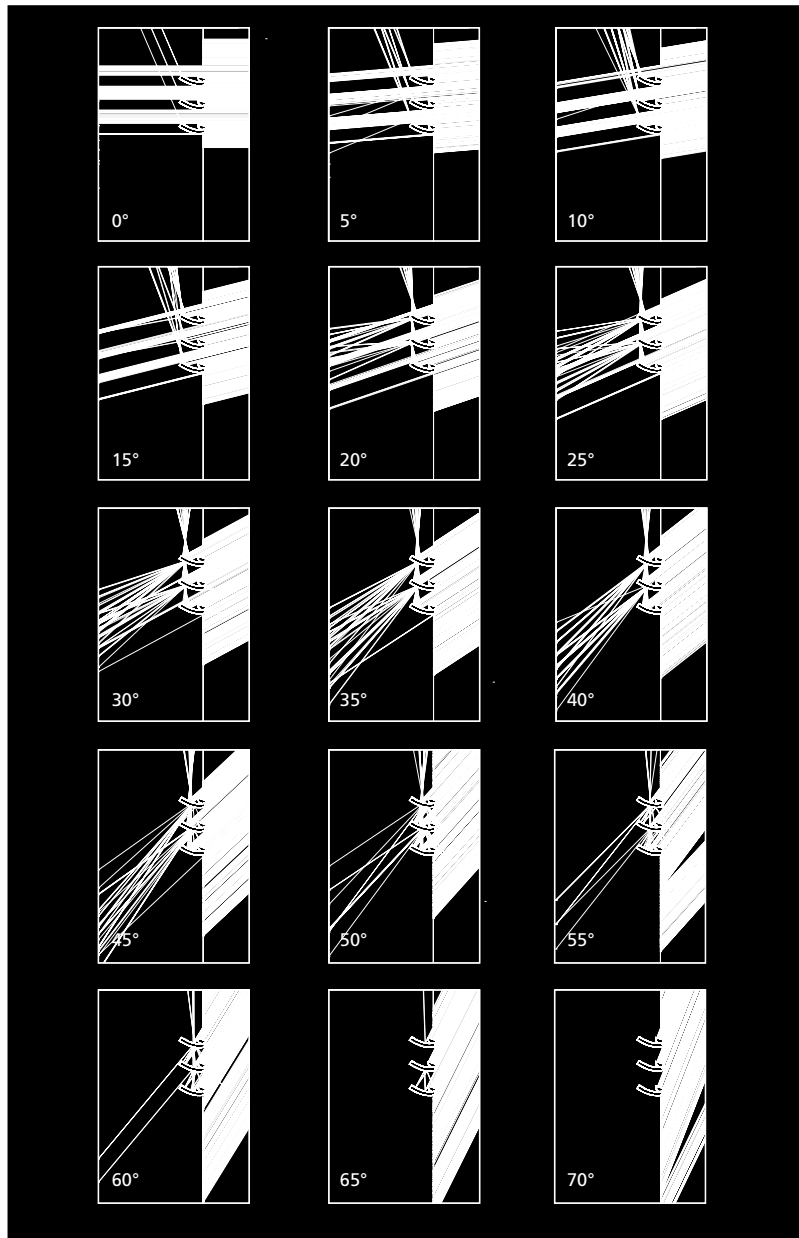


Figure 9.6 Ray-tracing images illustrating the effect of reducing the rotation of the reflector from 95° to 90°, so that the risk of glare occurs only at solar heights of 10° or less.

### 9.2.3 Discussion

As shown, there is a small risk of glare from concentrated sunlight at solar heights at 20° and below. According to figure 2.7, this occurs during the winter months (October to February) at all times for a latitude equal to that of Stockholm. Even though the concentration of the light rapidly diffuses



*Figure 9.7 The optical performance of a set of three open reflectors, for angles between 0 and 70°, generated in Zemax by Johan Nilsson, division of Energy and Building Design. At 20° and higher, the light is reflected onto the reflector above and diffused.*

to a level similar to the original situation at a distance of approximately 10 cm from the focus point, and then spreads even more, this phenomenon should be avoided by design measures.

The problem can be partly solved by reducing the rotation angle from  $95^\circ$  to  $90^\circ$ . A new ray-tracing analysis for this angle shows that the possible problem of glare occurs at solar heights of  $10^\circ$  or below.

This occurs during the whole day only during December and January, most of the day for November and for early mornings and late afternoons in October and February for the same latitude. However, it should be noted that “the whole day” (with daylight) in November lasts from 8.30 to 15.30 (and even shorter for December and January), when a residential house in most cases stands empty during the weekdays. Hence, for residential use, the risk of glare is mainly occurring during winter weekends and during mornings (during approximately one hour respectively) in February and October.

These ray-racing analyses give a clue on when problems can occur, but a judgement based on experience on site is essential, in order to determine whether this is a true problem or not.

## 9.3 Daylight

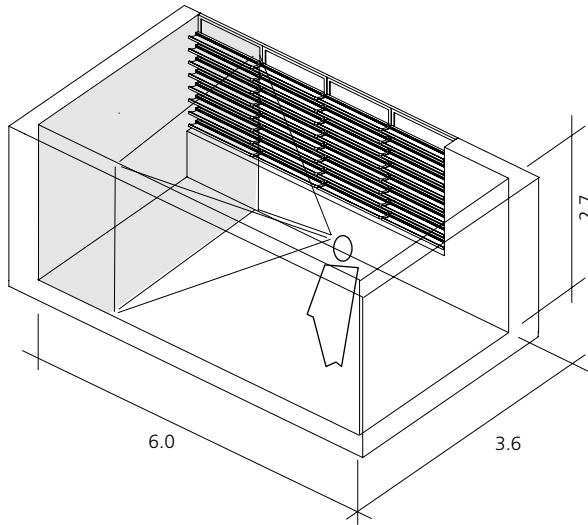
Due to the need of air-tightness to achieve a good insulating effect, the visual shading effect of the reflectors as sunshades in a closed position is obviously total. However, the visual shading effect of the reflectors in an open position needs to be evaluated.

When turned down, the reflectors can function as daylight redirecting devices, which reflect the sunlight upwards into the interior. By analysing this impact of the Solar Window at different situations, the quality of the system as a daylight shading and redirecting device can be evaluated.

### 9.3.1 Method

The daylight simulations of the Solar Window were made in the computer program Rayfront (Mischler, 2002), a user interface to the light rendering program Radiance. Radiance renders images based on a back-wards ray tracing of light from the surfaces of the model to the light source. The 3D geometry of the model was exported from ArchiCAD to Rayfront via the DXF format interface. The same model was used as in the view obstruction study in section 9.1, but the position of the spectator’s view was changed,

according to figure 9.8. The wall containing the Solar Window system faces south and contains 4 windows with 8 absorbers and reflectors each.



*Figure 9.8 The geometry of the room studied for the daylight simulations with the position of the spectator for the renderings, facing the western wall. The grey area indicates the picture plane in the renderings below.*

Renderings were made for three situations: summer solstice (21 June), and equinox (21 March/September) at three daily times: 8 a.m., noon, and 4 p.m. For the winter solstice (21 December), renderings were made for 10 a.m., noon and 2 p.m., due to the shorter day. The renderings were made for the fully open mode. The situation is Stockholm (lat 59.4°), and the model was orientated so that the Solar Window is facing south. The following parameters were used for the renderings:

Quality:	medium
Detail:	high
Variability:	high
Indirect:	high
Prenumbras:	false
Zone type:	interior
Sky:	intermediate sky with sun

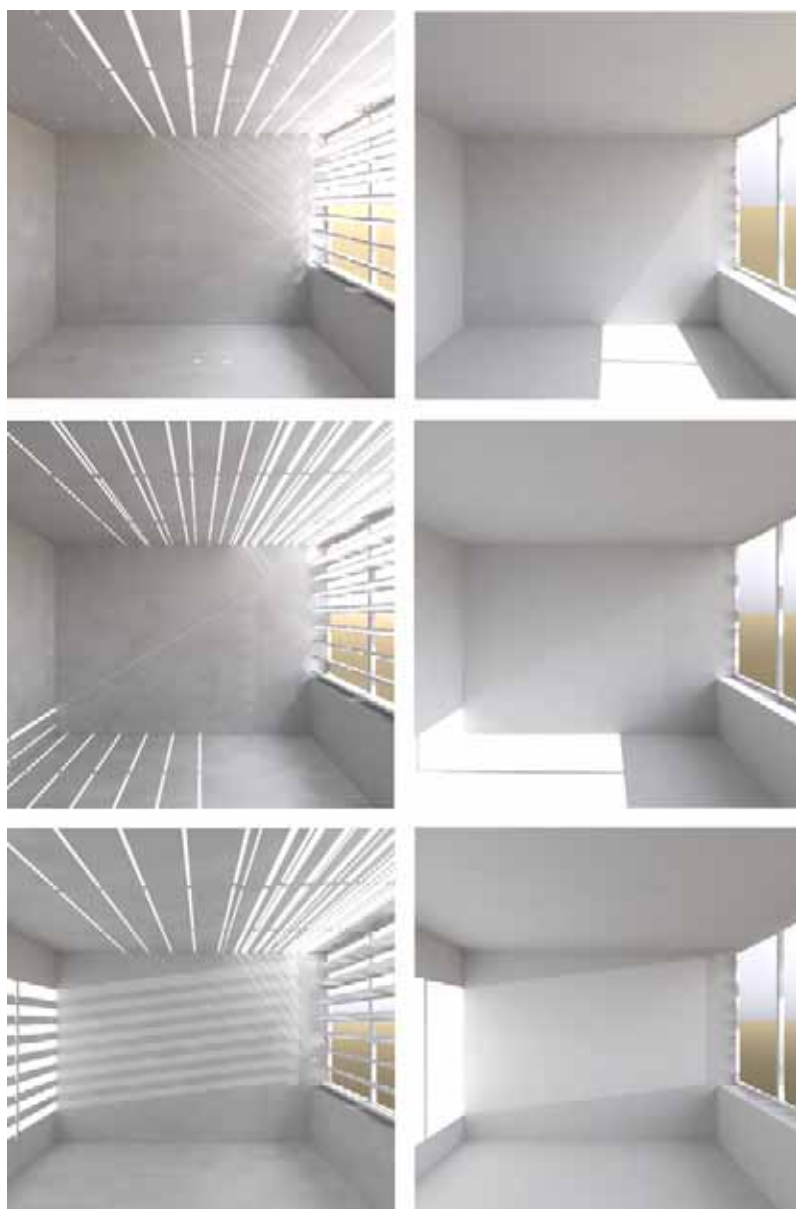
For comparison to a normal window, the geometry was rendered without the modules in the noon situations. Sky conditions are explained and discussed in (Bülow-Hübe, 2001).

### 9.3.2 Results

From renderings in Radiance, illuminance levels can be determined in the simulated room. Illuminance is the luminous (light) flux per area unit, measured in lux. The figures below contain the rendered images.



*Figure 9.9 Renderings made in Radiance/Rayfront of the east-facing wall. The first row shows the midsummer situation on June 21 at (left to right) 8 a.m., noon and 4 p.m. The middle row shows the equinox situations on March/September 21 and the bottom row shows the midwinter situation on December 21, at other times due to the shorter day: 10 a.m., noon and 2 p.m. The renderings were made with an intermediate sky with sun.*



*Figure 9.10 A comparison of renderings of perspectives facing the eastern wall with the noon cases for the open mode (left) and for the same amount of windows without the modules (right) for midsummer (top), equinox (middle) and midwinter (bottom). Renderings were made with an intermediate sky with sun.*

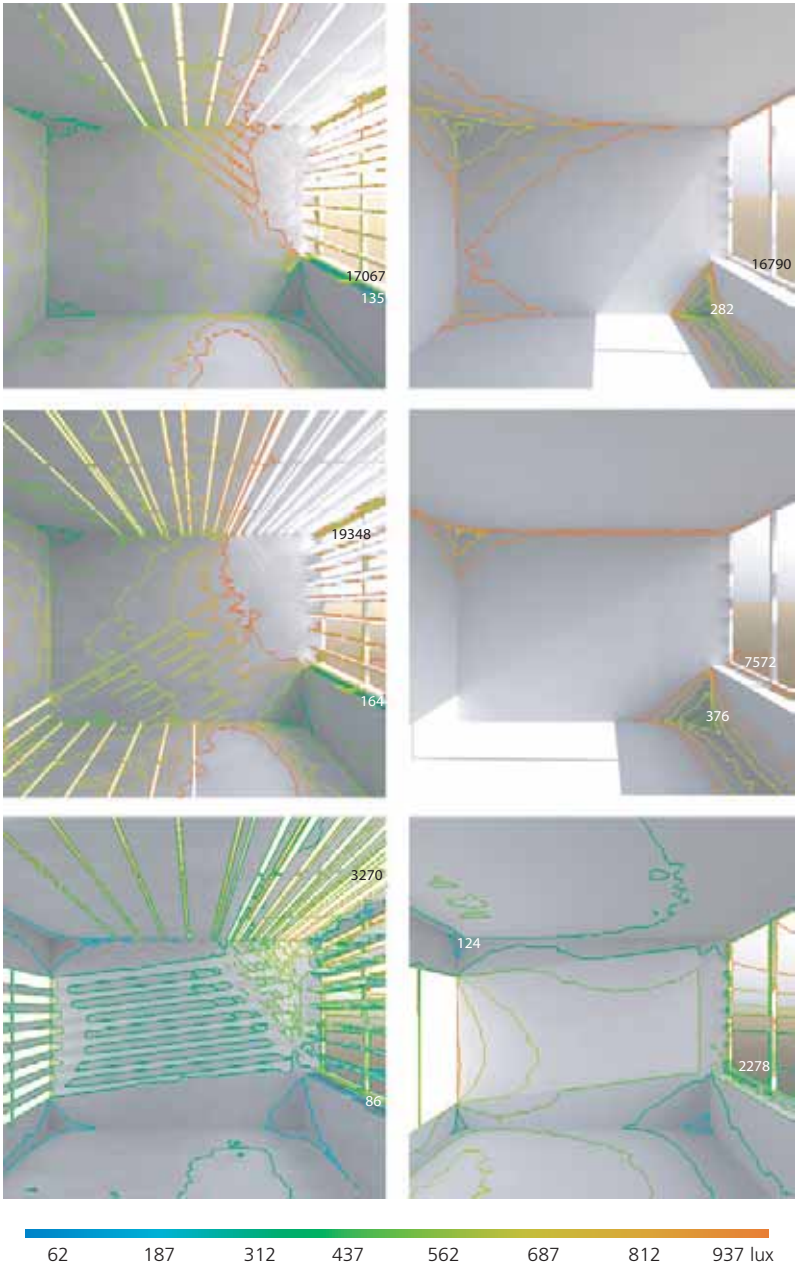
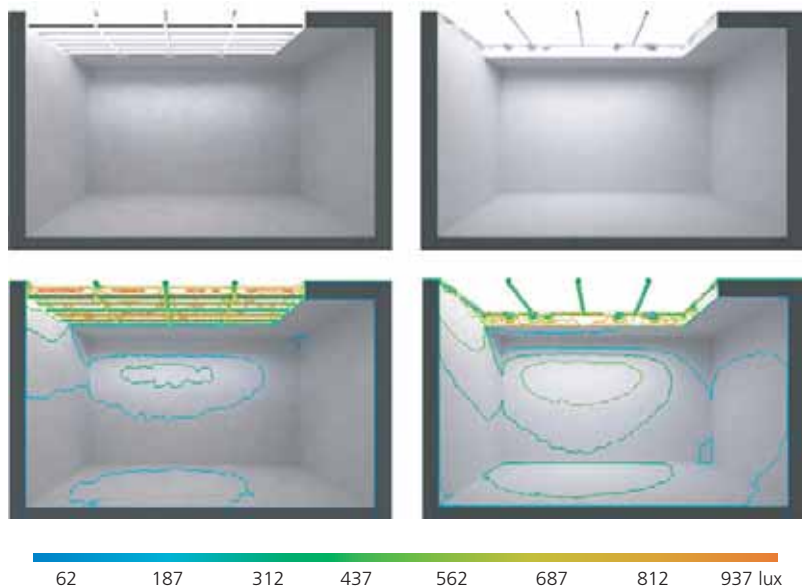


Figure 9.11     *Illuminance levels for the renderings in figure 9.10. The numbers in the pictures show the lowest and highest simulated values, and the colored lines show values according to the scale below.*

As seen in figure 9.9, direct sunlight reaches the room only at low solar heights. Here, this is visible when the direct irradiance goes almost horizontally into the room in the morning of equinox and winter solstice. For the other situations, the room is indirectly day-lit via the reflectors.

