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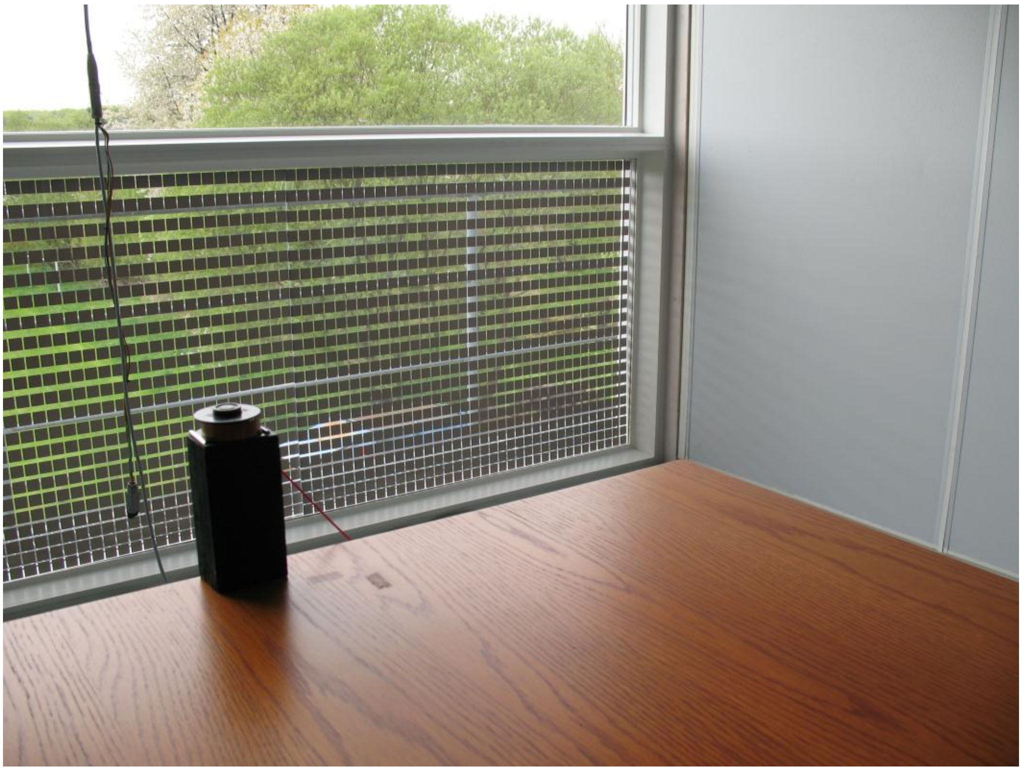
Impact on indoor climate and energy demand when applying solar cells in transparent facades



Danish Technological Institute

Energy and Climate Division

Impact on indoor climate and energy demand when applying solar cells in transparent facades

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Preface

The report concludes the work regarding the thermal indoor conditions and energy demand when using solar cells in transparent facades. The work is part of the project Thi-Fi-Tech - Application of thin-film technology in Denmark financed by PSO ForskEL project no. 2008-1-0030.

The project is a continuation of the PSO ForskEL project LYS OG ENERGI – solceller i transparente facader project no. 2006-1-6302 reported in (Wedel, 2008). The work in this report is a continuation of the work reported in (Jensen, 2008a).

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Thi-fi-tech has been carried out by a team consisting of:

Danish Technological Institute (project leader), Danish Building Research Institute, En^{2}tech, EnergiMidt A/S, PhotoSolar A/S, Gaia Solar A/S, Caspersen & Krogh Arkitekter A/S, Entasis, Esbensen Rådgivende Ingeniører A/S, Arkitema A/S, Danfoss Solar Inverters A/S.

The project is documented in the following reports:

Application of thin-film technology in Denmark – Summary Report

With the following annex reports:

1 Application of thin-film technology in Denmark - Feasibility study
2 Application of thin-film technology in Denmark – Measurements and comparison of performance under realistic operational conditions
3 Assessment of indoor light and visual comfort when applying solar cells in transparent facades
4 Impact on indoor climate and energy demand when applying solar cells in transparent facades (the present report)
5 Application of thin-film technology in Denmark - Product development
6 Application and design of light filtering solar cells
7 Application of thin-film technology in Denmark - Medium and large scale demonstration

The reports are available on: www.teknologisk.dk/projekter/projekt-thi-fi-tech/32454.

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Summary

Solar radiation entering a building may cause discomfort either because a person is directly heated by the sun or because the building generally is overheated. The purpose of the report is to investigate if solar cells imbedded in the transparent parts of the façade (windows) may reduce these problems. The solar cells in the transparent parts of the façade will act as sun-screening while at the same time produce electricity.

It is, however, rather difficult to describe/determine how solar cells in the transparent part of surfaces of a building will influence the perceived indoor climate of the building. This is highly dependent on the design and use of the building, the applied technical installation (heating, ventilation, cooling and artificial lighting) and the control of these, the size of the transparent surfaces and how large part of these have integrated solar cells, the size of internal gains, where the people are situated, the comfort level of these people, etc.

Two ways of characterising the impact of solar cells in windows on comfort has been investigated in the report:

- direct heating of a person either by being hit directly by the sun or sitting next to a window which the sun heats up
- the derivative effects: how the solar cells influence the energy demand necessary to obtain a good indoor thermal climate. In this way the influence on the indoor climate may be quantified and it is possible based on energy cost to evaluate and choose between different designs and degrees of solar cells in the transparent surfaces.

In chapter 2 and 4 it is shown that by reducing the transparent area of a window when including solar cells this will lead to a reduction of the temperature of the internal glass pane of the window and the person being hit by solar radiation will be less annoyed. An equation for the discomfort of being hit directly by solar radiation has been developed. However, in order to obtain these effects it is necessary that the opening degree of the window is low (i.e. a large part of the window is covered with solar cells), which may lead to visual discomfort. A solution may be to work with different opening degrees in different parts of the façade.

In chapter 3 it is investigated how solar cells in the transparent part of the façade will affect the energy demand of the building. It is concluded that this measure should mainly be considered in buildings with a large cooling demand, as no cooling demand leads to no energy benefits. At high cooling demands solar cell windows perform from an energy point of view better than traditional solutions as solar control coating and movable sunscreening.

Calculations of the benefit of applying solar cells in windows should, however, always be performed for the actual case. When calculating the benefit of applying solar cells in the transparent facades it is important to include the efficiency of the energy supply systems especially for the cooling system, the primary energy conversion factors and the pv production. However, often the decision of introducing solar cells in the windows should be based on other reasons than energy: cost (e.g. cost of pv windows, reduction of cooling plant), visual comfort, signal value, etc.

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1. Introduction

Solar radiation is known to may cause considerable discomfort to people in buildings. This discomfort may be divided in three groups:

- discomfort due to elevation of the mean room temperature in the building
- discomfort due to temperature asymmetry – i.e. because one surface gets warmer that the other surfaces in the room e.g. a warm floor where the solar radiation hits or a warm window due to absorption of solar radiation in the window
- discomfort when people are directly hit by solar radiation

The discomfort of the first group may be reduced using cooling and solar shading devices, while the other two may be reduced using solar shading devices which however may create visual discomfort.

Much research has been carried out for the two first groups while less research has been performed on the relationship between comfort and solar radiation hitting people in buildings. Some studies have however been carried out concerning comfort and solar radiation in cars as the view here is mandatory and people therefore are hit by solar radiation.

Solar shading in buildings are normally obtained by e.g. external overhangs, shutters, lamellas, venetian blinds or internal venetian blind and curtains or solar control film within the windows. In this report the effect of screening of solar radiation by integration of solar cells in the glazed surfaces is investigated. Figure 1.1 shows different ways of introducing solar cells in glazed surfaces.

The different ways of integrating solar cells in transparent facades in figure 1.1 are:

a) evenly distributed thin film solar cells. Solar transmittance is allowed due to the distance between the solar cells.
b) graduated distribution of thin film solar cells. Solar transmittance is also here allowed due to the distance between the solar cells.
c) PEC (Photo electrochemical) solar cells. PEC cells can be made partly transparent for different wave length of the light.
d) crystalline solar cells. Solar transmittance is allowed due to the distance between the solar cells.
e) PowerShades which is a thin metal foil on one of the glasses with small intelligent holes for solar transmittance – see also section 2.1.1.2. Thin film solar cells are integrated on the opaque parts of the thin metal foil.

As the focus of the present project is thin film solar cells only a), b) and e) will be investigated in the following. However, the obtained results may also be applied in connection with c) and d).

Further - the work of the present report is focused on discomfort due to elevation of the mean room temperature and discomfort due to direct radiation on the body – i.e. the first and third of the above bullets. The second bullet was already dealt with in (Jensen, 2008a) and the results from here will be presented in chapter 2.