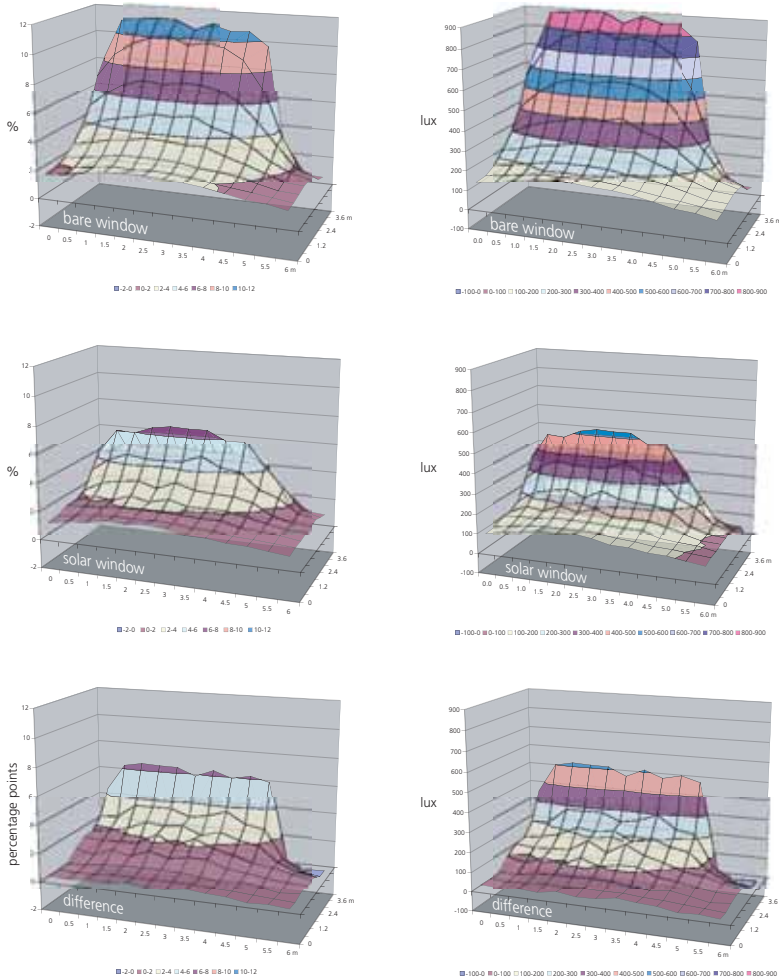
The light that hits the open reflectors is reflected either onto the backside of the next reflector above, or towards the ceiling, depending on the solar height, as discussed in 9.2. Among the examples in figure 9.9, it is only during the winter situations that the effective solar height is low enough for the direct irradiance to be reflected towards the ceiling. This can be seen as the hard contrast reflections along the ceiling in the bottom row renderings, as opposed to the gradient luminance, due to indirect irradiance.

Renderings were also made with a perspective facing the floor with all walls visible, see figure 9.12. These renderings were made with a cloudy sky, since they are intended to illustrate the daylight factor (where no direct sun should be present).



*Figure 9.12 Floor plans comparing the situation for 20 March, 10 a.m. with a cloudy sky. The numbers in the pictures show the lowest and highest simulated values, and the colored lines show values according to the scale below.*

Rayfront can also make numerical analyses of the illuminance and the daylight factor (the ratio between the indoor illuminance compared to the ambient condition) for a number of coordinates in a matrix representing a planar surface at a desired location. Calculations were made for the horizontal plane, 0.8 m above the floor. Figure 9.13 contains diagrams where the horizontal plane represents the floor area, and the back surface represents the wall containing the Solar Window, corresponding to the view in figure 9.1.



**Figure 9.13** Daylight factors (left) and the illuminance (right) of the floor of the room with bare windows (figure 9.12, right) and for the Solar Window. The bottom diagrams show the difference. Calculations were made for a cloudy sky (7530 lux outside) on March 20, 10 a.m.

The average daylight factor for the room with bare windows is 4.3%, which is reduced to 2.7% with the addition of the open reflectors and absorbers. The illuminance has an average value of 343 lux for the bare windows, and 210 lux for the Solar Window.

The same study was made for the ceiling, in order to see whether some of the diffuse daylight “lost” with the Solar Window modules is directed towards the ceiling. Figure 9.14 shows the results of this simulation, where the parameters are the same except for the vertical position of the horizontal plane (2.4 m), and the view direction of the plane (inversed).

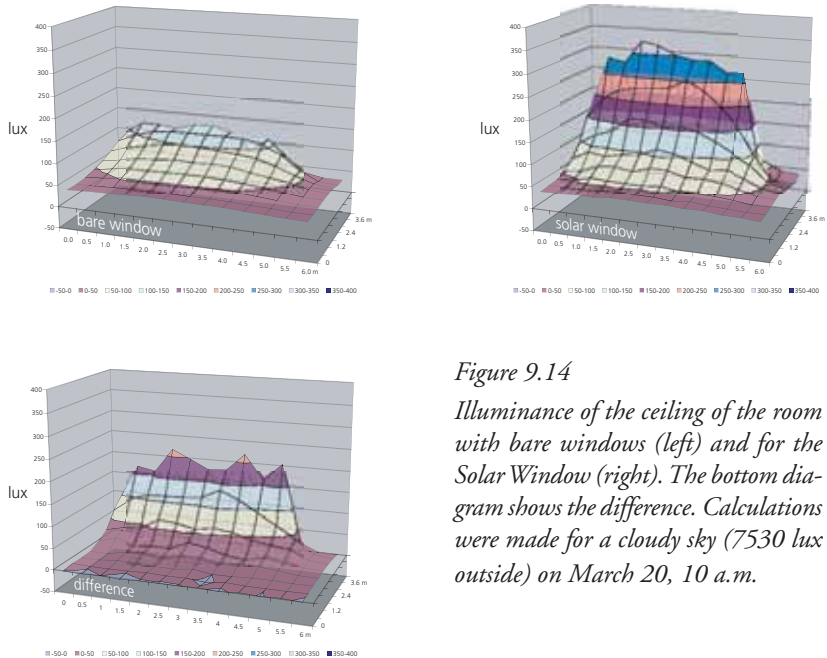


Figure 9.14

*Illuminance of the ceiling of the room with bare windows (left) and for the Solar Window (right). The bottom diagram shows the difference. Calculations were made for a cloudy sky (7530 lux outside) on March 20, 10 a.m.*

In the ceiling, the illuminance has an average value of 100 lux for the room with the Solar Window, which is reduced to 63 lux with bare windows. It is obvious that much of the daylight that normally would hit the floor in a room with normal windows, will be distributed towards the ceiling.

### 9.3.3 Discussion

The integration of PV/T absorbers and reflectors in the window has obvious effects on the daylight access for the interior. As expected, the ceiling is more illuminated with the Solar Window, compared to the same situation with normal windows. This is done at the expense of the illumination of the walls and floors, which are slightly darker. One can also note that the walls of the room with the Solar Window have less contrast between dark and bright areas, which might be more comfortable for the eye. However, architecturally this can make the room feel more flat.

An advantage with the effect of the internal illumination of the interior caused by the Solar Window might be the fact that the ceiling often is painted in a white colour, while the walls often have another colour, which obviously is darker. Since the distribution of daylight has an overweight for the ceiling with the Solar Window, a colour on the walls will have a smaller reducing effect on the daylight situation, than what would be the case with normal windows, since more daylight then would be absorbed by the walls. The same argumentation can be applied on the usage of darker paintings, furniture and carpets, which are obvious elements for any used space.

A clear disadvantage with the Solar Window is that the daylight does not reach as deep into the room as with normal windows. The avoidance of possible glare from concentrated light is done by letting the daylight hit the reflector above after reflection, which might require a smaller rotation angle. If there is no glare, it might be worth considering a larger rotation angle for the reflectors, so that the light of greater solar height would be allowed to go deeper into the room.

However, the most critical issue considering the daylight access is whether the reflectors are opened or whether they are closed, and obviously give no daylight. This choice is primarily dependent upon the desire for output from the PV/T absorber and the desire to shade from passive overheating. The balance between these features is further discussed in chapter 11.

# 10 Solar collector measurements

## 10.1 Introduction

The prototype described in chapter 7 was used for measurements, in order to determine the optical efficiency of the system and to develop models for simulations of the system performance. In chapter 11, a detailed model of the system is presented, based on a theoretical optical efficiency from ray tracing simulations and long time measurements presented in this chapter. The contents of this section is based on the work of Helena Gajbert, Johan Nilsson, Håkan Håkansson and Björn Karlsson at the division of Energy and Building Design, Lund University.

## 10.2 Solar thermal properties

The active thermal absorbers for water carried heat serves two main purposes; delivering heat for domestic hot water and possibly also for space heating, and cooling the photovoltaic cells in order to increase the electrical efficiency. As an indirect effect, it also reduces the heat load in the interior during summer by transporting away solar heat. The performance of this function is dependent on the optical efficiency, like the photovoltaic feature, but also on the collector's U-value.

### 10.2.1 Measurements and model design

The prototype described in 7.6 was installed on the testing roof in the Älvkarleby laboratory for long-term testing. The glazed area is 1,11 m<sup>2</sup> and the active area is 0,92 m<sup>2</sup>. An area of 1 m<sup>2</sup> was used during evaluation. The backside of the window was insulated by 70 mm EPS insulation.

The thermal performance of the window as a solar collector was evaluated with a method for dynamic testing. The parameters were derived by Multi Linear Regression of the following model (Perers, 1993):

$$P = \eta_{ob}K_{\tau\alpha}G_b + \eta_{od}G_d - F'U((T_{out} + T_{in})/2 - T_{amb}) - (mC)_e dT/dt$$

$$\text{where } K_{\tau\alpha} = 1 - b_o(1/\cos\theta - 1) \quad [\text{Eq. 10.1}]$$

#### Monitored Parameters

$P$	Power from collector (W/m <sup>2</sup> )
$G_b$	Beam Irradiance (W/m <sup>2</sup> )
$G_d$	Diffuse Irradiance (W/m <sup>2</sup> )
$T_{in}$	Inlet temperature (°C)
$T_{out}$	Outlet temperature (°C)
$T_{amb}$	Ambient temperature
$dT/dt$	Increase in the average temperature of the collector during the monitored period. (K/s)
$\theta$	Angle of incidence (°)

#### Parameters in the collector model derived by MLR

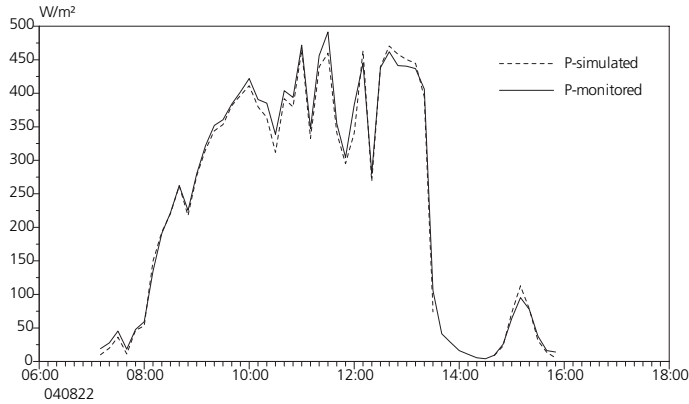
$\eta_{ob}$	Beam efficiency (-)
$\eta_{od}$	Diffuse efficiency (-)
$F'U$	Heat loss factor (W/m <sup>2</sup> K)
$(mC)_e$	Heat capacity of the window (J/kgK)

$K_{\tau\alpha}$	Angle of incidence modifier for beam irradiance
$b_o$	Angular coefficient

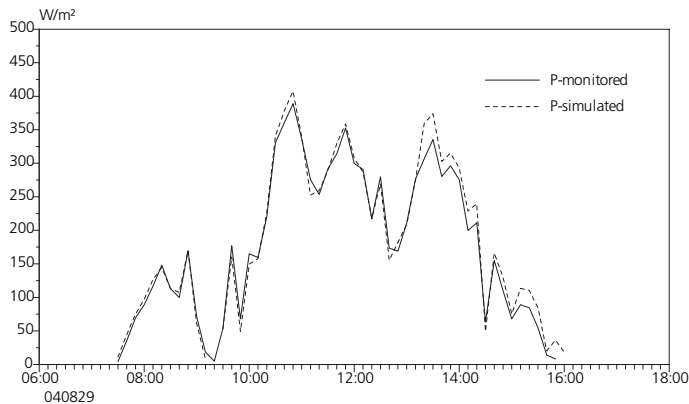
The following parameters were derived from the MLR during the period 2004-08-18 to 2004-09-05:

$$\eta_{ob}=0.81, \quad \eta_{od}=0.355, \quad U_I=3.84 \text{ W/(m}^2\text{K)}, \quad (mC)_e= 21585 \text{ (J/kgK)}, \quad b_o=0.235$$

Figures 10.1-10.3 show comparisons between the monitored data and the performance predicted by the model during three different days. Figure 10.4 shows a comparison between simulated and monitored power during the whole period. The figures indicate good agreement between monitored and simulated performance.



*Figure 10.1 Monitored and simulated thermal effect of the Solar Window 2004-08-22.*



*Figure 10.2 Monitored and simulated thermal effect of the Solar Window 2004-08-29.*

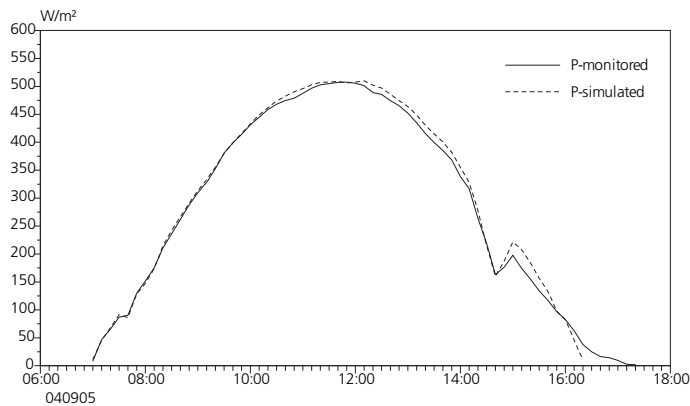


Figure 10.3 Monitored and simulated thermal effect of the Solar Window 2004-09-05.

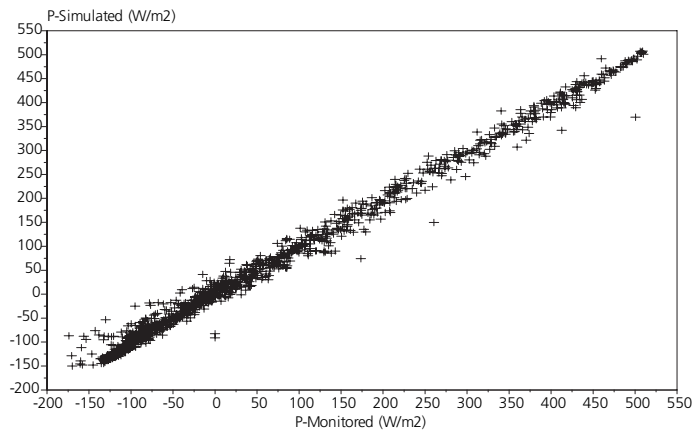


Figure 10.4 Correlation between monitored and simulated thermal effect of the Solar Window during the period 2004-0818 to 2004-09-05.

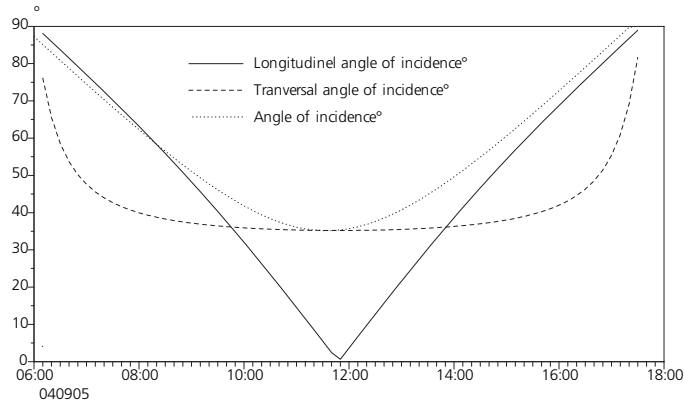


Figure 10.5 Angle of incidence, transversal angle and longitudinal angle during 2004-09-05.

The Solar Window has different angular dependence of the optical efficiency in the longitudinal and transversal direction. Figure 10.5 shows that the transversal angle  $\theta_T$  is nearly constant during the measurement period. This means that the  $b_o$  function essentially gives the angular dependence in the transversal plane. The angular dependence in the  $\theta_T$  direction is derived by ray-tracing and presented in figure 10.6. The impact of the lower acceptance angular  $15^\circ$  is clearly visible in the figure. When the radiation vector of the beam irradiance is below this angle the light impinging on the reflector will not reach the absorber.

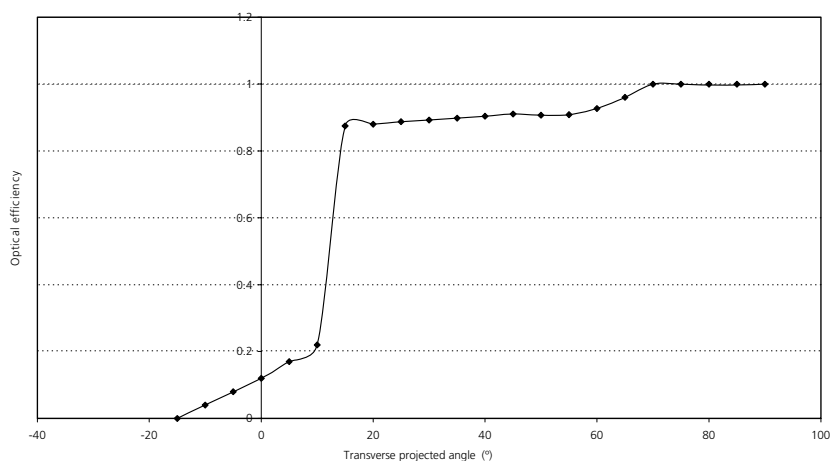


Figure 10.6 Angular dependence of the optical efficiency as a function of the transversal angle of incidence.

In order to consider the strong influence of the reflector in the transversal direction, the performance equation is extended by a biaxial angular function. The  $K_{\tau\alpha}(\theta)$  function gives the influence of the cover glass and the  $R(\theta_T)$ -function gives the influence of the reflector.

$$K_{\tau\alpha}(\theta_T, \theta) = K_{\tau\alpha}(\theta) \cdot R(\theta_T) = (1 - 0.19(1/\cos\theta - 1)) \cdot (0.85 + 0.0027 \cdot (\theta_T - 15))$$

The  $R(\theta_T)$  function is a linearization of the result from ray tracing, shown in figure 10.6, and the  $K_{\tau\alpha}(\theta)$  function comes from the thermal evaluation. They are adjusted so that the product is 0.81 at normal incidence and  $R(\theta_T=70)=1$ , since then the beam radiation will not see the reflector. This model gave a reasonable agreement with measurements during 2004-06-15 to 2004-09-06.

### 10.2.2 Solar collector U-value

In order to estimate a U-value for the prototype of the solar wall operating as a solar collector, measurements of the heat loss from the collector have been performed in a dark surrounding at different temperatures of the inlet water. The values of  $U_0$  and  $U_1$  were estimated to  $4.0 \text{ W/m}^2\text{K}$

and  $0.046 \text{ W/m}^2\text{K}^2$  and the resulting collector U-value as a function of  $\Delta T$  is shown in figure 10.4.

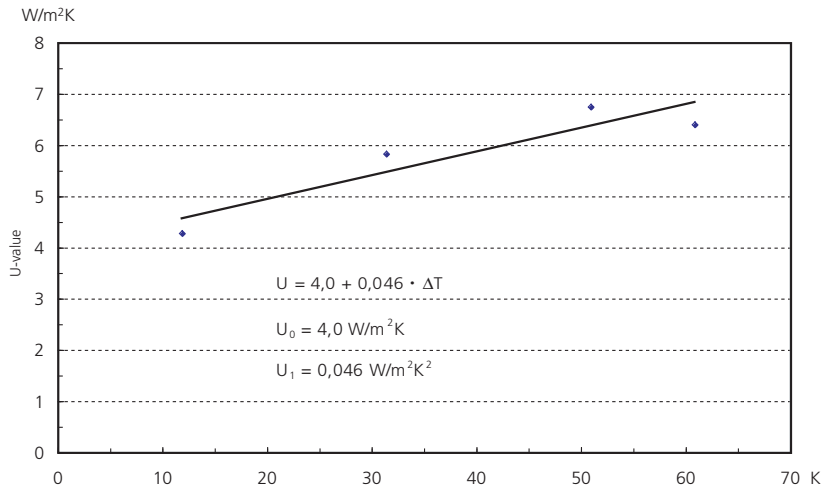


Figure 10.7 The U-value of the thermal collector as a function of  $\Delta T$ .

At  $\Delta T = 30 \text{ K}$ , the U-value is  $5.4 \text{ W/m}^2\text{K}$  per glazed wall area. During the measurements, the prototype was surrounded on both sides with the same temperature. However, in a building the back side of the window will usually be surrounded with air of higher temperature, thus the U-value will be lower in reality. Of the total heat losses during the test, approximately 10% are estimated border losses.

## 10.3 Photovoltaic properties

### 10.3.1 PV prototype

A small prototype with only one reflector was used for monitoring of the electrical performance, see figure 10.8. The hybrid absorber has a 50 mm poly-crystalline PV cell laminated on top of the heat absorbing aluminium profile. The components were assembled by a simple construction in MDF board, with a rounded bottom in order to virtually change the solar height during measurements.

The cell was cut in halves from a 100 by 100 mm poly-crystalline cell, although it was intended to come from a 120 by 120 mm mono-crystalline cell. This led to a 5 mm gap to the absorber's edges, which makes it difficult to directly predict the design's potential. This was partly solved by making it possible to move the absorber forward, in order to simulate the cell being in focus of the reflector's geometry.



*Figure 10.8*     *Single prototype for measuring the photovoltaic performance. Note the extended reflection of the PV cell in the reflector and the narrow strip of concentrated light on the absorber.*

### 10.3.2 Evaluation of electrical performance

The PV prototype was used for measurements during a clear and a cloudy day. An identical module mounted in the same plane as the aperture of reflector was used as a reference and the short circuit current  $I_{sc}$  of the modules was monitored. The results are shown in figures 10.9 and 10.10. Figure 10.11 and 10.12 show the correlation between the  $I_{sc}$  from the reference and the reflector module. It is visible that the concentration factor during a clear day is around 2.7 and during a cloudy day around 2. This result is in relatively good agreement with the optical efficiency of figure 10.6.

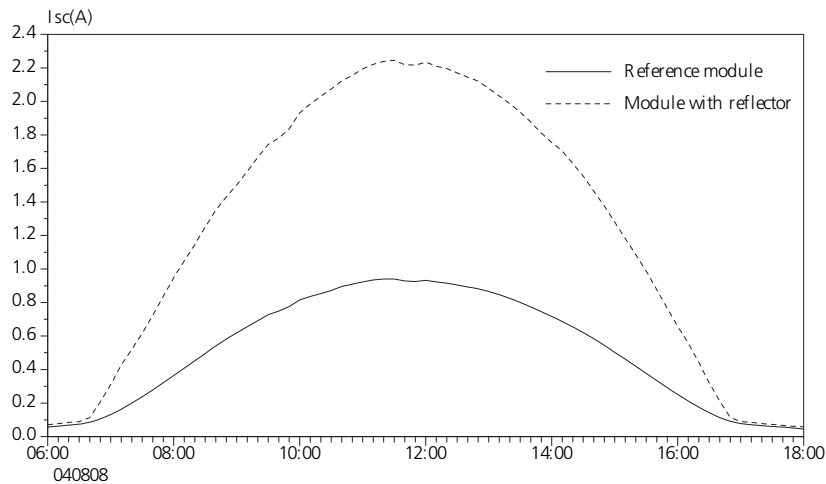


Figure 10.9  $I_{sc}$  for the reference and the reflector module during a clear day.

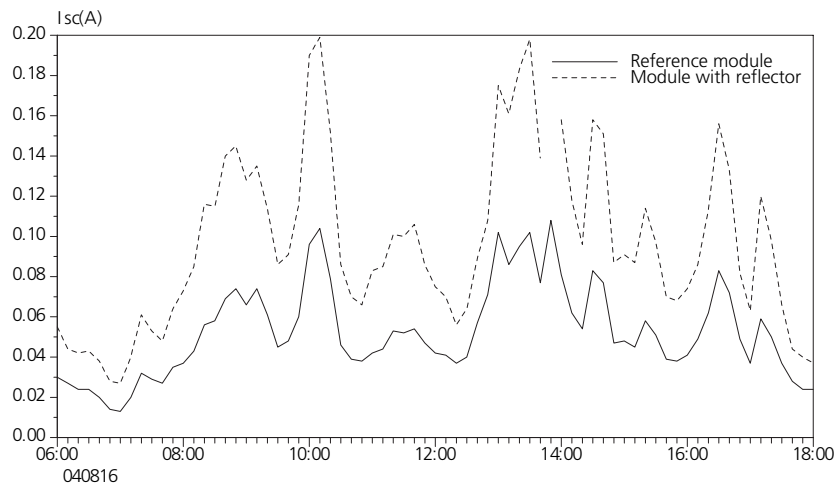


Figure 10.10  $I_{sc}$  for the reference and the reflector module during a cloudy day.

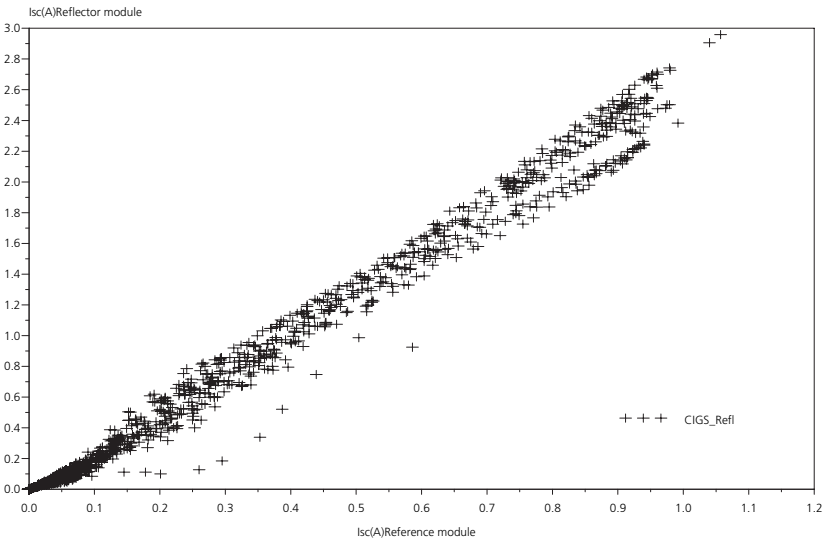


Figure 10.11 Correlation between Isc for reference and reflector module during all days.

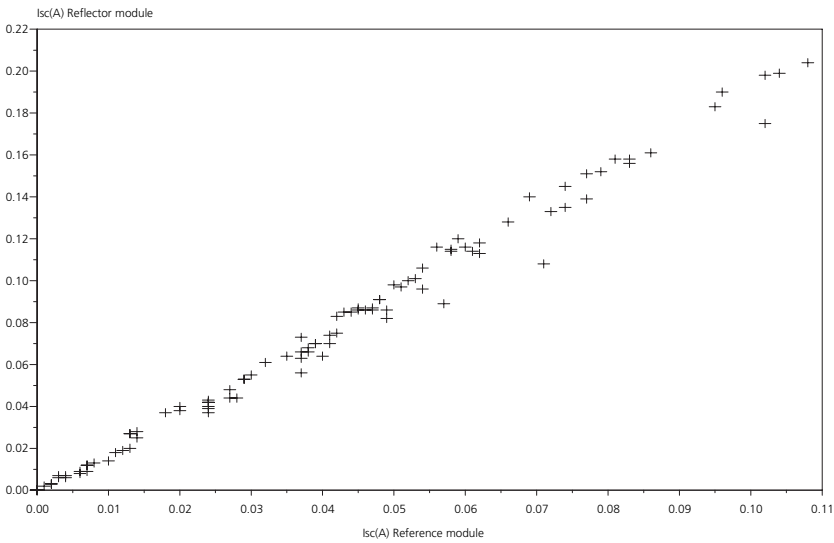


Figure 10.12 Correlation between Isc for reference and reflector module during a cloudy day with a diffuse sky..

# 11 Control strategies and simulations

The final distribution between the different forms of solar gains and thermal losses through the Solar Window, are dependent on how the system is controlled between the two reflector modes. The complexity also increases due to more subjective response from the users and their desire for thermal comfort, daylight and view. A closed reflector means higher PV and active heat performance, while an open reflector means more passive gains (including the risk of overheating), daylight and view outside.

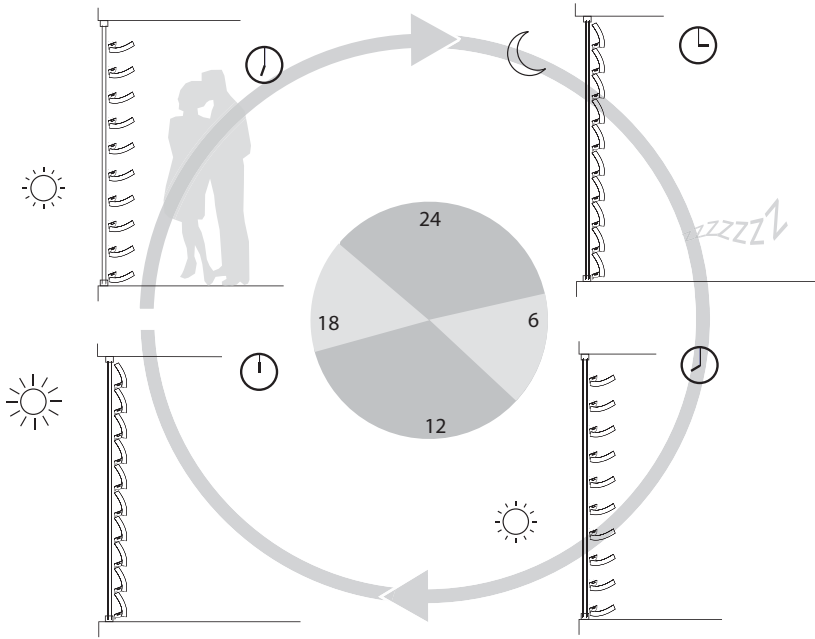
Within this chapter, some different control strategies, which can be used separately or combined, are discussed. A model of the whole system is developed, in order to identify suitable control strategies and to analyse the consequences of these. This model also contains more detailed sub-models of the PV and active heating performance, derived from the measurements presented in the previous chapter.

## 11.1 Possible control strategies

### 11.1.1 Time bound control

The system was initially designed for integration into a single family house, where most bright hours during weekdays are characterised by the absence of the inhabitants. A rough operating schedule for this situation is outlined: during morning hours, with low solar flux and high user activity, the reflectors can be opened to allow for daylight, view and direct passive heat gain. During solar peak hours, with family members being at work or at school, the reflectors can be closed for maximum active performance. Late afternoons and evenings have similar characteristics as the mornings, thus the reflectors are likely to be opened. For avoiding view inside (i.e. allow for privacy) and thermal losses during dark hours, the reflectors should be

closed until the next morning. When integrated into larger areas, zoning of the system allows for combinations of closed and open modules during this cycle, which is illustrated in figure 11.1.



*Figure 11.1 Illustration of a time-bound control strategy for the Solar Window in a single family house. The reflectors are opened during mornings, late afternoons and evenings, and closed during the rest of the day and night.*

### 11.1.2 Irradiance based control

Another operating strategy could be to automate the movement for the reflectors in response to the radiation intensity. It could be programmed for closure at radiation levels too high for thermal or visual comfort, or at levels too low for any practical use, e.g. at night time. Figure 11.2 illustrates the principle of controlling the reflectors in accordance with irradiance levels.  $I_L$  is the lowest irradiance level allowed for the reflectors being open, and  $I_H$  is the highest. As shown, this strategy aims at being more or less in accordance with the time-bound control strategy described above.