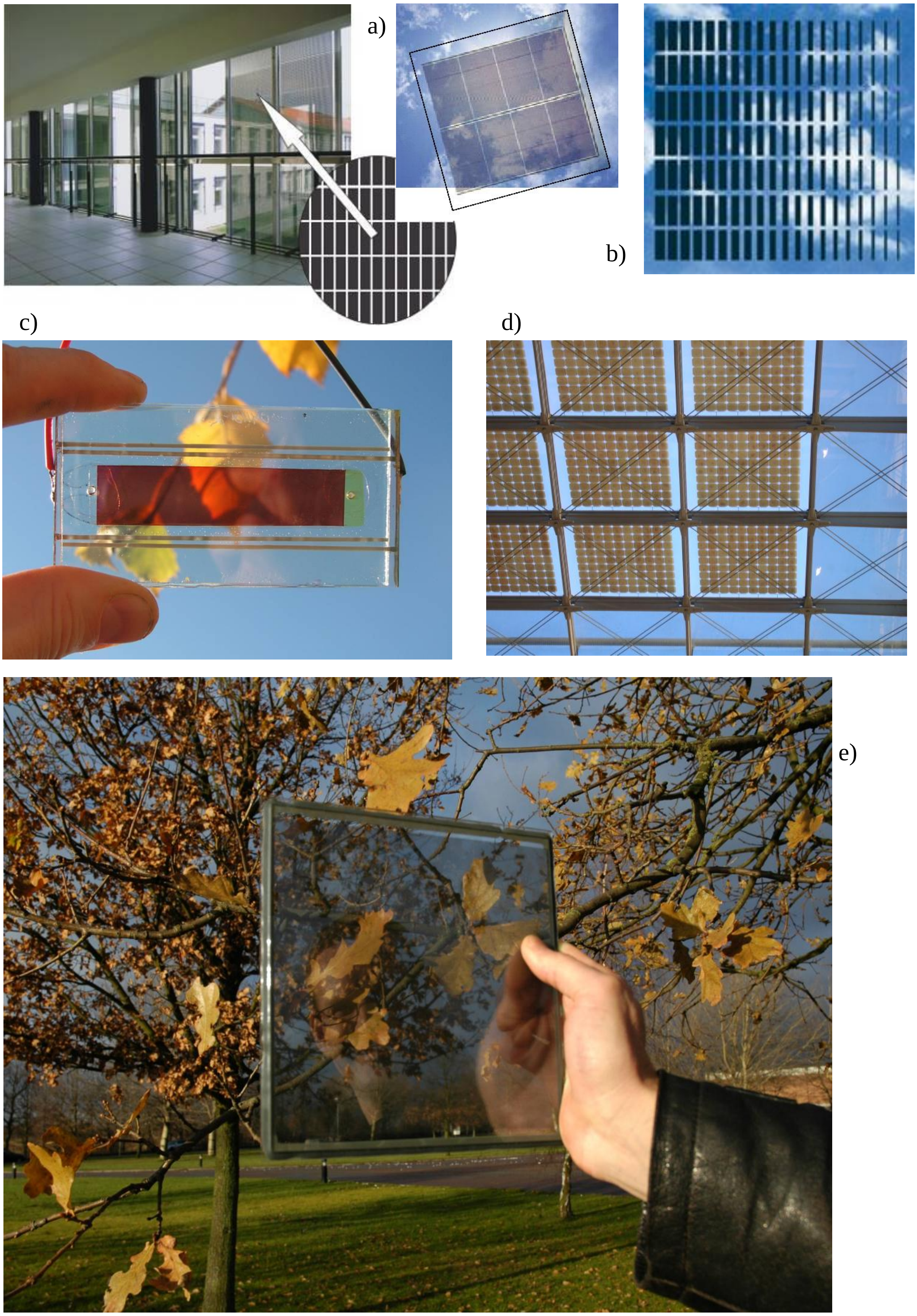


Figure 1.1. Glazed surfaces with different kinds of integrated solar cells as screening devices.

1.1. Theory

Figure 1.2 shows the thermal and optical processes which occur in a window. The figure shows the rather complex nature of the occurring processes: transmission, absorption, reflection, convection, conduction, long wave radiation, 2 and 3D heat flows and infiltration.

Usually it is not necessary to describe windows at this level of details when the energy demand and indoor thermal climate are being evaluated. Typically several of the processes may be combined in two main parameters as shown in figure 1.3: the U- and g-value. The U-value characterise the combined heat loss through the window (except for the infiltration) while the g-value characterise how large a part of the solar energy hitting the window is transferred to the room behind it. The g-value consists of two parts: the directly transmitted solar energy and the solar energy transferred to the room due to the heating up of the internal pane of the window – in figure 1.3 denoted q_i. In a more precise determination of the energy demand and indoor thermal climate the following three parameters is also needed:

- the infiltration – normally an overall values for the whole building or room is used instead of for each construction in the thermal envelope
- the light transmittance in order to be able to determine the need for artificial lighting. Normally not identical to the transmittance of solar radiation as visible light is only part of the wave lengths of the solar radiation
- the directly transmittance for solar radiation – to be used when determining the discomfort when being hit directly by solar radiation through the window

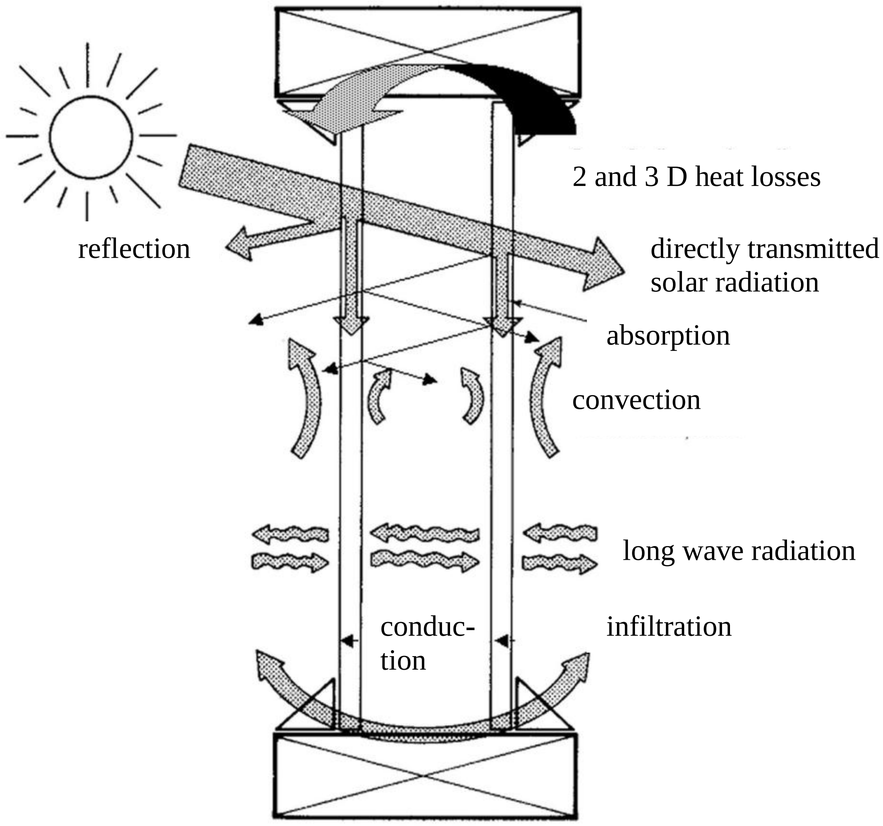


Figure 1.2. The optical and thermal processes in a window.

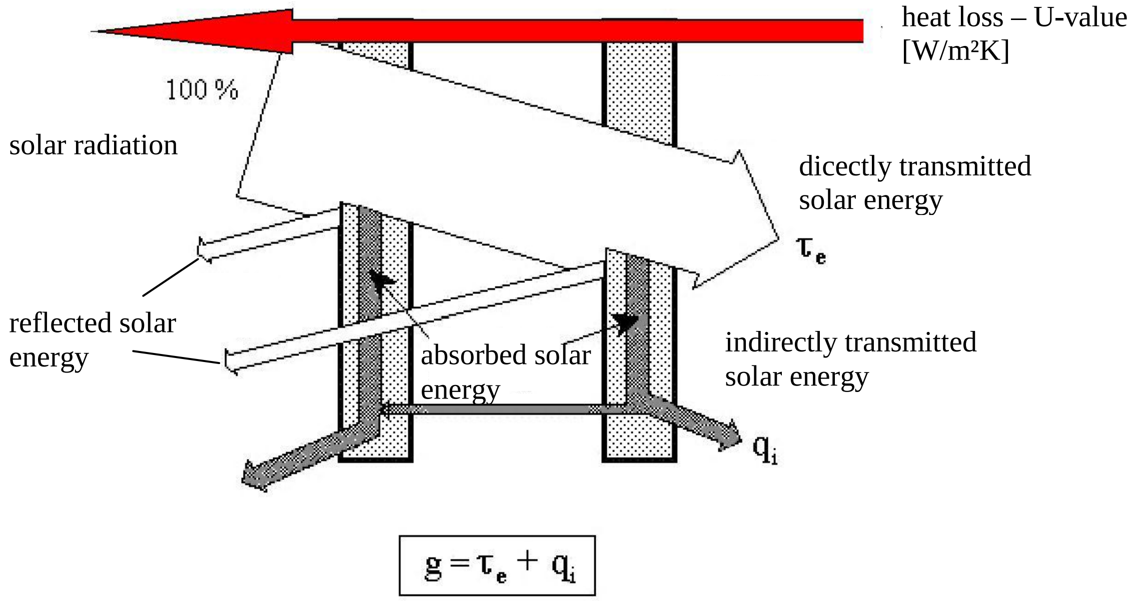


Figure 1.3. A window is normally characterized by an U-værdi (heat loss) and a g-værdi (total transmitted solar energy).

In case the wish is to investigate the heating up of the internal window pane most of the parameters in figure 1.2 have to be known.

1.1.1. The U- and g-value of windows with integrated solar cells

The U-value (also called the dark U-value) is independent of if solar cells are integrated in the window or not as this value is determined without solar radiation. Furth the heat conduction of the solar cells and glass has only very little influence of the overall U-value of a window.

The g-value depends on the amount of clear glass between the solar cells – the opening degree - a), b), c) and d) in figure 1.1. The larger the opening degree is the larger is τ_e in figure 1.3. The larger τ_e is the more solar heat may be absorbed in the internal window pane which results in a larger q_i in figure 1.3. However, the g-value is also dependent on the U-value because the absorbance of the solar cells is normally high which during solar radiation leads to high temperatures of the external window pane where the solar cells normally are mounted. How much of this heat is transferred to the internal window pane is dependent on the U-value of the window. The higher U-value the more energy is transferred from the external to the internal window pane and the higher q_i gets. See also section 2.2.