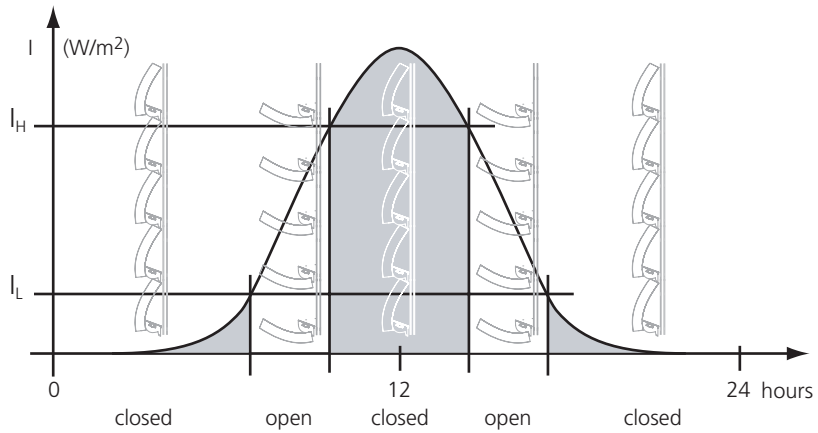
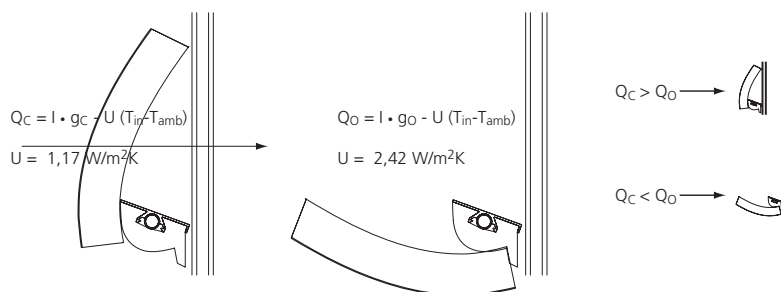


Figure 11.2 Illustration of a control strategy based on irradiance levels. The reflector is closed for high and low values, and closed at intermediate levels. This range is defined by the lowest irradiance level for opening,  $I_L$ , and the highest,  $I_H$ .

### 11.1.3 Thermal balance control

During winter months, the low irradiance gives little contribution to the performance of the PV/T system. Control based on irradiance levels will lead to too few hours of open reflectors, and hence daylight and view. It might be more suitable to regard the passive characteristics of the system, i.e. make use of the solar irradiance for passive heating, and hence keep the reflectors opened when the sun is shining and keep them closed when it is not, in order to reduce thermal loss. By calculating the thermal balance for every hour with the reflectors closed or open, according to figure 11.3, the most beneficial mode for the thermal balance is achieved. However, an automated regulation based on this model will be complicated since the temperatures also are needed as input for the control system, and a calculation needs to be made.



*Figure 11.3 Models for comparing the thermal balance  $Q$  of the Solar Window when the PV/T system is of little use. The most beneficial balance when open ( $Q_O$ ) or closed ( $Q_C$ ) determines the mode.*

#### 11.1.4 Combined control strategy

The presented models for controlling the reflectors are suitable for different purposes. For the part of the year when the PV/T system is in effect, the control strategy based on irradiance levels is the most suitable one. During the rest of the year, a model based on thermal balance might be more suitable. No matter what model is used, the desire of the user comes in first hand, which is hard to estimate in a simulation. However, from what was discussed in 11.1, a time schedule can simulate the desire for daylight and view when the house is generally occupied, i.e. during mornings, late afternoons and evenings. This schedule then overrules the irradiance or thermal balance based regulation schemes.

## 11.2 An evaluation tool for the Solar Window

The Solar Window system has a complex character since its performance is dependent on spatial, seasonal and user behaviour factors. The performance of the system as a PV system, thermal collector, sunshade and internal insulation are also interdependent, why an accurate model that concerns all these factors simultaneously for an hourly simulation of the system performance would be of great help for an analysis of the system's optimal geometrical design, constructional properties and control strategy. By using the energy flow simulation software TRNSYS (Klein, 1976), a model of

the system can be made for simulations and parametric studies. The model and its modules, described in 11.3.2.6, were written by Johan Nilsson at the division of Energy and Building Design, Lund University.

### 11.2.1 Model design

A system scheme describes the desired characteristics of the model, and how it could be used, see figure 11.4. The model is divided into the fixed parameters, which should be possible to adjust within the system code for alternative designs, and the input parameters, which should be possible to easily adjust within the user interface for every simulation. The fixed parameters include the “hardware” of the system, such as design characteristics like absorber and reflector geometry, window properties and U-values. These data are connected to the design of the system. The input parameters include “soft” data like climatic properties, control strategy and orientation of the system. These data are mainly concerned with the building integration of the system.

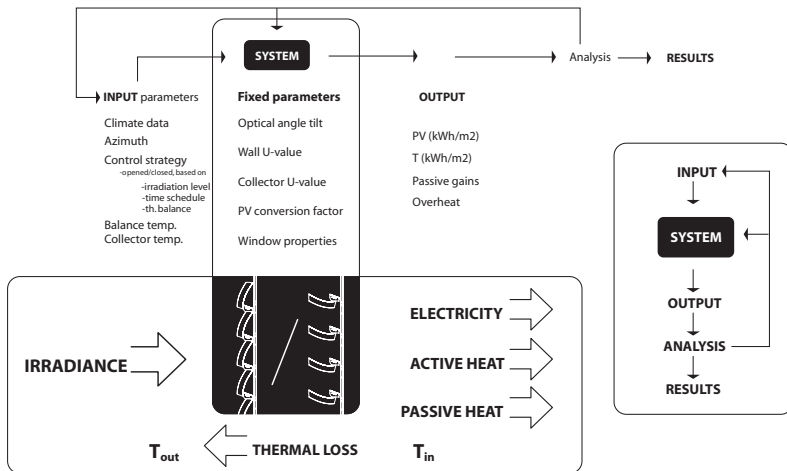


Figure 11.4 System scheme of the TRNSYS model of the Solar Window

The model processes the data, basically transforming the irradiance energy data to the three different energy forms: photovoltaic electricity, active thermal energy gains and passive thermal energy gains. The distribution on these forms depends on the nature of the irradiance, the outer temperature, the system design and the control mode of the reflectors. In turn, the mode of the reflectors depends on the climatic conditions.

## Fixed parameters – design criteria

### *Absorber area / absorber angle*

The size of the absorber with the attached PV cell determines the ratio of energy output for the system in an opened mode.

### *Optical angle tilt*

The tilt of the optical axis (i.e. the symmetry axis of the parabolic curve), from the horizontal plane, describes the span of solar heights in the transversal plane,  $\theta_T$ , which the concentrating geometry accepts. The higher the latitude, the lower the tilt.

### *Wall U-value*

The heat transfer coefficient for the whole Solar Window construction derives mainly from the composition of the IGU (insulation glass unit) and the reflector, and the air tightness between the reflectors. The U-value of the residential house application of the Solar Window has been measured in a hot-box, see chapter 8. Modifications of the design can however lead to different U-values. A characteristic for the Solar Window is the difference in U-value for the opened and the closed mode of the reflectors. Due to the convection reduction of the reflector in an opened mode, the Solar Window performs better even in an opened mode than the window itself.

### *PV conversion factor*

The efficiency of the PV cell is determined whether it is a mono- or polycrystalline cell or an amorphous thin film cell. Their efficiency is ~15, 12 and 7% respectively.

### *Window properties*

The windows' characteristics are essential for both the system's ability to transmit the solar irradiance to the PV/T absorber, and for the heat losses through the structure. The window's g-value describes the windows ability to transmit the irradiance, and is determined by the transmittance and the reflectance of the glass. The window's U-value is determined by the number of panes, the gas fill between the panes, the frame construction and material and the physical properties, i.e. the emittance of the glass.

## Input parameters – building integration criteria

### *Climatic data*

The performance of the Solar Window and its impact on the interior environment and the building's thermal balance is dependent on the climatic conditions surrounding the building. The climatic data should include global and diffuse irradiance and ambient temperature. It is normally contained in an hourly climate data file, read by the model. Data can be based on real measurements or generated by climate data software like Meteonorm (Meteotest, 2004).

### *Azimuth*

The impact of irradiance and its penetration through the window is dependent on how the system is orientated. For maximal performance, facing south is preferred on the northern hemisphere.

### *Control strategy*

PV and active thermal performance, thermal and visual comfort and thermal balance of the building also depends on the chosen control strategy for the system, i.e. to what extent the reflectors are opened or closed. This should depend on the climatic conditions and on the user's desire for thermal or visual comfort. Automation is compatible with the climatic conditions, where the control can be connected to a sensor registering the irradiance intensity. Since the user's comfort and desire is not likely to always match with the control derived from the irradiance level, the automation should be able to be overruled by manual intervention. The main aim of this evaluation tool is to test different irradiance levels for control of the system, in order to obtain an optimal balance between energy performance and user comfort.

### *Balance temperature*

Whether passive solar gains through the windows are of any use, or just surplus heat that must be ventilated away, depends on the buildings' balance temperature, i.e. the ambient temperature for which the building is in thermal balance and heat losses are balanced by the passive gains. If the ambient temperature is lower, the building needs heating, if it is higher the building needs cooling. A low balance temperature means lower auxiliary heat demand in a cold or temperate climate. However, a higher balance temperature means that the house gains more from solar irradiance during winter, and has less overheating during summer. The balance temperature

indicates for every hour in the simulations whether the passive gains are useable or leading to overheating.

## Output data

The model is designed to give six output data as a result for every simulation:

1. Active solar heat when closed (kWh/m<sup>2</sup>)  
The solar thermal function is assumed to operate only when the reflectors are closed, at high irradiance levels.
2. PV electricity output when closed (kWh/m<sup>2</sup>)  
The concentration with closed reflectors gives a higher performance.
3. PV electricity output when opened (kWh/m<sup>2</sup>)  
Since the PV cells remain in the same position, with open reflectors, a smaller but non-negligible performance is expected.
4. Passive (useable) gains with heating demand present (kWh/m<sup>2</sup>)  
Heat transferred through the structure when the ambient temperature is lower than the buildings' balance temperature.
5. Passive (overheating) gains with cooling demand present (kWh/m<sup>2</sup>)  
Heat transferred through the structure when the ambient temperature is higher than the buildings' balance temperature.
6. Indication of opened or closed reflectors (1=closed, 0=open)  
This value is used for determining the diurnal quantity of daylight, except for the values above. It also determines the thermal loss through the structure due to different U-values when open or closed.

All energy gains refer to the glazed area.

## Model design

In order to calculate the output parameters, a corresponding number of modules were designed by Johan Nilsson, EBD.

The following parameters for the irradiation are used in the models:

$I_{beam}$	is the direct irradiation on a surface normal to the irradiation (W/m <sup>2</sup> ).
$I_{diff, hor}$	is the diffuse horizontal irradiation (W/m <sup>2</sup> ).
$I_{tot}$	is the total irradiation on a vertical surface (W/m <sup>2</sup> ).
$\theta$	is the angle of incidence for beam irradiance.

*Active solar heat*

The active solar system is assumed to work only when the reflectors are closed, which, according to the control strategy, should correspond to a sufficient irradiance level.

Design parameters:

$T_{glass}(\theta)$ , the transmittance of the glass, depending on the angle of incidence, is derived as

$$T_{glass}(\theta) = \eta_{ob} \cdot K_{\tau\alpha} = \eta_{ob} \cdot \left( 1 - b_0 \cdot \left( \frac{1}{\cos(\theta)} - 1 \right) \right) \quad [\text{Eq. 11.1}]$$

$\eta_{ob}$	is the optical efficiency for beam irradiance normal to the glass, 0.92.
$K_{\tau\alpha}$	is the incidence angle modifier for the glass. $K_{\tau\alpha} = 1 - b_0(1/\cos(\theta) - 1)$ .
$b_0$	is an angular coefficient, 0.235, see 10.2.2.
$\eta_{0d}$	is the optical efficiency for diffuse irradiance.
$U_{in}$	is the U-value for the thermal loss from the absorber towards the interior, 2.0 W/m <sup>2</sup> K, from measurements.
$U_{out}$	the U-value for the thermal losses to the outside, 2.8 W/m <sup>2</sup> K, from measurements.
$(mC)_p$	is the thermal mass of the window when it works as a collector, 21585 J/K.
$\eta_{opt}(\theta_T)$	is the optical efficiency in the transversal plane, see figure 10.6. Taken from ray tracing.
$f$	is the share of the aperture area exposed for transmittance (175 mm/200 mm=0,875).

Input parameters:

$T_{in}$	indoor temperature (20°C).
$T_{coll}$	solar collector temperature (60°C)
$T_{waterin}$	temperature of the water entering the system (from file or constant).
$T_{amb}$	ambient (outdoor) temperature (°C, from climate data file).

The output is calculated according to equation 11.2:

$$P_1 = \left( T_{glass}(\theta) \cdot \eta_{opt}(\theta) I_{beam} + \eta_{diff} \cdot I_{diff, hor} - \frac{p_2}{0,87} - U_{in} \cdot \left( \frac{T_{coll} + T_{waterin}}{2} - T_{in} \right) - U_{out} \cdot \left( \frac{T_{coll} + T_{waterin}}{2} - T_{amb} \right) - (mC)_p \cdot \frac{\partial T}{\partial t} \right) \cdot f \quad [\text{Eq. 11.2}]$$

Only values above 0 are delivered as output.

The model assumes that the pump starts when  $P_1 > 0$ , and stops when  $P_1=0$ .

$P_2$  is described below.

### PV electricity

Design parameters:

- $T_{glass}(\theta)$  is the transmittance of the glass, depending on the angle of incidence, described above.
- $\eta_{opt}$  is the system efficiency at a specific solar height, see figure 11.5. Taken from ray tracing.
- $\eta_{diff}$  is the measured diffuse optical efficiency, 0.355

Input parameters:

- $\eta_{PV}$  is the cell efficiency (-), depends on the chosen PV cell. For a polycrystalline cell in this case, 15% .
- $f$  is the fraction of the aperture area exposed for transmittance (175 mm/200 mm=0,875).
- $r$  is the ratio between the absorber area and the glazed area, 72/200=0.36

For the closed mode, the PV electricity output is calculated according to

$$P_2 = \left( T_{glass}(\theta) \cdot \eta_{opt}(\theta_T) \cdot I_{beam} + \eta_{diff} \cdot I_{diff,hor} \right) \cdot \eta_{PV} \cdot f \quad [\text{Eq. 11.3}]$$

For the opened mode, the delivered PV electricity is calculated according to

$$P_3 = \eta_{PV} \left( f \cdot I_b \cdot \cos(\theta) \cdot T_{glass} \cdot \eta_{ob} + I_{diff,hor} \cdot f_{a,diff} \cdot r \right) \quad [\text{Eq. 11.4}]$$

$f_{a,diff}$  is the absorber's fraction of the horizontal diffuse irradiation. It was derived as (the transmittance of the glass (at normal incidence))<sup>no of panes</sup> · (transmittance for diffuse irradiation) · (part of the sky seen by the cell) =  $0,95^2 \cdot 0,9 \cdot 0,46 = 0,37$

The part of the sky seen by the cell (0.46) was derived by integrating the cosine of the incidence angle, between 0 and 67°, according to eq. 11.5.

$$\frac{\int_0^{67} \cos(\theta_T) d\theta}{\int_0^{180} |\cos(\theta_T)| d\theta} = 0.46 \quad [\text{Eq. 11.5}]$$

This means that with no optical losses, the cell will receive 46% of the horizontal irradiance.

### *Passive gains and overheating*

Design parameter:

- $f$  is the fraction of the aperture area exposed for transmittance. (175 mm/200 mm=0.875)
- $g$  is the g-value in monthly mean values, derived in section 9.1

For the opened mode, the passive heat gain is calculated according to

$$P_4 = I_{tot} \cdot g \cdot f - P_3 \quad [\text{Eq. 11.6}]$$

For the closed mode, the passive heat gain is calculated according to

$$P_4 = 0.42 \cdot (I_{tot} \cdot g \cdot f - P_2 - P_1) \quad [\text{Eq. 11.7}]$$

The constant 0.42 derives from the measured U-value of the Solar Window (1.17 W/m<sup>2</sup>K) and the U-value of the window alone (2.8 W/m<sup>2</sup>K), which gives a U-value from the reflector to the room of 2.0 W/m<sup>2</sup>K, according to figure 9.4. Hence, the ratio of incoming heat absorbed by the reflector and absorber that is transported backwards into the interior is 2/(2+2.8) = 0.42.

If the ambient temperature is higher than the balance temperature of the building, the passive gains are classified as overheating. One output parameter shows the passive gains  $P_4$  ( $T_{amb} < T_{balance}$ ), and one shows the overheating  $P_5$  ( $T_{amb} > T_{balance}$ ).

#### *Open or closed reflectors*

The mode of the reflector is indicated as 1 for closed or 0 for opened. With control determined by irradiation, the input of  $I_L$  and  $I_H$  determines whether the reflectors are closed or opened:

$$P_6 = 1, \text{ for } I_H < I < I_L \quad [\text{Eq. 11.8}]$$

$$P_6 = 0, \text{ for } I_L < I < I_H \quad [\text{Eq. 11.9}]$$

A time schedule can overrule these settings, so that the reflectors are opened or closed at specified periods of the day.

## 11.3 Parametric studies with the evaluation tool

The aim of the parametric studies of the TRNSYS model of the Solar Window is to obtain the optimal control strategy for obtaining a good balance between photovoltaic energy output, domestic hot water output, passive heating, minimized passive overheating and a maximum of hours

with open reflectors for daylight and view outside. In theory, this factor could also be quantified in terms of energy, due to saved electric energy for artificial lighting. However, this is complicated to estimate and is dependent on the type of space behind the Solar Window and how it is used. It is enough to accept the desire for maximum supply of daylight and not least view outside. Passive heating in its useable form and as overheating are hard to estimate the impact of, since they are dependent on the context. However, they are treated as an energy post (the useable form as a positive value and the overheating as a negative one), when the energy outcome factors are summed up for a comparative analysis.

Simulations were made for a south-facing Solar Window with the climatic data for Stockholm, described in chapter 2.

Besides the results from the model, the heat losses through the whole structure were calculated for every hour. The calculations were made according to

$$Q_{o/c} = U_{o/c} (T_{in} - T_{amb}) \quad (\text{Wh/m}^2) \quad [\text{Eq. 11.10}]$$

$Q_o$	is the thermal loss when the reflector is open
$Q_c$	is the thermal loss when the reflector is closed
$U_o$	is the U-value of the open Solar Window, 2.42 W/m <sup>2</sup> K
$U_c$	is the U-value of the closed Solar Window, 1.17 W/m <sup>2</sup> K
$T_{amb}$	is the ambient temperature, taken from the climatic data
$T_{in}$	is the indoor temperature, set to 20°C

Parameters for the simulations:

$T_{in}$	is the indoor temperature, set to 20°C
$PV_{eff}$	is the cell efficiency, set to 15%
$T_{bal}$	is the balance temperature of the building, set to 13°C

### 11.3.1 Model results for always closed reflectors

Table 11.1 shows the output parameters  $P_1$  to  $P_5$  and the thermal losses  $Q_c$ , if no control strategy is used, and the reflectors are closed for the whole year ( $P_6=8760$ ). Since  $P_3$  refers to PV performance with open reflectors, this column is empty.

Table 11.1 Results for always closed reflectors

	$P_1$	$P_2$	$P_3$	$P_4$	$P_5$	$Q_c$ (kWh/m <sup>2</sup> a)
jan	0	0,9	-	6,8	0	19,6
feb	0,7	2,6	-	13,3	0,1	17,9
mar	21,3	6,4	-	12,1	0,2	17,1
apr	28,1	7,7	-	9,2	1,6	12,8
may	27,3	8,4	-	6,2	5,0	7,9
jun	34,2	8,6	-	0,9	7,6	3,5
jul	25,5	7,6	-	1,0	8,37	2,2
aug	32,4	7,6	-	1,0	6,	3,1
sep	24,7	6,2	-	4,3	4,3	6,6
oct	4,0	3,2	-	9,5	3,3	10,7
nov	0,1	1,2	-	8,1	0,03	15,8
dec	0	0,6	-	5,5	0	16,8
<b>year</b>	<b>198</b>	<b>61</b>	<b>-</b>	<b>78</b>	<b>37</b>	<b>134</b>

### 11.3.2 Model results for always open reflectors

Table 11.2 shows the output parameters  $P_1$  to  $P_5$  and the thermal losses  $Q_c$ , if no control strategy is used, and the reflectors are open for the whole year ( $P_6=0$ ). Since the model assumes that there is no active solar yield ( $P_1$ ) when the reflectors are open, and  $P_2$  refers to PV performance with closed reflectors, these columns are empty. The values indicate that the annual PV performance drops from 61 to 40 kWh/m<sup>2</sup>, and that passive gains ( $P_4$  and  $P_5$ ) and thermal losses are substantially higher.

Table 11.2 Results for always open reflectors

	$P_1$	$P_2$	$P_3$	$P_4$	$P_5$	$Q_o$ (kWh/m <sup>2</sup> a)
jan	-	-	0,3	16,7	0	40,6
feb	-	-	1,0	33,9	0,2	37,0
mar	-	-	2,6	52,7	1,8	35,4
apr	-	-	4,7	43,9	12,9	26,4
may	-	-	6,6	24,2	31,5	16,3
jun	-	-	8,7	2,8	51,4	7,3
jul	-	-	6,0	3,1	46,3	4,6
aug	-	-	5,4	3,6	49,7	6,4
sep	-	-	2,9	18,9	29,8	13,7
oct	-	-	1,2	26,9	9,7	22,1
nov	-	-	0,4	20,1	0,1	32,6
dec	-	-	0,2	13,4	0,0	34,7
<b>year</b>	-	-	<b>40</b>	<b>260</b>	<b>233</b>	<b>277</b>

### 11.3.3 Control based on irradiance levels

Parameters:

$I_L$  is the lowest irradiance for open reflectors (W/m<sup>2</sup>)  
 $I_H$  is the highest irradiance for open reflectors (W/m<sup>2</sup>)

Simulations were made for  $I_L$  within a range from 10 to 90 W/m<sup>2</sup>, at intervals of 40, and for  $I_H$  between 100 to 400 W/m<sup>2</sup> at intervals of 50. The wide range was chosen in order to get a picture of how the system behaves for different settings.

Figure 11.7 shows how every output parameter is affected by the different combinations of  $I_L$  and  $I_H$ . It is obvious that the number of hours with open reflectors is heavily dependent on both the regulation parameters.

The active thermal performance ( $P_1$ ) is obviously only dependent on the upper limit, since this function is only in effect when the reflectors are closed, and make no use of such low irradiance levels that  $I_L$  is varying between. However, the upper limit is an important criterion for the active thermal output. An increase of  $I_H$  from 250 to 400 W/m<sup>2</sup>, leads to a performance drop from 170 to 131 kWh/m<sup>2</sup>, annually.

For the PV output ( $P_{2,3}$ ), the dependence upon the upper limit,  $I_H$ , is more important than the lower limit  $I_L$ . This can be ascribed the scale

difference between the ranges of  $I_L$  and  $I_H$ . Within a range of similar length, the difference is marginal. However, it is obvious that the more the reflectors are closed, the better is the output from the PV cells. For comparison with the active thermal performance above, an increase of  $I_H$  from 250 to 400 W/m<sup>2</sup>, with a constant  $I_L$  at 50 W/m<sup>2</sup>, leads to a performance drop from 53 to 48 kWh/m<sup>2</sup>, annually.

The passive thermal performance ( $P_4$ ,  $P_5$ ) follows the opposite trend compared to the active thermal performance. The lower the  $I_H$ , the more are the reflectors open and the higher are the passive gains. The sensitivity is also greater to  $I_H$  than to  $I_L$ , since the low irradiance levels give small passive gains.

The number of hours with open reflectors (6) obviously depends strongly on both  $I_L$  and  $I_H$ . Especially the choice of  $I_L$ , which does not have a large impact on the active energy yield, is sensitive in regard to the opening time.

Finally, the thermal losses through the Solar Window depend heavily on especially the  $I_L$  value. This is due to the lower ambient temperatures which generally occurs when irradiance is low.

### 11.3.4 Choice of regulation combinations based on irradiance in combination with control due to thermal balance

The diagrams in figure 11.7 show the trends which could be expected from the model. A high degree of closed reflectors results in a higher active solar output in the form of hot water, hence  $I_H$  should exceed 200 W/m<sup>2</sup>. The photovoltaic output slowly increases with a decreasing  $I_H$ . A high degree of open reflectors results in a higher passive heat gain and greater access to daylight and view, but also problems of overheating and greater thermal loss from inside out. The gains are sensitive to  $I_H$ , while the losses are sensitive to  $I_L$ . Hence, there is a conflict between keeping the reflectors open or closed, which makes it challenging to find a suitable control strategy.

The next step was to find a range of combinations of  $I_L$  and  $I_H$ , which show a good balance between active energy output and amount of hours with open reflectors. In order to find those combinations, the results from figure 11.7 must be studied together. First, the sums of the active energy gains were plotted against the amount of open hours, see figure 11.8. In this sum, the PV energy has been weighted by a factor of 4.2 due to the higher exergy value of electricity compared to heat (Coventry, 2003). Hence, the sum represents a *primary* energy conversion.

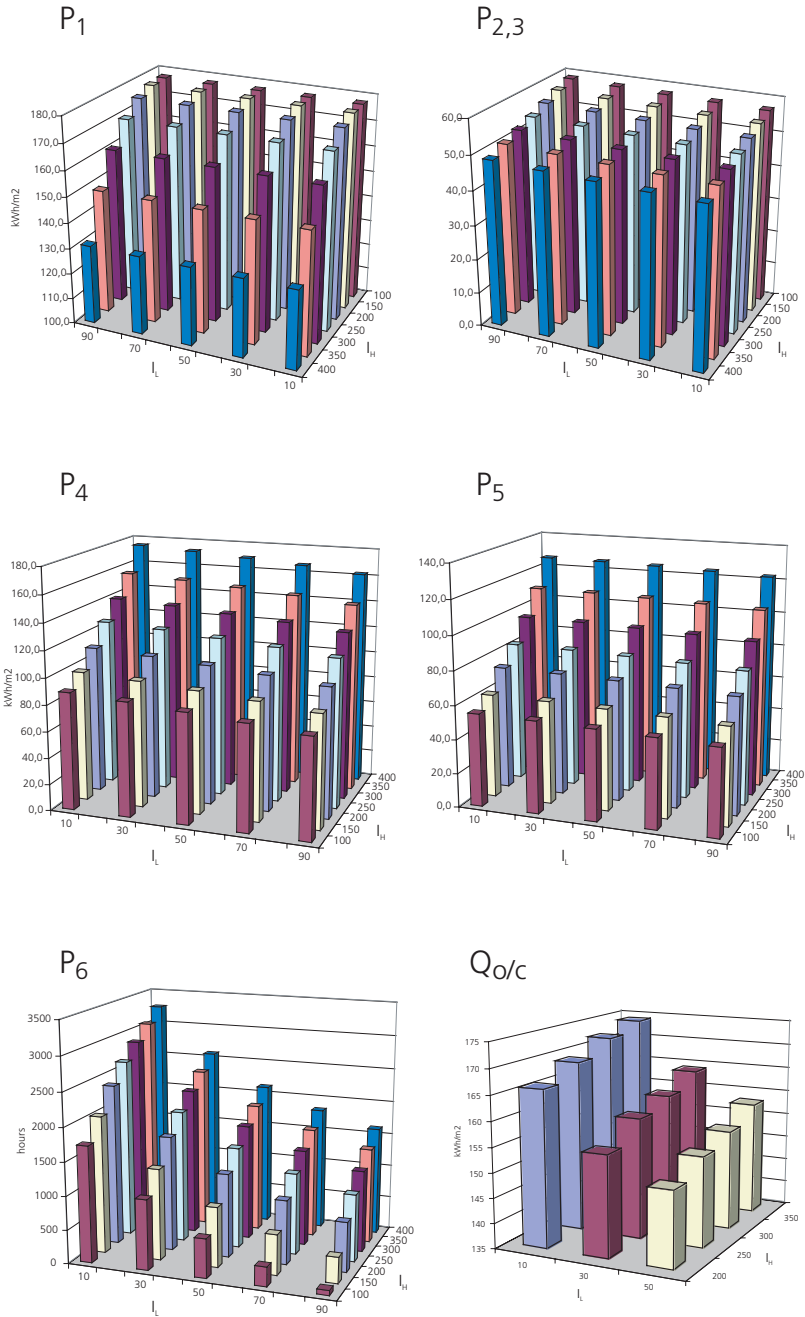


Figure 11.7 The relation between  $I_L$ ,  $I_H$  and active thermal ( $P_1$ ), PV ( $P_{2,3}$ ), passive heat ( $P_4$ ), passive overheat ( $P_5$ ), number of hours with open reflectors ( $P_6$ ) and thermal losses ( $Q_{o/c}$ ) annually.

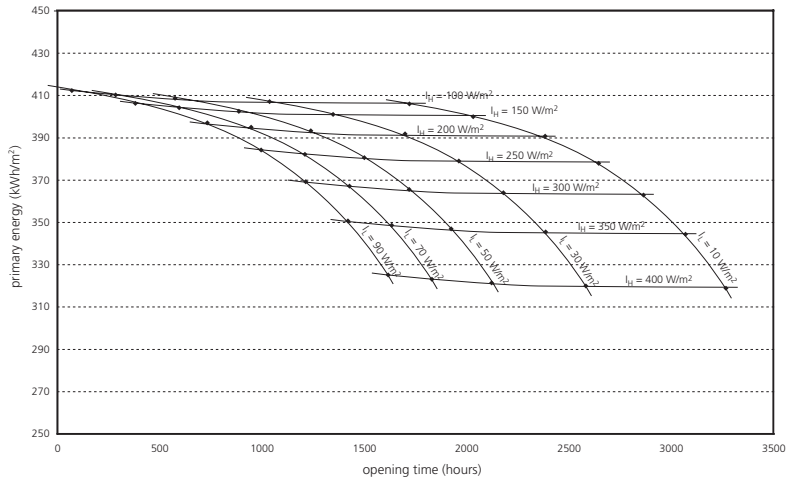


Figure 11.8 Diagram of the summed active energy gains and number of hours with open reflectors depending on different combinations of  $I_L$  and  $I_H$ , within the range ( $I_L/I_H$ ) 10/100 to 90/400  $\text{W/m}^2$ .

Without the passive gains or thermal losses taken into account yet, one can note that the choice of  $I_H$  has an impact on both the energy yield and the amount of open time. For  $I_L$ , the choice has a larger impact on the open time than on the energy yield. Hence, with only the active energy yield and daylight taken into account, a low  $I_L$  value should be chosen in order to compensate for the daylight losses caused by a low  $I_H$  value. A reasonable compromise within this range might be an  $I_L/I_H$  combination of 10/250  $\text{W/m}^2$ . However, passive gains must also be taken into account. Figure 11.9 shows the same situations with the useable passive solar yield added.

The diagram shows that the lower  $I_H$  levels are of little interest when the passive thermal gains are taken into account. An  $I_H$  value of around 250  $\text{W/m}^2$  seems to be the breaking point for a maximal accumulated active and passive yield. It is also interesting to note that the choice of  $I_L$  level has a greater impact on the energy yield than before, where the lowest levels are the most beneficial, as opposed to the former case. From this perspective, the combination 10/250 still seems to be a wise choice, or perhaps 10/300.

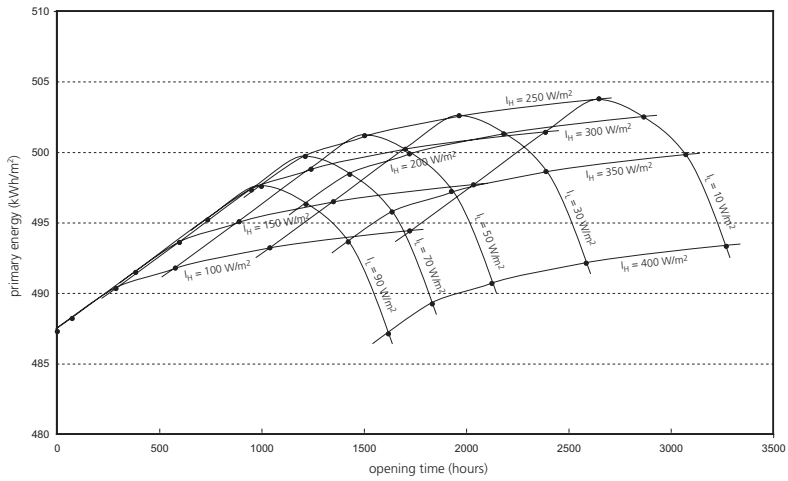


Figure 11.9 Diagram of the summed useable energy gains (active and passive) and number of hours with open reflectors depending on different combinations of  $I_L$  and  $I_H$ , within the range  $(I_L/I_H)$  10/100 to 90/400  $\text{W/m}^2$ . Thermal losses are not taken into account here.