2. Summary of previous work

The three areas:

- discomfort due to elevation of the mean room temperature in the building
- discomfort due to temperature asymmetry
- discomfort when people are directly hit by solar radiation

have earlier - with regards to the influence of solar cells in transparent facades - been investigated at the Danish Technological Institute (Jensen, 2008a and 2010). The results from these investigations will briefly be summarized in the following as they form the basis for the work carried out in relation to the present report.

2.1 Discomfort due to elevation of the mean room temperature

It is rather difficult to describe/determine how solar cells in the transparent surfaces of the building will influence the perceived indoor climate of the building. This is highly dependent on the design and use of the building, the applied technical installation (heating, ventilation, cooling and artificial lighting) and the control of these, the size of the transparent surfaces and how large part of these have integrated solar cells, the size of internal gains, where the people are situated, the comfort level of these people, etc.

Instead of trying to determine the direct influence of solar cells (in the transparent surfaces) on the indoor comfort it is in (Jensen, 2008a) suggested to focus on the derivative effects: how the solar cells influence the energy demand necessary to obtain a good indoor thermal climate. In this way the influence on the indoor climate may be quantified and it is possible based on energy cost to evaluate and choose between different designs and degrees of solar cells in the transparent surfaces.

Installation of solar cells in the transparent surfaces influences several energy processes in a building:

- the cooling demand (if any) will be reduced
- the heating demand will typically increase
- the need for artificial lighting will typically increase

i.e. integration of solar cells in the transparent surfaces may lead to a reduced cooling demand but an increased demand for heating and artificial lighting. The optimal solution thus has to be found based on calculations/simulations with different degrees of solar cells in the transparent surfaces – further explained in section 2.1.2.

2.1.1. U-, g-values and light transmittance

In order to be able to calculate the demand for cooling, heating and artificial light it is among many other things necessary to know the U-, g-value and light transmittance of the transparent surfaces with solar cells.

The U-value is as explained in chapter 1 not dependent on the degree of solar cells in a window. The U-value is dependent on number of glasses in the window, the type of gas in the gap(s) between the glasses and if low emissivity coating is applied on the glasses.

The g-value and light transmittance is however highly dependent on the degree of solar cells in a window. In the previous project (Wedel, 2008 and Jensen, 2008a) a number of glasses/panels with different degrees of integrated solar cells were purchased. 6 of these glasses where tested in the gonios spectrometer at BYG·DTU (Schultz, 2007) where the transmittance of solar radiation and light were measured. The 6 glasses with integrated solar cells are listed in table 2.1. The first 5 products in table 2.1 were thin film solar cells like a) i figure 1.1 while the reference had integrated crystalline solar cells like d) in figure 1.1. The solar cells of the 6 panels where all imbedded within two layers of glass – ie. a total thickness of about 10 mm instead of the normal 4 mm glass used in windows.

Manufacture	Name of product	opening degree, %
Wûrth Solar	WSS0007	8
	WSS0008	21
	WSS0009	22
MSK	HQ PV Glass 44 Wp	10
	HQ PV Glass 50 Wp	4
Interpane	(reference)	31

Table 2.1. Opening degree (% of transparent area compared to the total area of the glass) for the 6 glasses with integrated solar cells tested at BYG•DTU.

Table 2.2 shows the measured transmittance of solar radiation (τ_e) and light (τ_v). At an incidence angle of 0° for all glasses and at different incidence angle for one of the glasses.

i_v	**Product**											
	WSS0007		WSS0008		WSS0009		MSK-HQ 44 Wp		MSK-HQ 50 Wp		Reference Interpane	
	τ_e	τ_v	τ_e	τ_v	τ_e	τ_v	τ_e	τ_v	τ_e	τ_v	τ_e	τ_v
0°	0.06	0.07	0.16	0.17	0.17	0.18	0.07	0.08	0.03	0.04	0.24	0.25
30°			0.15	0.17								
45°			0.15	0.17								
60°			0.14	0.16								
75°			0.12	0.14								

Table 2.2. Measured transmittance of solar radiation (τ_e) and light (τ_v) (Schultz, 2007).

The measurements for different incidence angle for WSS0008 show not surprisingly that the relationship between the incidence angle and transmittances is the same as for glasses without solar cells – equation [2.1] and figure 2.1. There was thus no reason for doing the measurements for the other glasses at different incidence angles:

$$\tau_\theta = \tau_0 \times (1-\mathrm{tg}^{\alpha}(\theta/2)) \quad \text{where } \theta \text{ is the incidence angle} \qquad [2.1]$$

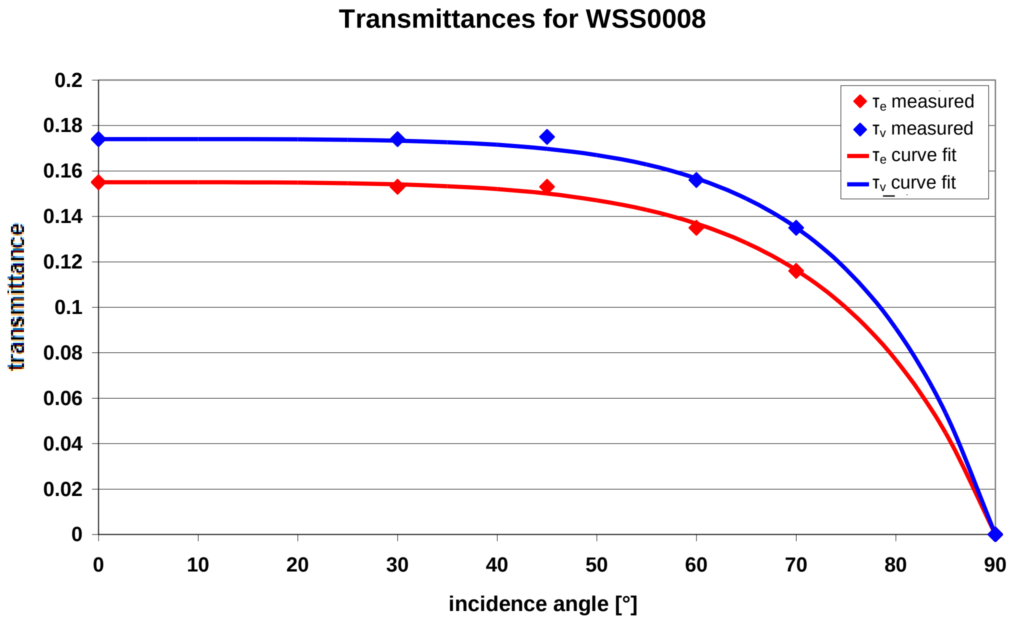


Figure 2.1. The measured transmittances dependent on the incidence angle for WSS0008 (Schultz, 2007).

Based on the transmittance of solar radiation from table 2.2 it was possible to calculate the g-values for windows where the glasses in table 2.2 are the external glass of a two pane window. The program WINDOW 5 (LBNL, 2012) was applied for the calculation of the g-values and light transmittance. The result is shown in tables 2.3-4 for two types of windows: a traditional two pane air filled window (U-value = 2.8 W/m²K) and a two pane Argon filled low-E window (U-value = 1.2 W/m²K) as the U-value as earlier mentioned influences the g-value.

The g-values are further shown for two seasons: heating season and summer as the ambient and indoor temperature levels are different for these two seasons. The heating season g-value for determining energy demand and the summer g-value to investigate the risk of overheating.

Figure 2.2 shows the calculated six g-values and light transmittances (+ for the g-value also for a window with no integrated solar cells) for a two pan low-E window (U_g = 1.2 W/m^{2}K) for the heating season from table 2.3. The figure shows a linear dependence of the transmittances on the opening degree:

g-value: $g = 0{,}045 + 0{,}0053 * A$ [2.2]

light transmittance: $\tau_v = 0{,}0072 * A$ [2.3]

where A is the opening degree [%].

The above investigations show that it for this type of windows with integrated solar cells isn't necessary to perform detailed measurements in order to define the g-value and the light transmittance. If the opening degree and the optical properties of the glass is known the values can directly be obtained using equation 2.1 and 2.2 if the window is a low-E window with an U-value of 1.2 W/m²K. For other window types it is possible based on the measurements in table 2.2 and the program WINDOW to generate similar equations as 2.2 and 2.3.

Product as external glass	Air filled 2 pane window $U_g = 2.8$ W/m²K		Argon filled 2 pane low-E window $U_g = 1.2$ W/m²K	
	Transmittance of solar radiation, g	Light transmittance, τ_v	Transmittance of solar radiation, g	Light transmittance, τ_v
WSS0007	0.15	0.07	0.09	0.06
WSS0008	0.23	0.16	0.15	0.15
WSS0009	0.24	0.17	0.16	0.16
MSK-HQ 44 Wp	0.16	0.07	0.09	0.07
MSK-HQ 50 Wp	0.13	0.04	0.07	0.04
Referenceglas	0.29	0.23	0.20	0.22

Tabel 2.3. Heating season ($T_{ambient} = 0$ °C. $T_{indoor} = 20$ °C. Standard thermal resistance: $I_{sol} = 500$ W/m²). The g-value is calculated for both a traditional air filled 2 pane window and a 2 pane Argon filled low-E window (Schultz, 2007).

Product as external glass	Air filled 2 pane window $U_g = 2.8$ W/m²K		Argon filled 2 pane low-E window $U_g = 1.2$ W/m²K	
	Transmittance of solar radiation, g	Light transmittance, τ_v	Transmittance of solar radiation, g	Light transmittance, τ_v
WSS0007	0.23	0.07	0.13	0.06
WSS0008	0.30	0.16	0.19	0.15
WSS0009	0.31	0.17	0.20	0.16
MSK-HQ 44 Wp	0.23	0.07	0.13	0.07
MSK-HQ 50 Wp	0.20	0.04	0.11	0.04
Referenceglas	0.35	0.23	0.24	0.22

Tabel 2.4. Summer ($T_{ambient} = 30$ °C. $T_{indoor} = 25$ °C. Standard thermal resistance: $I_{sol} = 500$ W/m²). The g-value is calculated for both a traditional air filled 2 pane window and a 2 pane Argon filled low-E window (Schultz, 2007).