While overheating gains might be more suitable to be regarded rather as a comfort than an energy issue in the analysis, the thermal losses through the structure, depending on whether the reflectors are closed or not, must be taken into account. The thermal balance of the window was calculated according to Eq. 2.4, i.e. only gains and losses occurring at ambient temperatures below the balance temperature of the window are taken into account. The gains,  $Q_{solar}$ , are equivalent to  $P_4 + P_5$ , and the losses,  $Q_{loss}$ , are calculated according to Eq. 11.10. Figure 11.10 shows the thermal balance of the Solar Window for a smaller but more relevant selection of control combinations, with the balance temperature set to  $13^\circ\text{C}$ .

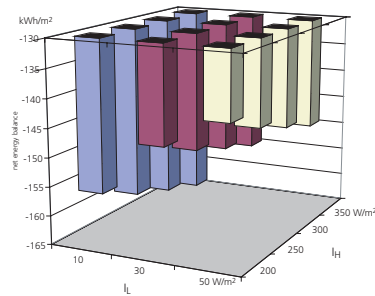


Figure 11.10 Overview of the effect of different control combinations on the thermal balance of the Solar Window, for the balance temperature 13°C.

In figure 11.11, the accumulated active energy yield from figure 11.8 is added to thermal balance from figure 11.10.

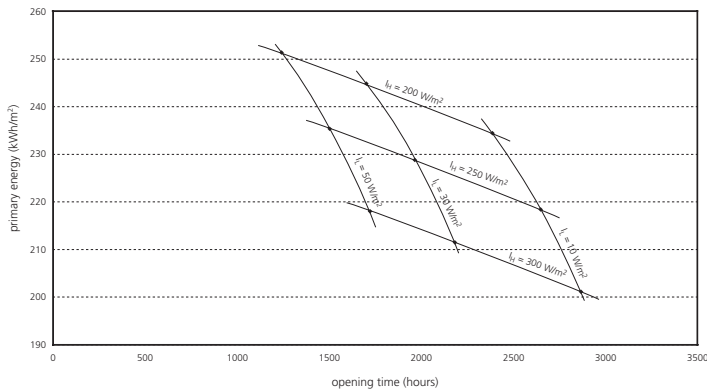


Figure 11.11 Diagram of the summed active energy yield from figure 11.8 and the thermal balance presented in figure 11.10.

So far, an  $I_H$  value of 200 W/m² seems to be the best choice with respect to the overall performance of the Solar Window. However, as discussed in 11.1.3, a control strategy based on the most beneficial thermal balance might be more suitable for the winter months, when the active solar systems are of little use. Figure 11.12 compares the thermal balance based on this strategy with the thermal balance based on the 10/200 strategy for the whole year.

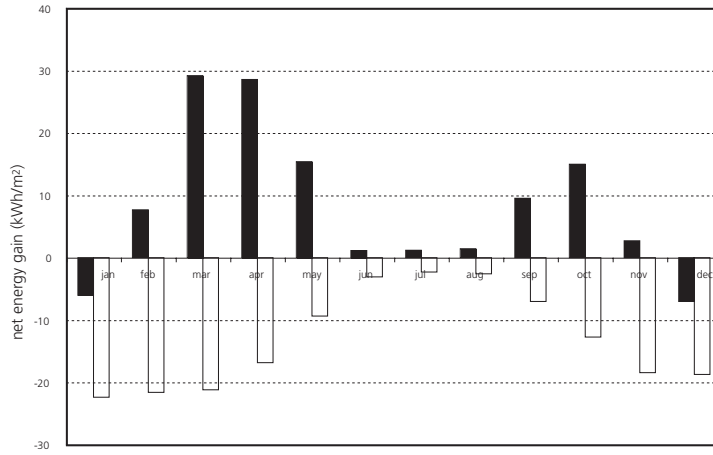


Figure 11.12 Comparison between the thermal balance of the Solar Window, controlled due to irradiance ( $10/200 \text{ W/m}^2$ , white) and due to best thermal balance (black).

There is much energy to be saved by applying a control strategy based on best thermal balance during the winter months, especially from November to February. However, a control strategy based on best thermal balance is not beneficial for the active solar energy yield. Figure 11.13 compares this yield with the yield of the  $10/200 \text{ W/m}^2$  control strategy.

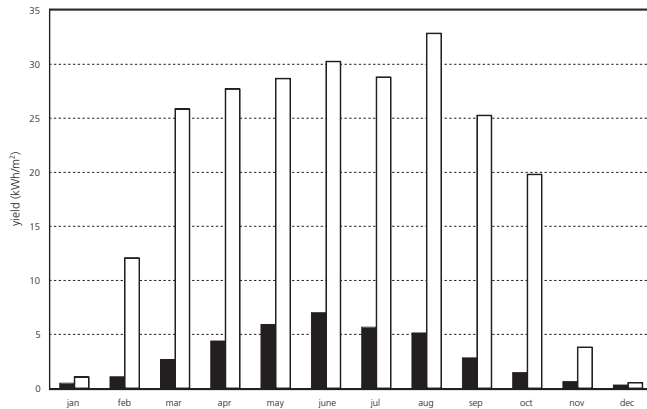


Figure 11.13 Comparison between the active solar yields of the Solar Window, controlled due to irradiance ( $10/200 \text{ W/m}^2$ , white) and due to best thermal balance (black).

The active solar gains are negligible during these months, at least from November to January. Therefore, a combined control strategy is recommended. Figure 11.14 shows the results from figure 11.10, where the control strategy for the winter months is replaced with the "best thermal balance" strategy.

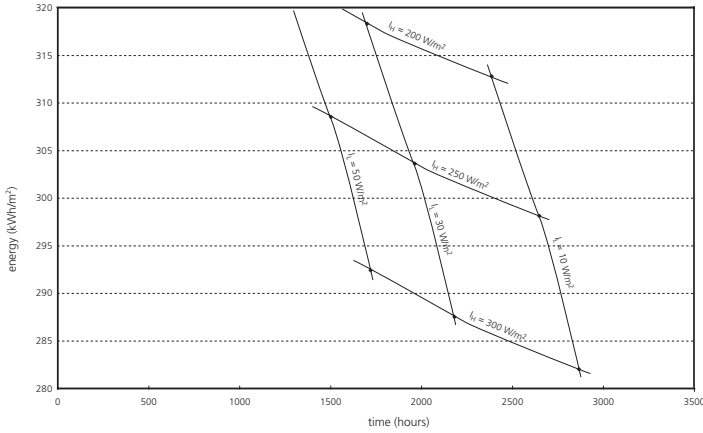


Figure 11.14 Diagram of the summed active energy yield and thermal balance for a combined control strategy based on irradiance levels and on "best thermal balance" during November to February.

Which control strategy based upon irradiance is better, is a matter of subjective priorities for every user. After this presentation on the consequences for different combinations of  $I_L$  and  $I_H$ , the combination 10/200  $\text{W/m}^2$  with control due to best thermal balance during the winter months is chosen for a more detailed analysis on the consequences. An overview is presented in figure 11.15.

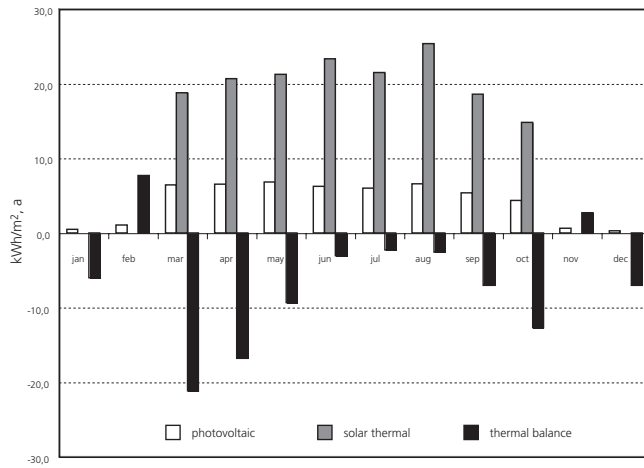


Figure 11.15 The performance of the Solar Window, with the reflectors controlled to be opened at irradiance levels between 10 and 200 W/m<sup>2</sup>.

The monthly sum of hours with open reflectors for this combined control strategy is shown in figure 11.16.

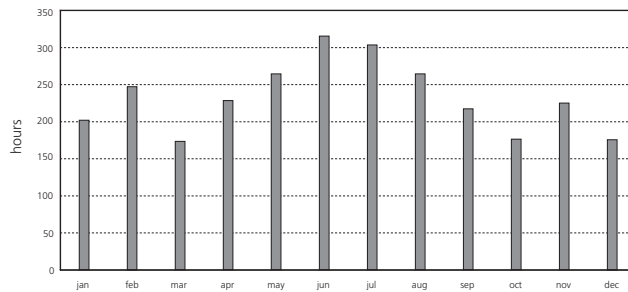
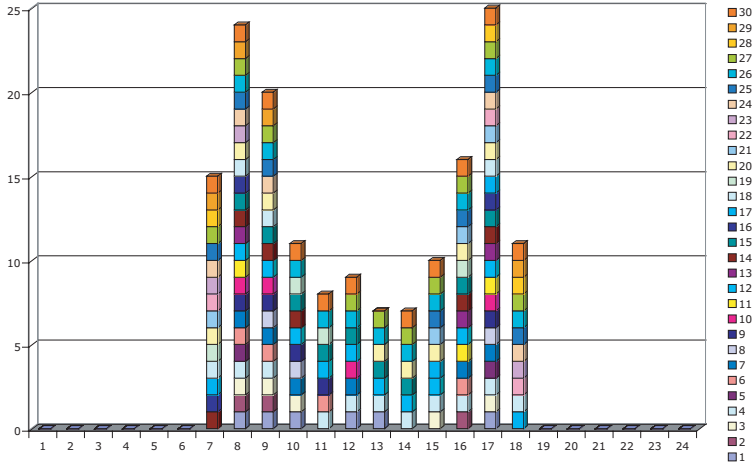


Figure 11.16 The distribution of hours with open reflectors for the combined 10/200 and thermal balance control strategy

The number of open hours/day for the reflectors is at a minimum level of 5,5 in March, and then increasing during spring and fall to a maximum of 10,5 in June. In order to get a picture on how these hours are distributed, March, June and December are studied in order to see at what times the reflectors could be expected to be closed or opened. For March, figure 11.17 shows the distribution of open hours. Each colour represents a

day of the month. From hours 1 to 6 and 19 to 24, i.e. from 6 p.m. to 6 a.m., the reflectors are always closed due to the lack of irradiance. From 10 to 15, the reflectors are closed 72% of the time in order to increase PV performance and activate the active thermal function, at irradiance exceeding  $200 \text{ W/m}^2$ . During mornings and late afternoons, i.e. from hour 7 to 9 and from 16 to 18, the reflectors are open 62% of the time, which corresponds fairly well to what was suggested for the time controlled model, described in 11.1.1.



*Figure 11.17 The distribution of hours with open reflectors in March. Each box represents an hour with open reflector. Each colour represents a day of the month, and the x-axis represents the hours of one day. For example, the reflectors are open hours 8 to 10, 12-13 and 17 on March 1st, and open from hours 7 to 18, except for hour 13, on March 30th.*

For June, shown in figure 11.18, the contrast is stronger, and corresponds better to the time control strategy. During the day, from hours 9 to 16, the reflectors are closed 76% of the time in order to increase active solar yields and avoid overheating. There is a potential to make the thermal balance better by closing the reflectors during early morning hours, such as 4 to 6.

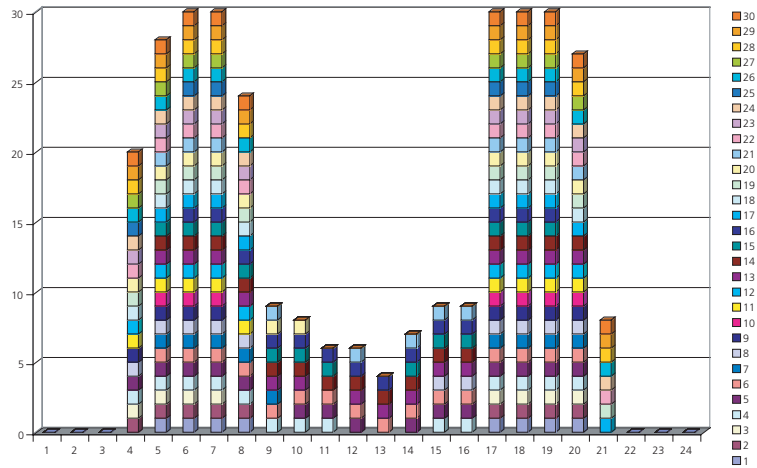


Figure 11.18 The distribution of hours with open reflectors in June. Each colour represents a day of the month, and the x-axis represents the hours of one day.

As discussed, it could be motivated to control the reflectors rather than on irradiation during winter. A comparison of the results of these two strategies for December is shown in figure 11.19, which confirms that control based on thermal balance is the most suitable for this season. Almost independently on weather, open reflectors during the bright hours of the day lead to the best thermal balance. The days are short, from 10 to 16 at its longest, why a closure of the reflectors is motivated for a large part of the diurnal cycle. The bottom diagram indicates that the reflectors should be closed around half of the month's days, when irradiance exceeds  $200 \text{ W/m}^2$ . As indicated in figure 11.6, these hours hardly contribute at all to the active thermal component of the system, and may hence make more use by being opened for passive solar gains, with the PV system working without concentration.

A model for an automated control based on thermal balance is in practice complicated and hence questionable. A manual control based on common sense and comfort is rather recommended. However, the top diagram makes the control simple. From hours 1 to 9, there is obviously no reason to keep the reflectors open. From a daylight and energy point of view, the same could be said for hours 16 to 24, but the desire for a (limited) view outside and a sensation of openness might lead to some time with open reflectors during night time, despite a lower thermal balance.

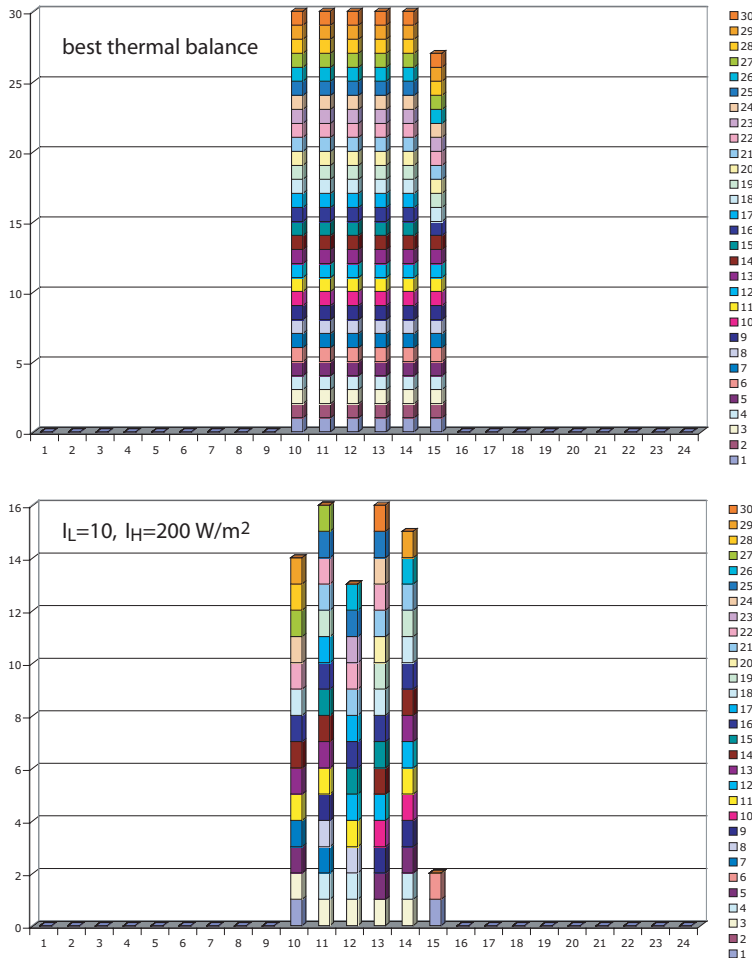


Figure 11.19 The distribution of hours with open reflectors in December. Comparison between control due to best thermal balance (above) and the 10/200  $\text{W/m}^2$  control strategy (below).

### 11.3.5 Summary and comparison with other façade elements

The Solar Window, operated with the control strategy described in the previous section, delivers annually 164  $\text{kWh/m}^2$  of hot water, 50  $\text{kWh/m}^2$  of electricity and has a negative energy balance of 78  $\text{kWh/m}^2$ . These

figures totals 137 kWh/m<sup>2</sup>. In primary energy terms, with the electricity weighted by 4.2, this totals 300 kWh/m<sup>2</sup>, annually.

Calculated with the same method as described by Eq. 2.4, a conventional wall of Swedish type (U-value 0.25 W/m<sup>2</sup>K) represents an annual loss of 27 kWh/m<sup>2</sup>. For a conventional two pane window (U-value 2.88 W/m<sup>2</sup>K), the thermal balance is positive, 36 kWh/m<sup>2</sup>. For a low-e coated 2 pane window (U-value 1.2 W/m<sup>2</sup>K), the thermal balance is 160 kWh/m<sup>2</sup>. Figure 11.20 compares the thermal balance between the Solar Window and a low-e window.

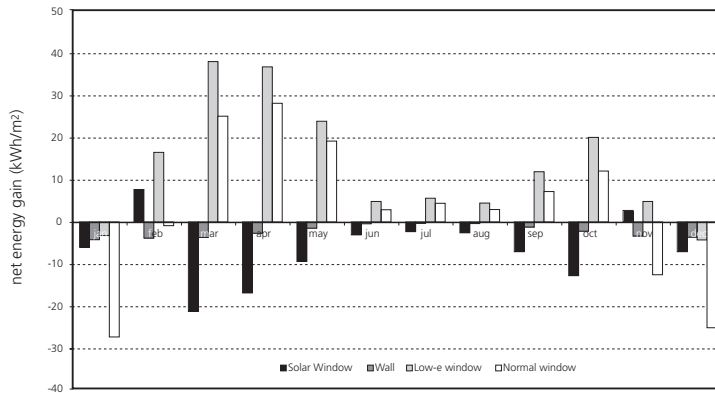


Figure 11.20 Thermal balance (kWh/m<sup>2</sup>) of the combined 10/200 W/m<sup>2</sup> strategy, compared to a wall (U-value 0.25 W/m<sup>2</sup>K) and a low-e window (U-value 1.2 W/m<sup>2</sup>K).

From an absolute energy and economical perspective, it might be questionable to install the Solar Window instead of a conventional low-e window. However, from a comfort point of view, the Solar Window offers more flexibility, except for the fact that it delivers hot water and electricity. Figure 11.21 compares the potentially over-heating solar yield between the Solar Window and a low-e window. The calculation for the Solar Window is made with the tool described in 11.2.1. For the low-e window, the yield is calculated as the transmitted irradiance when the ambient temperature is above the balance temperature 13°C.

The Solar Window, controlled with the combined 10/200 strategy, gives a total annual overheating solar yield of 72 kWh/m<sup>2</sup>, while a low-e window, with a g-value varying between 0.53 and 0.58, gives 228 kWh/m<sup>2</sup>.

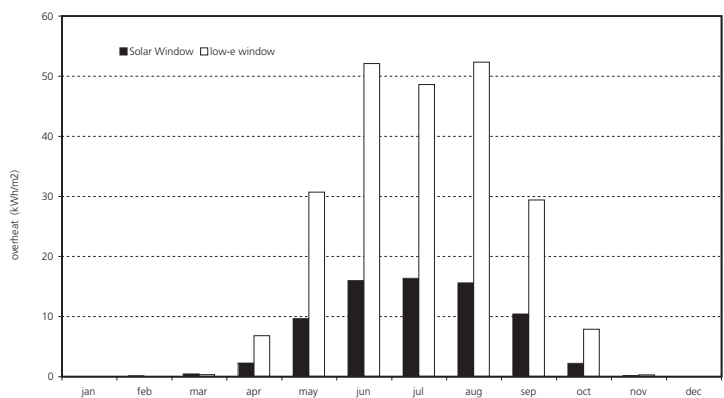


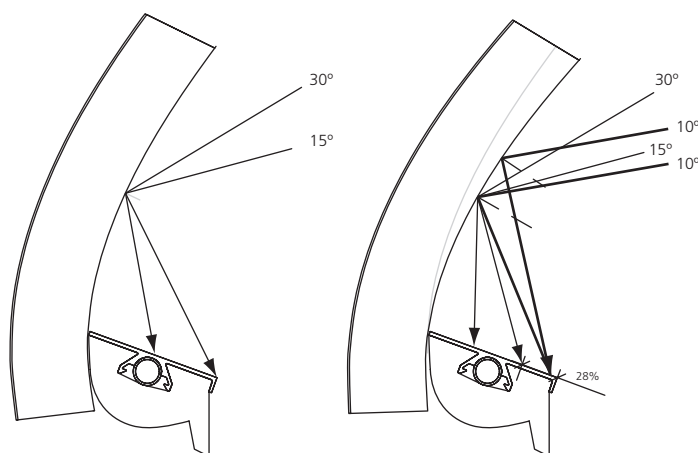
Figure 11.21 Solar overheat yield ( $\text{kWh/m}^2$ ) of the combined 10/200  $\text{W/m}^2$  strategy, compared to a low-e window ( $g$ -value 0.53-0.58).

## 12 Alternative designs

### 12.1 Variation of acceptance angles

The ray-tracing schemes in figure 7.10 show that the strip of concentrated light is narrow close to the focal point, i.e. the outer edge of the absorber, at solar heights near the lower acceptance angle  $15^\circ$ . At increasing solar height, the strip moves quickly along the absorber, and becomes wider as it moves inwards. This means that the outer part of the absorber is used considerably less than the inner part. Due to the concentration and hence higher temperature, the loss of photovoltaic power reaches its maximum on this part of the cell.

Since the PV cells are the most expensive part of the system, its price per kWh of electricity produced would drop considerably if the electricity output per PV cell area could be increased substantially. This could be achieved by reducing the cell area while making use of most of the irradiance. From the observations above, this can be obtained by making changes to the existing geometry. In the prototype, the parabolic reflector is rotated  $15^\circ$  from the horizontal plane, which results in an acceptance angle of  $15^\circ$ . By rotating it  $5^\circ$  towards the horizontal and thus reducing the acceptance angle to  $10^\circ$ , the light at  $15^\circ$  would hit the absorber closer to the reflector than before, see figure 12.1. Hence, the focus will climb up  $\sim 30\%$  of the reflector area, so the PV cell could be reduced by the same amount. Simultaneously, the aperture area would become  $\sim 3\%$  smaller. If the cell area would be reduced by  $40\%$ , the most focused light would miss the cells, but since the strip of concentrated light moves rapidly towards the reflector as the solar height increases, the light would probably hit the cells at a solar height around  $25^\circ$ . This solution would generate a little less electricity per year, but the price per kWh of electricity would be lowered.



*Figure 12.1 By moving the reflector 5° forward, the acceptance angle is reduced to 10°, and the focus of larger solar heights climbs up on the absorber area towards the reflector.*

## 12.2 Glazed office application without insulation

The initial design of the Solar Window was developed for application in residential housing, where heating demand is the most important design factor. Therefore, the reflectors also served as added internal insulation in the closed mode, in order to yield a low U-value of the whole system. For the integration into glazed office façades, the cooling demand of the building is more important than heating demand. Therefore, a glazed façade should be designed to let in as little passive solar heat as possible during daytime. Hence, the reflectors' primary function when integrated into office façades besides concentration should be sun-shading, and therefore they can be made in thinner and harder material, than the porous and insulating EPS, which is the core in the former reflector design. The aim for the new design was to directly use an anodized aluminium sheet as the reflector, in order to reduce production labour and hence system cost. Further simplification was made by changing the pivoting line from the central axis of the water pipe to the upper edge of the absorber, where it meets the bottom edge of the reflector, see figure 12.2.



*Figure 12.2 Illustration of a modified design of the Solar Window for office applications.*

### 12.3 Integration into double skin façades

The internal positioning of a sun-shading system is the least efficient regarding the avoidance of undesired passive solar gains. The main advantage is that the shading screens are protected from the outer climate, primarily from wind loads. A double skin façade's outer skin is usually made of a single glass, resembling the cover of a solar thermal collector, which has a higher transmittance than a double glazed unit. For these reasons, double skin facades might be a suitable object for the integration of the Solar Window system into glazed office buildings.

For the house application, a main advantage was the option to gain passive heat from the sun at low irradiation levels. This is not desired in office buildings, why a differentiation between the glazing of the outer and inner skin of the double-skin façade is desirable. For the outer skin, mainly serving a wind-protection function, a high level of transmittance is suggested. For the inner layer, a low-E coating is suggested in order to reduce thermal losses. However the dimensioning of these factors can be reduced due to the sun-shading effect of the reflectors at high irradiation

levels. By placing the reflectors in the cavity of the double skin façade, the reflectors will be more efficient as a sunshading device, since interpane sunshades are more efficient than internal ones (Wall & Bülow-Hübe, 2003). Double skin façades have been questioned for the multiple functions (like e.g. natural ventilation) that have been ascribed to them, but there is a general agreement on their most obvious advantage, i.e. they can contain climate protected, non-internal sunshading devices (Poirazis, 2004).

## 12.4 Integration into a glazed stairway façade

### 12.4.1 Background

An experimental installation of the suggested variation of the Solar Window for office building use, has been suggested for a glazed façade of the staircase space of an exhibition building in Augustenborg, Malmö, Sweden. This is an urban district with a pronounced “eco-profile”, where several projects have been carried out in order to increase the sustainability of the area, including natural water purification, energy conservation, car pools et c. Currently, a project funded by the Swedish government aims at integrating approx. 500 m<sup>2</sup> of solar collectors and some 100 m<sup>2</sup> of PV panels in Augustenborg. For a detailed background of the project, see (Nilsson and Olsson, 2004). One of the largest projects in the area’s sustainability programme is the extensive exhibition of green roofs, laid out on the roofs of several industry and office buildings and connected with ramps and platforms in order to let visitors see different kinds of green roofs in an “elevated park”. Some solar heating and PV systems will be integrated into this roof structure. The exhibition is reached via an internal exhibition building with a south-facing, glazed staircase hall. Over-heating and glare is a great comfort problem here, especially during summer, when the exhibition is most frequently visited. Therefore, it was suggested to make an experimental installation of the Solar Window into a part of this glazing, see figure 12.3. Hence, a novel approach towards solar energy could be displayed to a great audience, while bringing comfort to the entrance space.



*Figure 12.3 Illustration of the Solar Window integrated into the glazed staircase space of an exhibition building in Augustenborg, Malmö, Sweden.*

The staircase hall is in three stories with a fully glazed south-facing façade. The façade system consists of 18 windows. They are supported by a façade system, with aluminum frames of 50 mm width. The horizontal frames are 35 mm deep, and the vertical frames have a depth of 95 mm.

#### 12.4.2 New design of the Solar Window

Due to a modified design of the junction between reflector and absorber, the height of each module was reduced from 220 mm to 200 mm. Hence each window of the stairway hall can contain six modules. In order to cut investment costs and to keep a fair amount of daylight when the reflectors are closed in this public space, only six out of 18 windows were chosen for the integration of the system. Hence, this system contains 36 modules distributed on a window (aperture) area of 8.9 m<sup>2</sup>. The existing windows

have a transmittance which is lower than the application in the residential house discussed earlier. However, it would not be economically feasible to exchange them in order to achieve a higher transmittance of the system. As in the original design, the water pipe is also the supporting structure for absorber and reflector. They are statically integrated in the façade structure by drilling holes in the vertical frames for the water pipes.

The aluminium profile is the same as the one used in the original design. However, in accordance to what was discussed in 12.1, the PV cell size is reduced to 50 mm (which means that a standard 4" cell can be split in two), and placed along the upper edge of the absorber, close to the reflector.

### 12.4.3 Module design and mechanical regulation

All the reflectors are run simultaneously by one motor, placed on the inside of the central mullion profile. The rod motor is connected to a vertical beam with cranks fixed to an axis running parallel to the module, see figure 12.4. The axis also serves as the centre of rotation, and as the spring bolt in the hinges connecting the absorber to the reflector. The hinges are attached to the absorber via gable elements in massive aluminium. The lower part of the absorber, surrounding the water pipe, is insulated with poly-urethane foam and clad with thin aluminium sheet metal.

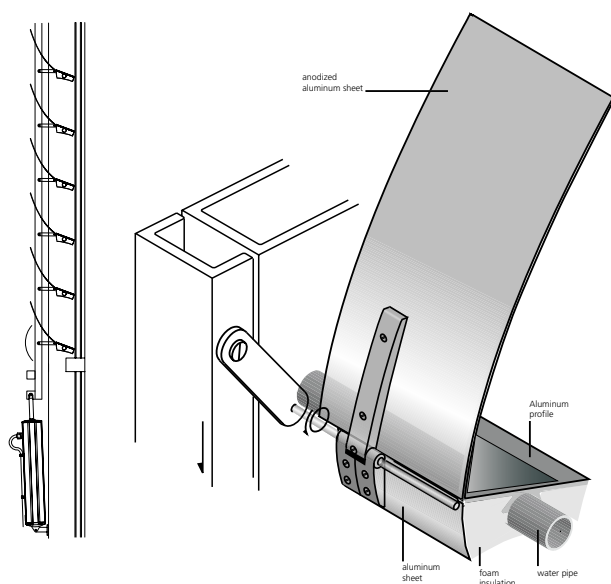


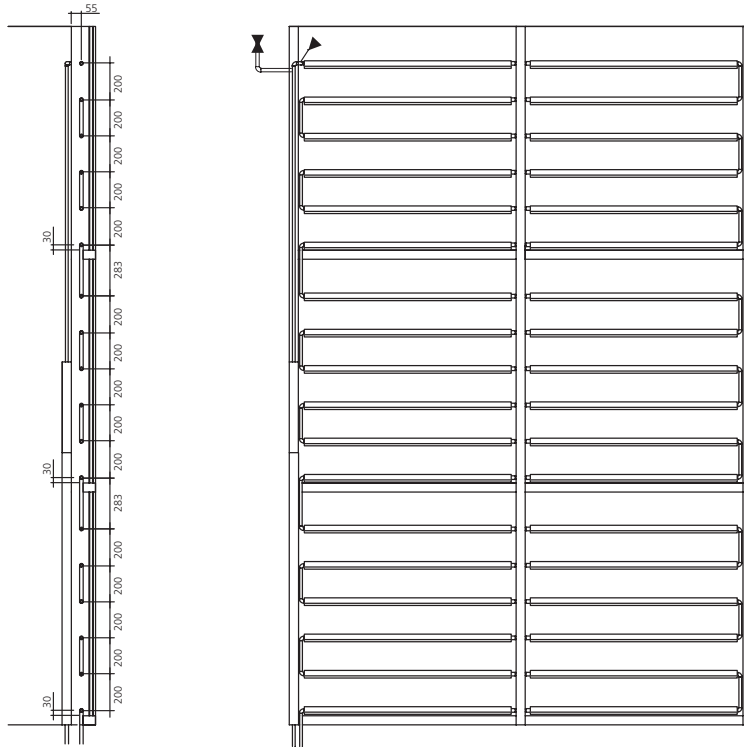
Figure 12.4 *The composition and the mechanical regulation of the Solar Window components.*

### 12.4.4 System design

The active heating system consists of all the absorbers connected into one series, according to figure 12.5. The other system components are gathered in the basement, shown in figure 12.6. The system was designed by Bengt Perers, division of Energy and building design.

The photovoltaic system is designed to obtain a voltage of 72 V. Each module has 8 PV cells of 0,5 V each. Thus, all of the 18 modules in one column of windows are connected in one series. The two columns are connected in parallel. The system is connected to an inverter for connection to the central grid.

The system is regulated automatically by a solar sensor system that controls the motor for the mechanical regulation.