2.1.1.1. PowerShades

However, the linear dependency of the g-value and light transmittance is only valid for the type a), b) and d) products in figure 1.1 and not for MicroShades where the angular dependency on the incoming solar radiation is more complex as seen later.

PowerShades constitutes - like venetian blinds - a product where there isn't a direct link between the resulting incidence angle and the g-value and light transmittance.

PowerShades are at the moment not commercially available but are planned to be introduced to the market in 2016. PowerShade is MicroShade™ with thin film solar cells on the surface facing the sun. MicroShade is a thin metal sheet with a microstructure of small holes. Figure 2.3 shows an example of MicroShade. MicroShade consists of many small super elliptic shaped holes manufactured in a thin stainless steel sheet – see figure 2.3. The holes have a tilting angle and resemble the way venetian blinds function. This means that it is possible to look through PowerShades but direct radiation especially around noon on a summer day is cut off. How much is cut of depends on the displacement of the back hole compared to the front hole – i.e. equal to the tilt angle of venetian blinds. This result in an angular dependency of the g-value and light transmittance that is dependent on the actual combination of solar height and azimuth of the sun.

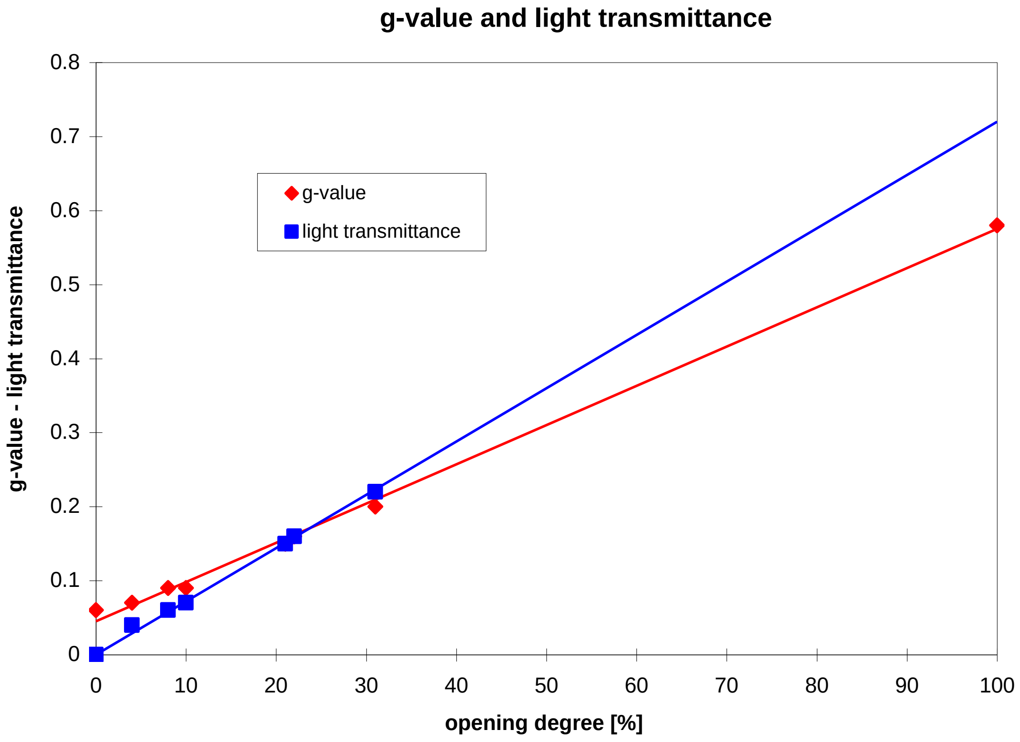


Figure 2.2. The dependency of the g-value and the light transmittance on the incidence angle for a two pane low-E window.

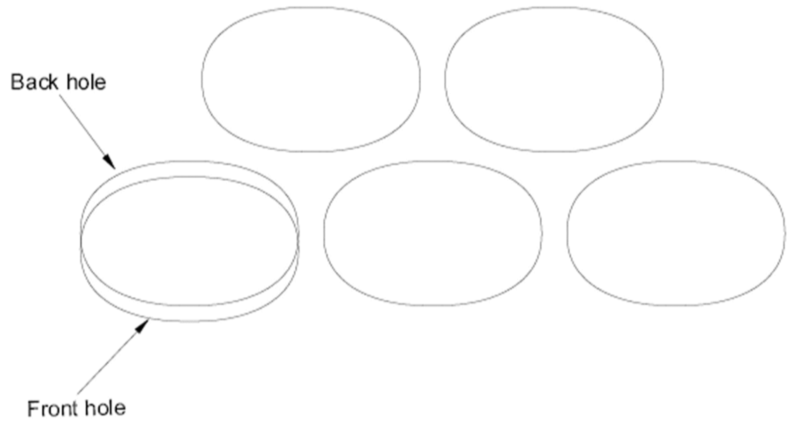


Figure 2.3. Example of the holes in MicroShade. The width of the holes is less than 1 mm.

Based on the research on MicroShades reported in (Jensen, 2010) a relationship between g-values/light transmittance and the solar height and azimuth of the sun has been established as shown in tables 2.5-6. The solar height is the vertical incidence angle on the window while the azimuth is the horizontal incidence angle.

Azimuth [°]	Solar height [°]					
	0	15	30	45	60	75
0	0.39	0.34	0.29	0.21	0.09	0.03
15	0.38	0.34	0.28	0.20	0.08	0.03
30	0.35	0.31	0.26	0.18	0.07	0.03
45	0.30	0.27	0.21	0.14	0.05	0.03
60	0.20	0.17	0.13	0.07	0.03	0.02
75	0.03	0.03	0.03	0.03	0.02	0.01

Table 2.5. The dependency of the g-value on the combination of the azimuth and solar height on the plane of the window. MicroShade type MS-A in a two pane Argon filled low-E window (U-value 1.1 W/m²K) (PhotoSolar, 2012).

Azimuth [°]	Solar height [°]					
	0	15	30	45	60	75
0	0.48	0.42	0.34	0.23	0.07	0
15	0.47	0.40	0.33	0.22	0.06	0
30	0.43	0.37	0.30	0.19	0.04	0
45	0.35	0.31	0.24	0.14	0.02	0
60	0.21	0.18	0.12	0.05	0	0
75	0	0	0	0	0	0

Table 2.6. The dependency of the direct light transmittance on the combination of the azimuth and solar height on the plane of the window. MicroShade type MS-A in a two pane Argon filled low-E window (U-value 1.1 W/m²K) (PhotoSolar, 2012).

2.1.2. Evaluation method

A method for evaluation of the energy demand of a building dependent on the use of solar cells was developed in (Jensen, 2008). The method was tested and demonstrated using the calculation program Be06 version 2.7.5.2 (the current version of the program is Be10 (SBi, 2012a)). As test case was use one floor of an office building.

2.1.2.1. Be06 (and Be10)

Be06 was chosen to be used in the development of the evaluation method because it is rather simple and fast to use. Be06 is not a simulation program but more of a registration program. The calculation core of Be06 is mandatory to be used when applying for a building permit – the aim here is to determine if the building comply with the energy requirements of the Danish Building regulation under standard use of the building. The calculation core is also applied in the labeling scheme of Danish buildings which means that Be06 input files exists for many Danish building.

The calculation is fast as it is based on mean monthly values and the geometry is a single zone model. Although simple it is possible in a rather detailed way to specify the thermal envelope and installations of the building. The main output is the total primary energy demand of the building per m² gross floor area. The primary factors were in Be06: 2.5 for electricity and 1 for other energy carriers. However net energy demands are also available.

2.1.2.2. Test case

It was chosen to test and demonstrate the evaluation method on a building where all necessary data already were available as it also has been used as test case of a project prior to the here summarized project (Hansen and Jensen, 2005).

The test case is a domicile for a bank with large south and east facing glazed facades as seen in figure 2.4. One floor containing one single open space office was chosen for the demonstration. The gross floor area is 642 m². The floor layout is shown in figure 2.5.

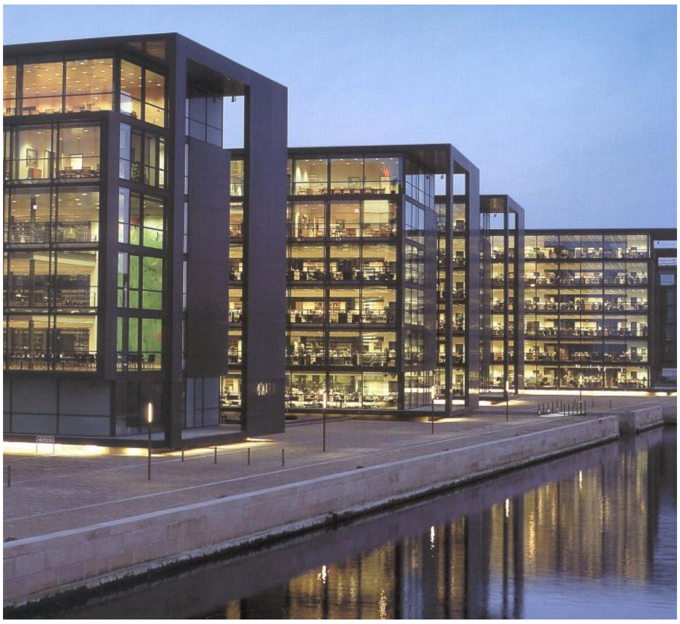


Figure 2.4. Photo of the building of the test case.

Figure 2.5. Floor plan of the single open office space used in the test case.

In order to avoid overheating the south façade is beside windows with solar control films (g-value: 0.32) equipped with semitransparent movable external blinds (see figure 2.6) which over the day automatically is positioned correctly with regards to the height of the sun. 90 % of the 135 m² south (and north) facing facades is glazing.

Figure 2.6. Automatically movable external blinds on the south façade.

For details on the input data for the calculations please refer to (Jensen, 2008a),

2.1.2.3. Results from the test case

In the Be06 calculations the exiting glazed south façade was replaced with the two pane Argon filled low-E windows shown in table 2.3. The result is shown in figure 2.7. In order to increase the range of the curves a two pane Argon filled low-E windows without solar cells were also introduced together with two “helping points” in order to obtain smooth curves. g-values and light transmittances of all simulations are shown in table 2.7.

Type of window	g-value	light transmitterne
WS0007	0,09	0,06
WS0008	0,15	0,15
WS0009	0,16	0,16
MSK HQ 44 WP	0,09	0,07
MSK HQ 50 WP	0,07	0,04
Interpane (reference)	0,2	0,22
Without solar cells	0,58	0,74
Helping point 1	0,29	0,30
Helping point 2	0,39	0,44
North side	0,32	0,53

Table 2.7. The applied g-values and light transmittances. The g-value of 0.58 for the window without solar is lower than normal because the outer glass is – as for the windows with solar cell – 10 mm instead of the normal 4 mm.

Figure 2.7 shows as expected that the energy demand for heating and artificial lighting decreases with increasing g-value while the cooling demand increases with increasing g-values.

The figure further shows that the optimal g-value is 0.15 (opening degree: 20%) when looking at the net energy demand and 0.2 (opening degree: 29%) when looking at the total gross energy demand.

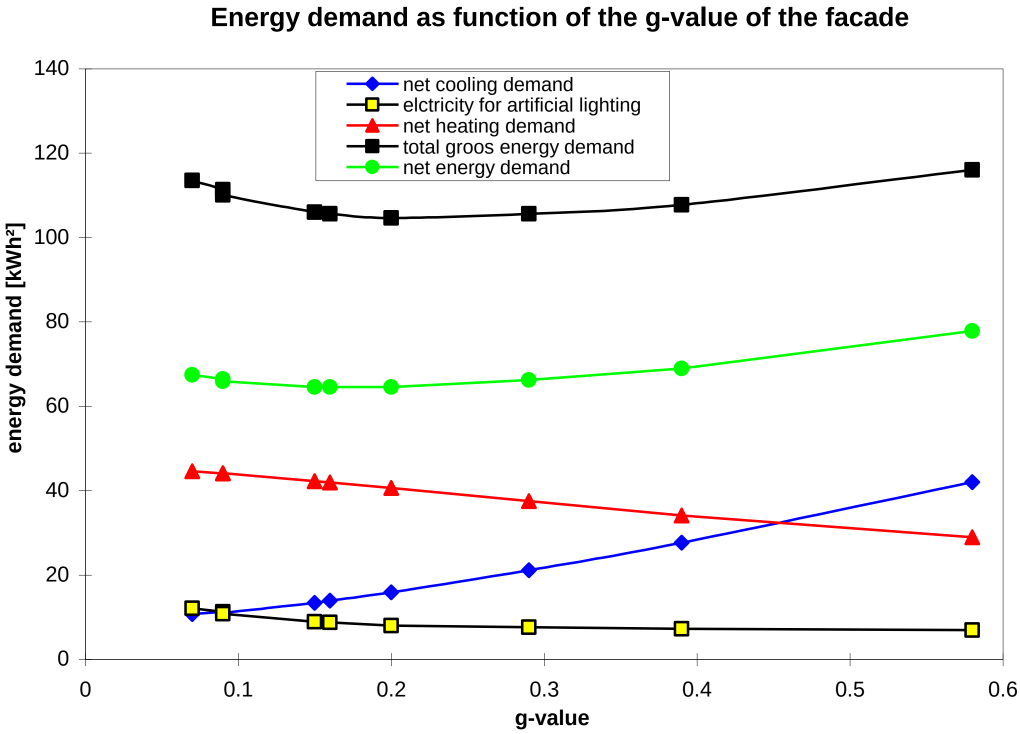


Figure 2.7. Net and gross energy demands dependent on the g-value of the south façade.
- net energy demand: sum of net cooling demand, electricity for artificial lighting and net heating demand.
- total gross energy demand: the total energy demand (also including electricity to e.g. fans of the ventilation system) where the electricity is multiplied with an primary energy factor of 2.5.

However the curves for the net and total gross energy demand are in this case rather flat between g-values of 0.15 – 0.4 (openings areas: 20 and 67%). This may be due to the fact that it is one single open space office where the cooling demand of the south part of the office is even out with the heating demand of the north part of the office. This is also the way Be06 calculates as it only assumes a single zone. The calculated cooling demand is further reduced as the cooling i Be06 differently for reality first starts at room temperatures above 25°. The method is therefore also tested with a detailed simulation program in chapter 3.

Figure 2.7 indicates that solar cells should not be introduced in the glazed facades if there is no cooling demand as the heating demand and electricity use for artificial lighting increases with decreasing g-value (opening degree). However, other reasons may speak for integration of solar cells in parts of the glazed facades: one is local comfort conditions next to the glazed facades – this is dealt with in the following sections – the other is need/wish for an electrify production also from the gazed facades. This is investigated in figure 2.8, where the electricity production of the applied solar cells also is included. The “chopped” appearance of the curve for the electricity production is as shown in table 2.8 caused by the fact that the efficiency of the solar cells are rather different. This is very clear in the curve "new total gross energy demand" where the electricity production is subtracted (and multiplied with the primary factor of 2.5) the "total gross energy demand". The introduction of the electricity production however does not shift the optimal g-value from around 0.2.

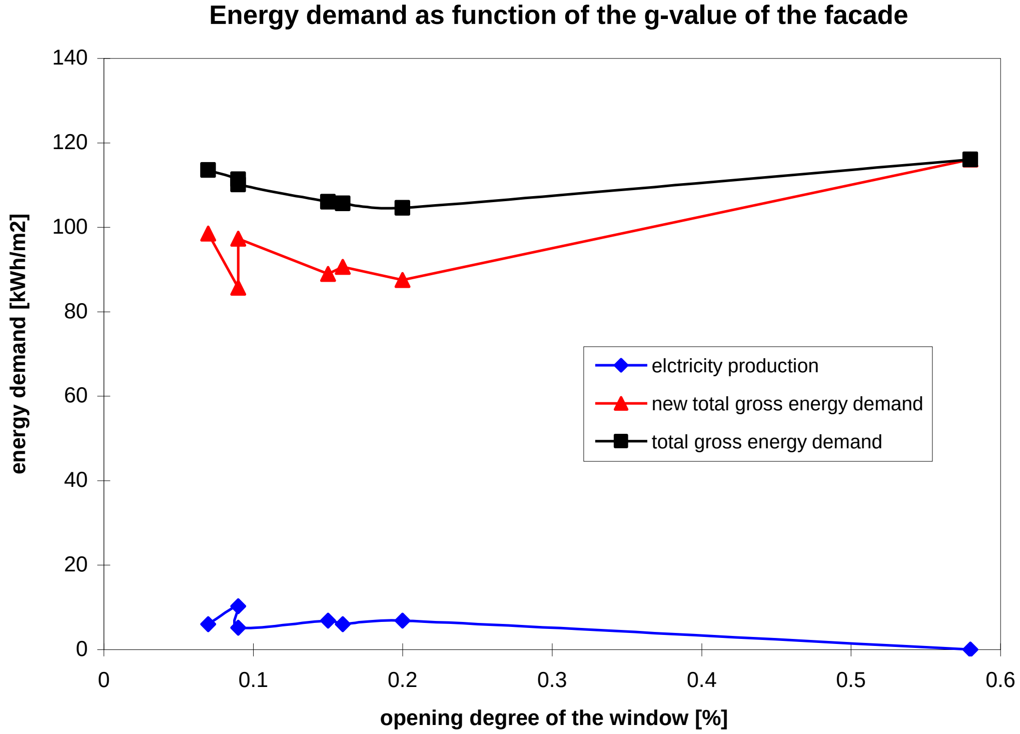


Figure 2.8. The electricity production of the solar cells and the influence of this on the total gross energy demand.

Solar cells in the window	g-value	annual eletricity production kWh/m²
WS0007	0,09	60
WS0008	0,15	40
WS0009	0,16	35
MSK HQ 44 WP	0,09	30
MSK HQ 50 WP	0,07	35
Interpane (reference)	0,2	40
Without solar cells	0,58	0

Table 2.8. Annual electricity production of the solar cell windows for a south oriented vertical location without shading.

2.2. Discomfort due to temperature asymmetry

Solar cells get hot when they are hit by solar radiation – up to above 70°C. One could therefore fear that the internal glass in windows with solar cells integrated in the external glass would become so hot that it would decrease the comfort level behind the window as it is uncomfortable to sit next to a surface which is considerable warmer than the air temperature.

Based on the measurements and calculations in section 2.1.1 (Schultz, 2007) the thermal and optical properties of the windows in table 2.3-4 are fully known including the absorptance of the glasses and solar cells. These properties were used as input to a very details simulation program (ESRU, 2012) which is capable of simulating the heating up of the two glasses that occurs in solar cell windows. The calculations were carried out for a south facing façade where the air temperature in the room behind the glazing was 21°C. As weather data was used the Danish Test Reference Year (TRY) (SBi, 1982).

The result is shown in figures 2.9-12 – more details may be found in (Jensen, 2008a). The figures show how many hours the glass temperature is below a certain level.