*Figure 12.5 The water pipes through the modules are connected into one series and run towards the other system components in the basement.*

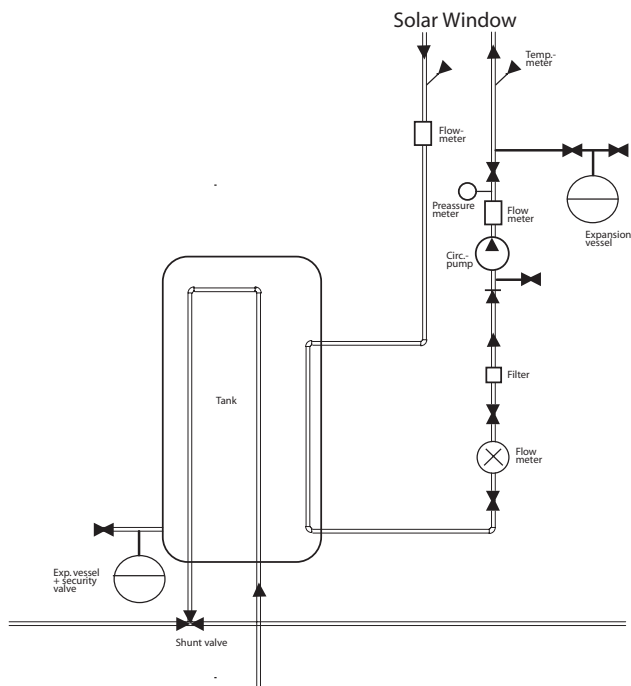
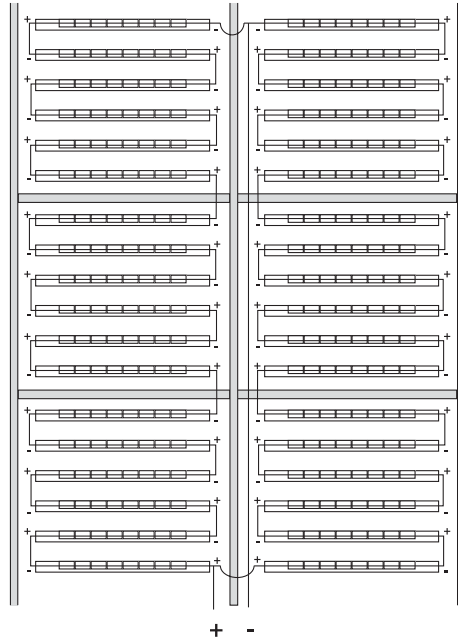


Figure 12.6     *The composition of the other system components, placed in the central in the basement.*



*Figure 12.7 The layout of the photovoltaic system. Each module have eight PV cells connected in a series, which gives a voltage of 4 V. The modules of three windows in one column are connected in a series, and the two columns are connected in parallel, giving a maximum voltage of 72 V.*



*Figure 12.8 Photographs of a prototype for the installation in the glazed façade.*



# References

- Adamson, B. & Hidemark, B. (1986) *Sol • Energi • Form*, Byggeforskningsrådet, Stockholm, ISBN 91-540-4471-5
- Andrén, L. (1999) *Solenergi - praktiska tillämpningar i bebyggelse*, Svensk Byggtjänst, ISBN 91-7332-872-3
- Baird, G. (2001) *The Architectural Expression of Environmental Control Systems*, Spon Press, ISBN 0-419-24430-1
- Banham, R. (1969) *The Architecture of the Well-tempered Environment*, Architectural Press
- Blasing, T.J. & Jones, S. (2005) *Current Greenhouse Gas Concentrations*, updated February 2005, [http://cdiac.ornl.gov/pns/current\\_ghg.html](http://cdiac.ornl.gov/pns/current_ghg.html)
- Bosselaar, L. et al, (2004) *World Wide Best practices for building integration of solar heating systems*, in the proceedings of EuroSun2004, Freiburg, Germany, 2004, ISBN 3-9809656-4-3
- Boverket, *Information om bidrag till solvärme i bostäder och lokaler*, Boverket, Sweden 2000
- Brogren, M. (2001) *Low-Concentrating Photovoltaic Systems with Parabolic Reflectors*, Uppsala Universitet, ISSN 0346-8887, UPTEC 01 006 Lic, 2001
- Brogren, M. (2004) *Optical Efficiency of Low-Concentrating Solar Energy Systems with Parabolic Reflectors*, Uppsala Universitet, ISBN 91-554-5867-X
- Brogren M. et al, (2004) *Biaxial model for the incidence angle dependence of the optical efficiency of photovoltaic and solar thermal systems with asymmetric reflectors*, Submitted to Solar Energy Journal.
- Bunge M. (1979) *Treatise on Basic Philosophy, vol. 7: A World of Systems*. Dordrecht-Boston: Reidel

- Bülöw Hübe, H. (2001) *Energy-Efficient Window Systems – Effects on Energy Use and Daylight in Buildings*, Lund Institute of Technology, ISSN 1103-4467
- Chant, V.G. & Håkansson, R. (1985) The MINSUN simulation and optimisation program. Application and users guide. IEA SH&C Task VII, Ottawa.
- Coventry, J.S. & Lovegrove, K. (2003) *Development of an approach to compare the 'value' of electrical and thermal output from a domestic PV/thermal system*, Solar Energy 75 (2003) 63–72.
- Dalenbäck, J.-O. (1996) *Solar energy in building renovation*, Energy & Buildings, 24, pp 39-50.
- Dalenbäck, J.-O. (1998) *Byggnadsintegrerade solfångare*, Byggeforskningsrådet, Stockholm, Sweden
- Edén, M. (1987) *Arkitektur med ekologiska förtecken - forskning om samspelet människa - teknik - estetik för ett framtida energisamhälle*, Chalmers tekniska högskola, ByAcht, ISBN 91-7032-300-3
- Ekholm, A. (1987) *Systemet människa - byggnadsverk*, ISBN 91-540-4691-2, Byggeforskningsrådet R22:1987
- Emery K. Et al. (1996) *Temperature dependence of photovoltaic cells, modules and systems*, in proceedings of the 25th IEEE PV Specialists Conference, Washington DC, USA
- Energiboken (1995) Byggeforskningsrådet, ISBN 54057264
- Energimyndigheten (2004), *Energy in Sweden 2004*, Eskilstuna, Sweden: Swedish Energy Agency.
- Energy design resources (2005) <http://www.energydesignresources.com>
- Fieber A. (2004) *Utförande av solvärmesystem för Skanskas olika typhus, Delrapport 1*, Energi och ByggnadsDesign, Lunds tekniska högskola, Rapport EBD-R--04/5
- Fieber A. & Karlsson B. (2003) *Design, construction and performance of a multifunctional hybrid solar wall element*, In the proceedings of ISES Solar World Congress 2003, Gothenburg, Sweden
- Fieber, A., Gajbert, H., Håkansson, H., Nilsson, J., Rosencrantz, T., & Karlsson, B. (2004) *Design, Building Integration and Performance of a Hybrid Solar Wall Element*, in the proceedings of EuroSun2004, Freiburg, Germany, 2004, ISBN 3-9809656-4-3

- Fieber, A., Nilsson, J. & Karlsson, B. (2004) *PV Performance of a Multifunctional PV/T Hybrid Solar Window*, in the proceedings of PV Conference 2004, Paris
- Fieber, A. & Nilsson, M. (2005) Solceller inom Malmö Stad, Elforsk Solelprogram 2005
- Gajbert, H. (2002) *Koncentrerande solenergihybrider för byggnadsintegrering*, Lunds universitet, Rapport TABK—02/5026
- Gajbert H., Håkansson H., Karlsson B. (2004) Measurement of concentrating solar collectors using a solar simulator with parallel light, Submitted to Eurosun2004, Freiburg, Germany 20-23 June 2004.
- GEO (2002) *Global Environment Outlook 3*, United Nations Environment Programme, available at <http://www.unep.org/geo/geo3/>
- Green, A. & Brogren, M. (2001) *Solel i bostadshus - vägen till ett ekologiskt hållbart boende?*, Program Energisystem, Arbetsnotat Nr 17, ISSN 1403-8307
- Green, M. (2002) *Solceller Från solljus till elektricitet*, svensk Byggtjänst, Stockholm, ISBN 91-7332-987-8
- Gustafsson, L. (1982) *System och modell – en introduktion till systemanalysen*, Studentlitteratur, ISBN 91-44-18551-0
- Hansen, E. K. (2001) *SOLcelle & SOLlys et arkitektonisk potentiale Idégrundlag for hvordan solceller og sollys kan spille sammen*, Arkitektskolen i Aarhus, Denmark. Available at [www.solarcell.dk](http://www.solarcell.dk)
- Hedström, J. (2004) *Solel 00-02s Driftuppföljning av svenska nätanslutna solcellsanläggningar*, Elforsk, [www.elforsk.se/solel](http://www.elforsk.se/solel)
- Helgesson, A., Krohn, P., & Karlsson, B. (2003) *Development of a MaReCo-Hybrid for Hammarby Sjöstad, Stockholm*, in the proceedings of Eurosun 2003
- Hestnes, A. G. (1999) *Building integration of solar energy systems*, Solar Energy Vol. 67, Nos. 4–6, pp. 181–187
- Hestnes, A. G. (2003) *Solar low energy buildings and the integrated design process*, In the proceedings of ISES Solar World Congress, Gothenburg, Sweden
- Ingelstam, L. (2002) *System - att tänka över samhälle och teknik*, Energimyndigheten, Sweden

- Ingelstam, L. (2003) *Implementing solar – reflexions on how to conquer the system*, In the proceedings of ISES Solar World Congress 2003, Gothenburg, Sweden
- ISO 8990 (1994) *Thermal insulation – Determination of steady state thermal transmission properties – Calibrated and guarded hot box*, ISO 8990:1994
- Johansson T. (2004) *Utvärdering av Solfönster, en integration av solhybrid och solskydd*, Dept. of Construction and Architecture, Lund University
- Karlsson, B., (2001) *Kemiska och Fysikaliska Mekanismer för Växthuseffekt och Ozonuttunning*, PM, Energi och byggnadsdesign, Inst för Byggande och arkitektur, LTH
- Karlsson, B., Brogren, M., Larsson, S., Svensson, L., Hellström, B. & Safir, Y., (2001) *A large bifacial photovoltaic-thermal low-concentrating module*, in the proceedings of the 17th European Photovoltaic Solar Energy Conference, Munich, Germany
- Klein, S.A. (1976) *TRNSYS-A Transient Simulation Program*, Ashrae Transactions, 92, 623
- Knowles, R. L. (2003) *The solar envelope: its meaning for energy and buildings*, Energy and Buildings 1470(2003)1–11
- Kovacs, P. & Pettersson, U. (2002) *Solvärmda Kombisystem - En jämförelse mellan vakuumrör solfångare och plana solfångare genom mätning och simulering*, SP Rapport 2002:20
- Küller, R. (2001) *The influence of daylight and artificial light on diurnal and seasonal variations in humans - a bibliography*, Commission International de l'Eclairage, Vienna, Austria, Publication CIE 139-2001, ISBN 3 901 906 04 5
- Kvist, H. (2004) *ParaSol v2.0*, Energy & Building Design, Lund University, available at [www.derob.se](http://www.derob.se)
- Le Corbusier (1976) *Vår bostad (La maison des hommes)*, Prisma, Stockholm, 1976
- Lundequist, J. (2000) *Byggnaden som system och upplevd helhet*, Design-journalen vol 7, no 1, Sweden
- Lundgren, M. & Wallin, F. (2004) *Aktiv solenergi i hus- och stadsbyggnad - samtida perspektiv och framtida möjligheter*, Arkus, ISSN 0284-78009

- Lundquist, G. (1980) *Camera Solaris - arkitektur för vårt klimat*, Statens råd för byggnadsforskning, ISBN 91-540-3365-9
- Meteotest (2004) *METEONORM, Global Meteorological Database for Solar Energy and Applied Meteorology*, www.meteotest.ch, 2004
- Mischler, G. (2002) Rayfront Version 1.0.4, Scorsch.com – Lighting Design Tools, www.schorsch.com
- Nilsson, M. & Olsson, O. (2004) *Solvärme i Augustenborg en förstudie*, Lunds tekniska högskola, ISBN 91-85147-06-0
- Nordström, C. (1982) *Historien om ett solhus*, Stockholm : Statens råd för byggnadsforskning : Sv. byggtjänst (distr.)
- Nordström, C. (1999) *Möjligheter för miljöprogrammet*, svensk Byggtjänst, Stockholm, 1999, ISBN 91-7332-874-X
- Nordström, C. (2003) *Architectural building integration of solar systems*, In the proceedings of ISES Solar World Congress 2003, Gothenburg, Sweden
- Pearson, D., (1998) *The New Natural House Book : Creating a Healthy, Harmonious, and Ecologically Sound Home*, Gaia boks Ltd
- Perers, B. (1993) *Dynamic method for Solar collector array testing and evaluation with standard database and simulation programs*, Solar Energy, Vol50, no 6, pp 517-526.
- Poirazis, H. (2004) *Double Skin Facades for Office Buildings – Literature Review*, Lund Institute of Technology, ISBN 91-85147-02-8
- Regeringens proposition 2003/04:100
- Roos, A. & Karlsson, B. (1994) *Optical and thermal characterization of multiple glazed windows with low U-values*. Solar Energy (4) 315-325.
- Rosencrantz, T. & Bülow-Hübe, H. (2004) *Estimation of the annual potential for increased solar energy utilisation and daylight availability by introducing anti-reflective coatings on low-e windows*, in the proceedings of EuroSun2004, Freiburg, Germany, ISBN 3-9809656-4-3
- Rådberg, J. (1997) *Drömmen om atlantångaren : utopier & myter i 1900-talets stadsbyggande*, Atlantis, Stockholm
- Rönnelid, M. & Karlsson, B. (1999) *The use of corrugated booster reflectors for solar collector fields*. Solar Energy, 1999. 65(6) p.343-351.
- Rörby, M. (1996) *En miljon bostäder*, Arkitekturmuseet, Stockholm

- Scarttrettzini. Courret: *Anidolic Daylighting Systems*, Solar Energy, vol 73, no 2, 2002
- Sick, F. & Erge, T. (1996) *Photovoltaics in Buildings*, ISBN 1 873936 59 1, IEA
- Silvi, C. et al. (2004) *Solar education combining art, history, science and technology at archaeological sites in Italy*, in the proceedings of Euro-Sun2004, Freiburg, Germany, ISBN 3-9809656-4-3
- Smets, J. (2004) *Energy Aspects in Swedish Building Legislation of the 20th Century Concerning Dwellings*, Division of Energy and Building Design, Lund Institute of Technology. Available at [www.byfy.lth.se/Publikationer/semuppg2004/JSmets.pdf](http://www.byfy.lth.se/Publikationer/semuppg2004/JSmets.pdf)
- SOLABS (2004) [www.solabs.net](http://www.solabs.net)
- SPF Solartechnik (2004) *Polysun 3.3, The simulation program to dimension thermal solar systems*, [www.spf.ch](http://www.spf.ch)
- Thomas, C et al. (2004) *Extinction risk from climate change*, Nature 427, pp 145-148, NaturePublishing Group
- Tripanagnostopoulos, Y et al. (2000) *Solar collectors with colored absorbers*, Solar Energy Vol. 68, No. 4, pp. 343-356, 2000, Elsevier ScienceLtd
- Tsung Leong, S. (2001) *Air conditioning*, essay in *Project on the City 2 - Harvard Design School guide to Shopping*, Taschen, ISBN 3-8228-6047-6
- Vejsig Pedersen, P. (2002) *Solenergi og Byøkologi*, Ingeniøren|bøger, Denmark, 2002, ISBN 87-571-2130-3
- Vitruvius (1960) *De architectura*; trans. M. H. Morgan, The Ten Books on Architecture, New York Dover
- Voltarlux, information on <http://www.glaswerke-arnold.de/Englisch/bau/voltarlux.htm>
- Wall, M., & Bülow-Hübe, H. (2003) *Solar Protection in Buildings Part 2: 2000-2002 Report EBD-R--03/1*. Lund (Sweden): Lund University (Inst. of Technology), Dept. of Construction & Architecture.
- Wallén, G. (1996) *Vetenskap och forskningsmetodik*, Studentlitteratur, Sweden
- ZEMAX Development Corporation (2005) *ZEMAX, software for optical design*, [www.zemax.com](http://www.zemax.com).