Figures 2.9-10 shows the results from simulations carried out on two pane Argon filled low-E windows with the six types of solar cells from table 2.2 and without solar cells. Figure 2.9 shows that the highest temperature reached in the external glass is 80°C for the solar cell window with the lowest opening degree while the max temperature of the window without solar cells only is 37°C. So occasionally there is a risk of getting burned when touching the external glass of a solar cell window. So solar cells should never be integrated in the internal glass. However, when looking at figure 2.10 the high external temperature is not reflected in the temperature of the internal glass. The internal temperature of the solar cell windows is in fact slightly lower than the internal temperature of the window without solar cells.

The reason for this is that although the external glass in a solar cell window gets very hot only little of this heat is transferred to the internal glass due to the Argon filling and the low-E coating of the internal glass. The reason for the internal glass being less warm compared to the window without solar cells is that due to the low opening degree only little solar radiation is hitting the internal glass which thus absorbs less solar radiation than the internal glass of the window without solar cells. Further: the low-E coating on the internal glass results in a high absorptance of this glass leading to the higher temperatures of the internal glass of the window without solar cells.

As the internal temperature of the windows is only slightly dependent on the opening degree this also means that the internal temperature of the windows will not be influence by how large a fraction of the solar radiation which is transformed into electricity by the solar cells. The indoor climate is, therefore, not influenced by the pv production.

The same figures as 2.9-10 was created for two pane air filled windows without low-E coating. This is shown in figures 2.11-12 where only the solar cell window with the lowest opening degree is shown together with the window without solar cells.

Again the external temperature of the solar cell window is highest – although now only up to 70°C due to a higher heat loss to the internal glass. Now the internal glass is also warmer in the solar cell window and up to 10 K warmer than shown in figure 2.10. The internal glass temperature of the window without solar cells is a little bit lower than in figure 2.10 because of the missing low-E coating which increases the absorptance of the internal glass in the low-E window.

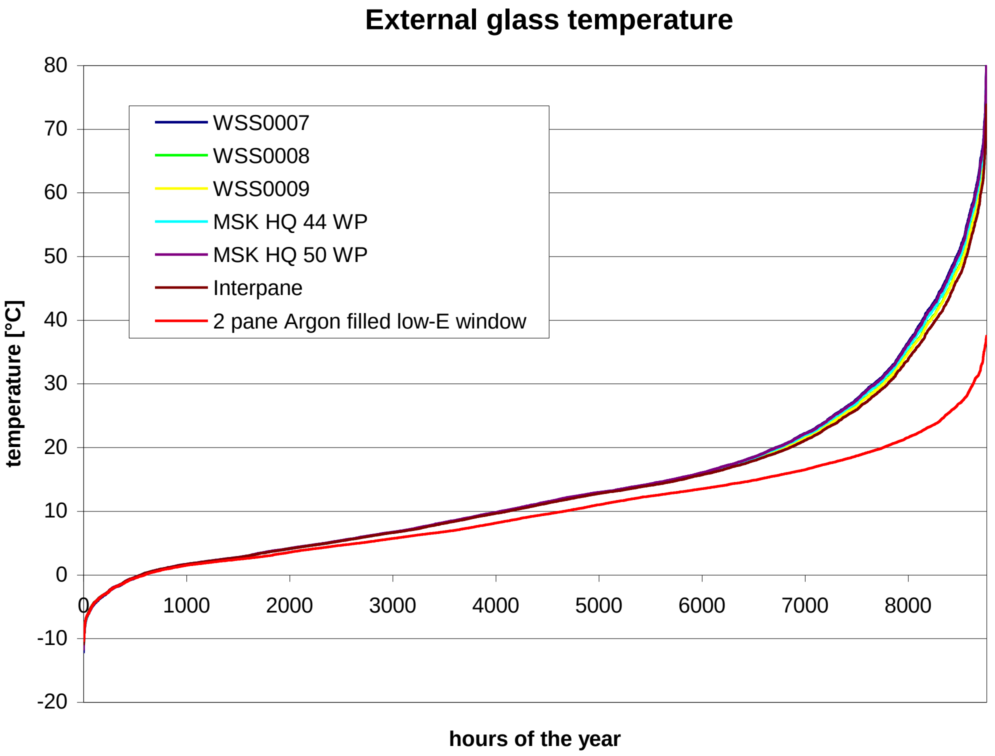
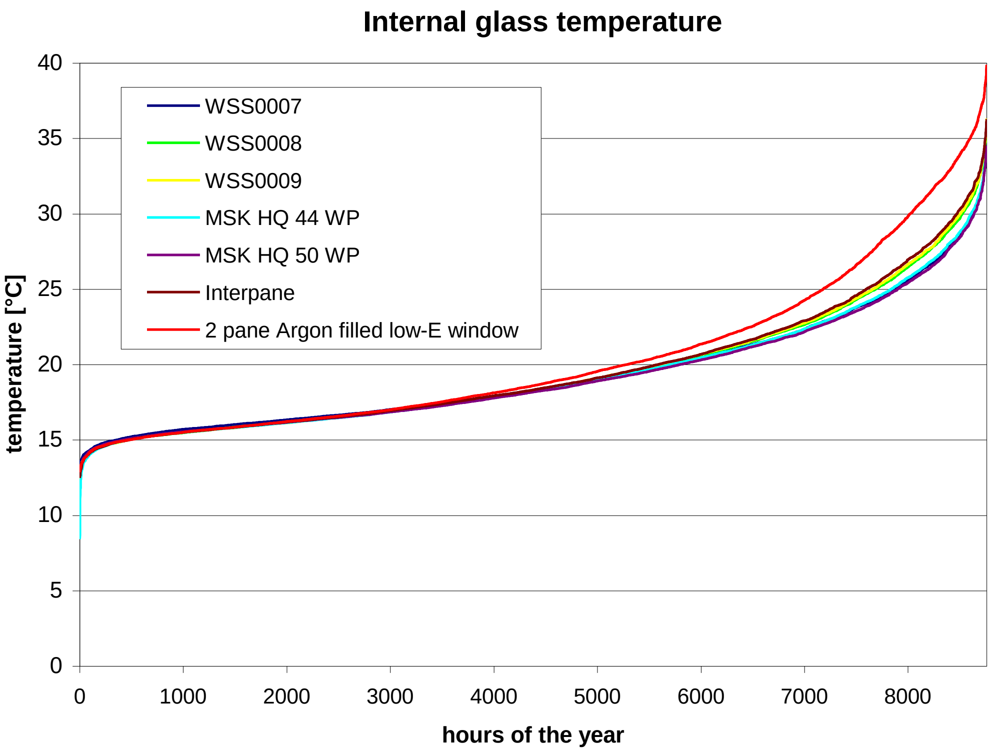
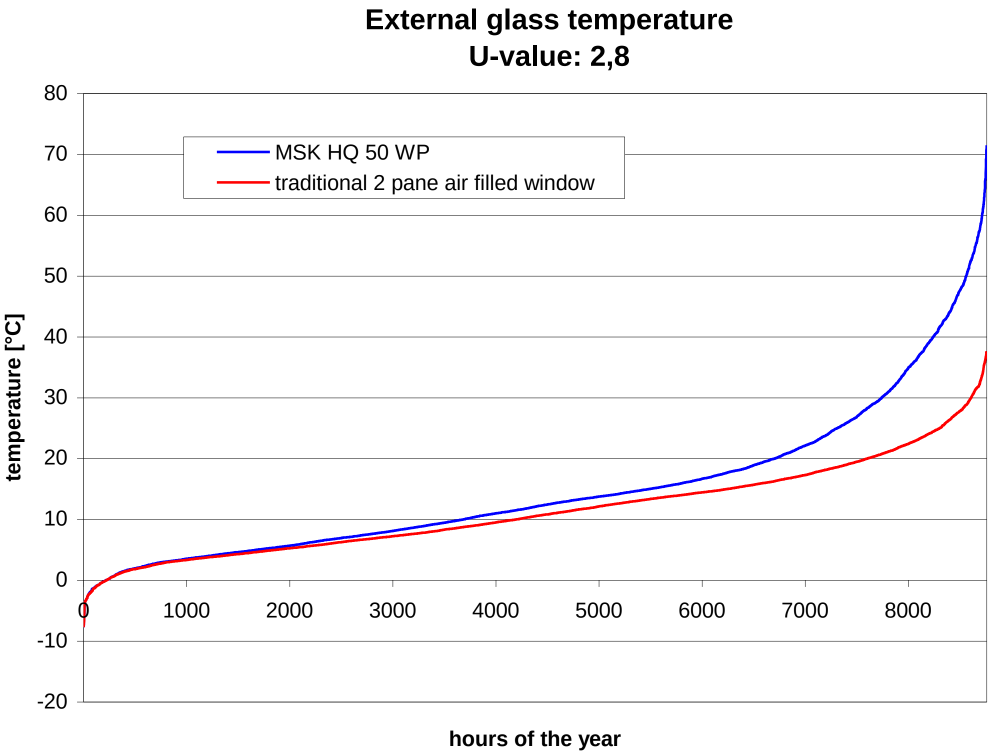


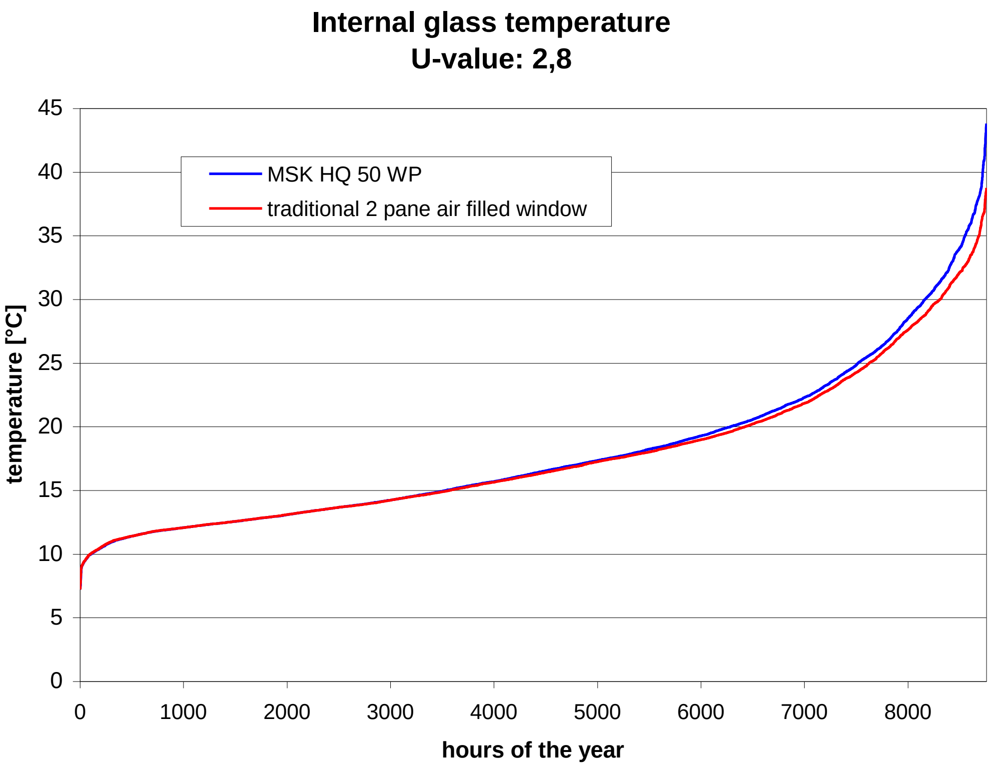
Figure 2.9. External glass temperature of two pane Argon filled low-E windows with the six types of solar cells from table 2.2 and without solar cells.



Figur 2.10. Internal glass temperature of two pane Argon filled low-E windows with the six types of solar cells from table 2.2 and without solar cells.



Figur 2.11. External glass temperature of two pane air filled windows with the MSK HQ 50 WP solar cells from table 2.2 and without solar cells.



Figur 2.12. Internal glass temperature of two pane air filled windows with the MSK HQ 50 WP solar cells from table 2.2 and without solar cells.

However, two pane air filled windows without low-E coating will hardly be applied any more as these increase the heating demand and decrease the comfort level as the internal surfaces during the winter gets so low that it may create discomfort due to temperature asymmetry and draft due to the indoor air getting cooled down along the internal surface of the window.

2.3. Discomfort when hit directly by solar radiation

Even though the internal temperature of a window does not create uncomfortable temperature asymmetry it may still be uncomfortable to sit next a window during clear sky condition when the person is hit directly by the solar radiation.

An investigation of this was started in the PSO ForskEL project PowerShades II - optimization and validation of highly transparent photovoltaic project no. 2008-1-004 financed by Energynet.dk (Jensen, 2010). It was not possible to obtain a firm conclusion within the timeframe of this project so the investigations were continued in the present project. The investigations from both projects are described in chapter 4.

3. Method for evaluation of the impact on indoor climate and energy demand when applying solar cells in transparent facades

It was original the intention to perform thermal comfort and energy measurements combined with the measurements performed in the daylight laboratory at SBi for determination of the visual comfort related to solar cells integrated in transparent facades (Markvart, 2012).

It turned, however, for several reasons out not to be possible to carry out the planned relevant measurements on thermal comfort and energy in the daylight laboratory.

One of the aims of the Thi-fi-tech project was not to be restricted by the semitransparent solar cell panels available on the market but allow architectural freedom in order to be able to investigate the full potential of integration of solar cells in glazed facades. For this reason architects were allow to design the pattern of the solar cells tested in the daylight laboratory according to how they would like the products to be in order to fulfill their architectural ambitions (Olsen, 2012)

However, going from an idea of a new design of semitransparent solar cell panels to the actual manufacturing of such panels takes time and is very expensive. So instead of trying to persuade a solar cell manufacture to produce the solar cells designed within Thi-fi-tech is was decided to produce dummy solar cell panels in the form of printed black area on thin transparent plastic sheets which could be mounted on the windows of the daylight laboratory. As the dummy solar cell panels were made of thin plastic sheets they could not be mounted at the external side of the window as they would be damaged by the wind. So they were mounted on the internal surface of the two pane low-E windows. This is quite alright when the aim is to investigate the visual comfort of applying solar cells in transparent facades. But it is not possible to perform measurements regarding thermal indoor climate and energy demand.

The temperature of the internal layer (the dummy solar cell panels) will during clear sky conditions get very high as explained in section 2.2 as main part of the incoming radiation will be absorbed in this layer. Normally the solar cells are integrated in the external glazing so that the absorbed solar energy isn't transferred to the room behind the window. The temperature of the internal "glazing" and the cooling demand will be unrealistic high in the daylight laboratory.

Photos of the three dummy solar cell windows are shown in figures 3.1-3.3. The PowerShade dummy is different from the two other dummy as the "dummy" here only is that the PowerShades are replaced with MicroShades. Visually and thermally MicroShades and PowerShades perform identically. As Microshade is a commercial product the MicroShade windows were constructed as intended: the MicroShades were mounted on the internal side of the external glass of a two pane Argon filled low-E windows.

A description of the tests carried out in the daylight laboratory may be found in (Markvart et al, 2012).

Even if the dummy solar cell panels were mounted on the external glass of the windows the daylight laboratory is not well suited for performing thermal and energy investigations.

Figure 3.4 shows a plan of the daylight laboratory at SBi including some sensors. As for the test rooms at the Danish Technical Institute for test of MicroShades (figures 4.6-4.8) the sensor set is comprehensive and the test rooms are aimed to be identical with respect to the purpose of the tests being carried out in the rooms. At the daylight laboratory at SBi focus has been of making the test rooms identical from a daylight point of view and less on the thermal behavior of the rooms.

Figure 3.1. Test object with a rather open pattern with an opening degree of 72%. The distance between the rows varies: Largest distance close to the middle window without solar cells.

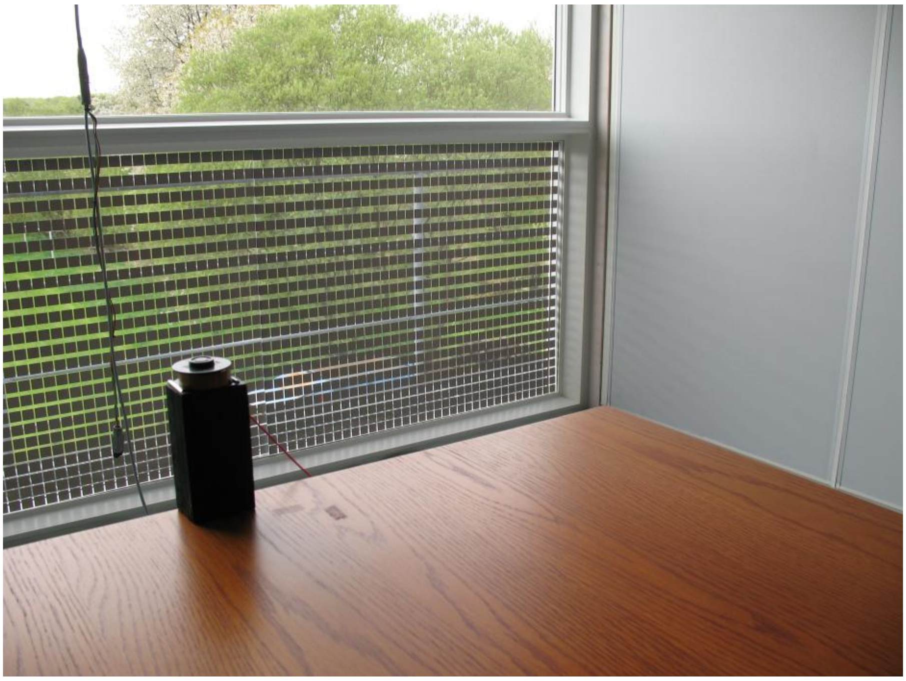


Figure 3.2. Test object with a somewhat closed pattern with an opening degree of 38%. The distance between the rows varies: Largest distance close to the middle window without solar cells.

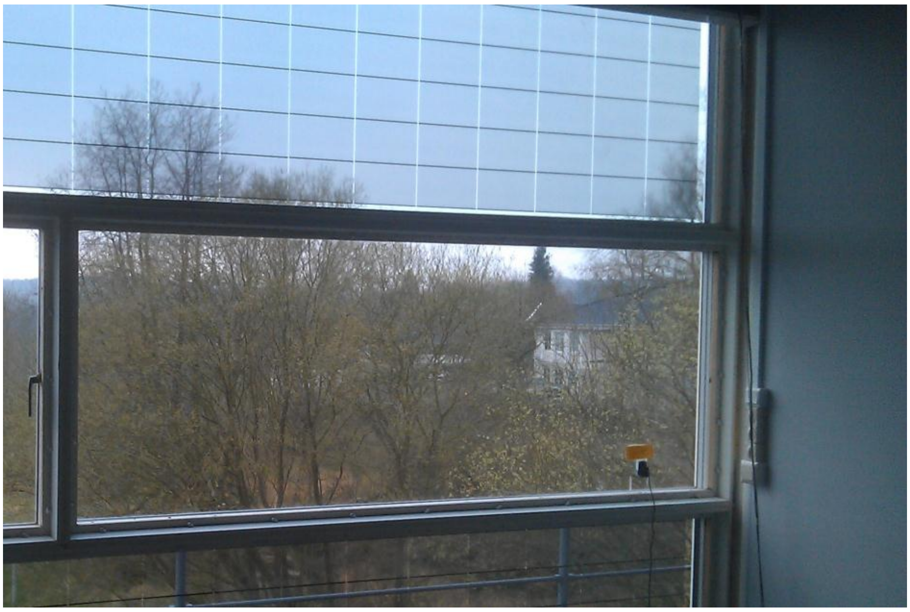


Figure 3.3. MicroShades with an overall opening degree of 60%. The MicroShade elements are mounted in the window the same ways as PowerShades would have been.

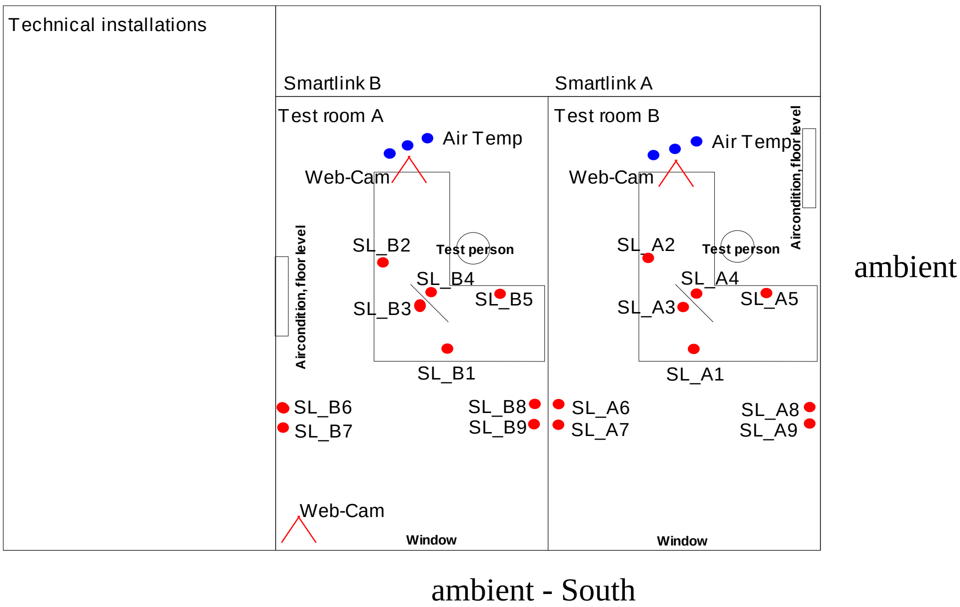


Figure 3.4. Plan for the daylight laboratory at SBi. The red dots are lux meters while the blue dots are temperature sensors.

Figure 3.4 shows that while test room B has two external walls test room A only has one external wall. This of course influences the heat loss of the two rooms which from a visual point of view constitutes no problem as long as the heating and cooling system are capable of maintaining identical room temperature in the two rooms. But it makes them less suited for test where the thermal comfort and energy demand is in focus. It is thus not possible to perform side-by-side comparison where the only difference between the rooms being the type of solar cells integrated in the windows – there will always be other differences in the thermal flows to and from the rooms.

One way to go about the above is to calibrate a model of the two test rooms based on measurements. However, this leads to two problems:

- the delivered energy to the rooms for heating and cooling has to be measured very precisely. This not possible as the cooling system in the two rooms are split units where room air is cooled directly by the evaporator and blown into the room. It is very difficult/impossible to measure/calculate the extracted heat by such systems.
- even if the energy flows by the heating and cooling systems to and from the test rooms could be measured correctly a calibration of a simulation program to give same behavior as the measurements is very difficult and often not possible as shown by the investigations on PowerShades/MicroShades (Jensen, 2008b and Jensen, 2010) even when the measurements are carried out in very well defined (from a thermal point of view) test rooms.

For the above reason it was decided not to perform the original intended tests in the daylight laboratory concerning indoor climate and energy demand as it was concluded that such tests would not be very conclusive.

However, as the focus of the investigations in this report is determination of the impact of solar cells in glazed facades on indoor climate and energy demand simulation is an appropriate tool as long as the processes of the transparent facades are well understood and modeled correctly. Based on the investigations in (Schultz, 2007, Jensen, 2008b and 2010) it may be assumed that the processes of the transparent facades with solar cells are well understood and may be modeled correctly. And further, - even if a model was calibrated based on measurements in the daylight laboratory this model should still be scaled to real buildings – again demanding for a correct model of the transparent facades with solar cells and of the rest of the building in which the impact of the facades is investigated.

Many simulation programs are able to simulate the thermal performance of buildings also including glazed facades with solar cells of the type a), b) and d) in figure 1.1. However, only two simulation programs can correctly simulate PowerShades/MicroShades: ESP-r (ESRU, 2012) and Bsim (SBi, 2012b). As it is easier to incorporate energy used for artificial lighting in Bsim this program was selected for the following investigations.

3.1. Simulation of buildings with solar cells in transparent facades

For the investigation of the impact of solar cells in the transparent part of the façade a model of a small office building was developed in BSim. The office building is a two floor building with both south and north facing offices as seen in figure 3.5. The gross floor area of the building is 345.5 m².

The office building consists of:

- south: ground floor: 3 single offices (each approx. 22 m²) to the west and 2 open space offices (each approx. 60 m²)
  first floor: 3 open space offices (each approx. 60 m²)
- north: ground floor: 3 open space offices (each approx. 60 m²)
  first floor: 3 open space offices (each approx. 60 m²)

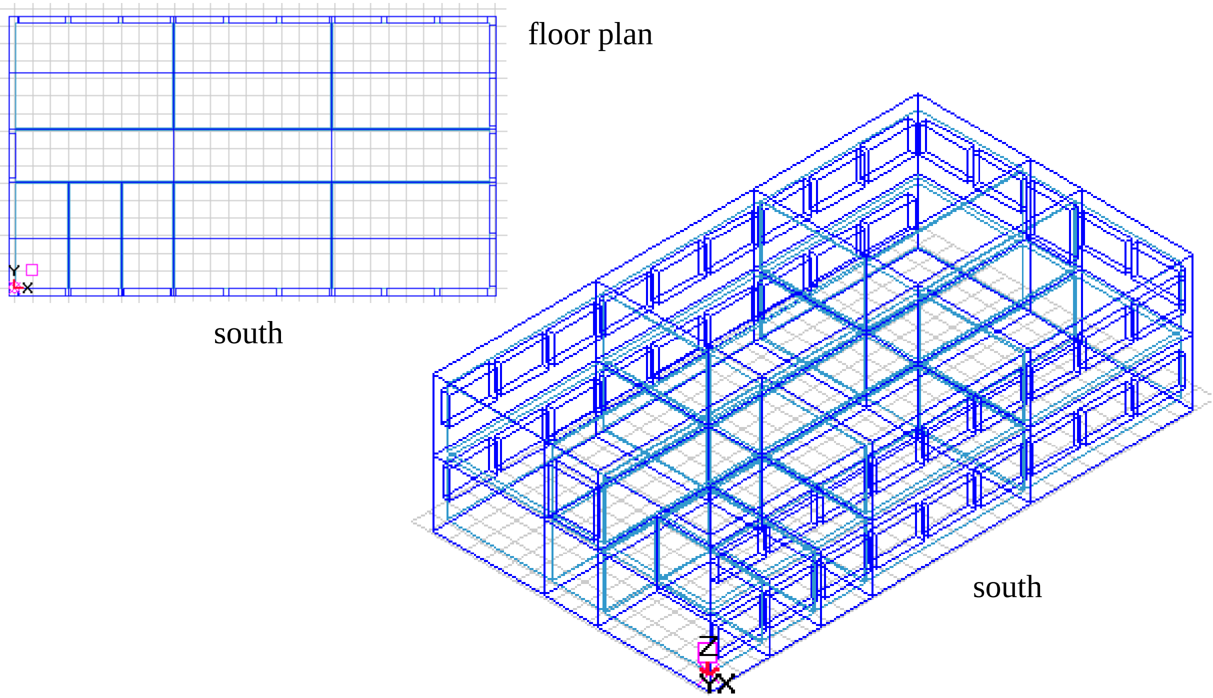


Figure 3.5. The office building considered in the simulations.

The south and north facing windows constitutes approx. 28 % of the façade and have lowE glazing with a U-value of 1.1 W/Km².

Construction	U-value	Materials
External walls	0.155	0.08 m hollow clay bricks 0.24 m stone wool 39 0.08 m Bricks
Internal walls	0.735	0.025 plaster board 0.050 m stone wool 45 0.025 plaster board
Floor slap towards ground	0.124	0.03 m beach 0.08 m concrete 0.20 m polyurethane 0.07 m lime mortar 0.15 m soil
Between floors with suspended ceiling	0.353	0.03 m beach (top) 0.07 m stone wool 39 0.02 m concrete 0.03 m stone wool 39
Between floors without suspended ceiling	0.484	as above but without the 0.03 m stone wool
Roof with suspended ceiling	0.138	0.03 m stone wool 39 0.15 m concrete 0.25 m stone wool 39
Roof without suspended ceiling	0.154	as above but without the 0.03 m stone wool

Table 3.1. Details of the constructions of the building.

The building is ventilated according to class A for non-smoking office buildings in the Danish Ventilation Norm DS 1752: 10 l/s per person. The ventilation system is running from 7:00 to 18:00. The fresh air is heated/cooled to have a supply temperature of 18°C. The efficiency of the heat recovery unit is 0.7.

The set points in the rooms are:	heating:	22°C
	cooling:	24°C

The internal gains are:

- 72 people in mean present 80% in the period: 8:00-18:00
- equipment: 80 % of 7.8 kW in the period: 8:00-18:00. Rest of the day: standby 15 % of 7.8 kW
- artificial light: task light: 1.3 kW and general light 7 kW. 100 % during the period: 8:00-18:00. The artificial light is daylight controlled. The sf-factors were obtained from the graphs in the BSim manual.

In order to investigate the impact of solar cells in the windows 11 different window types were investigated:

		g-value	LT-value
1)	traditional LowE window:	0.63	0.79
2)	pv with 70 % opening*:	0.42	0.50
3)	pv with 60 % opening*:	0.36	0.43
4)	pv with 50 % opening*:	0.31	0.36
5)	pv with 40 % opening*:	0.26	0.29
6)	pv with 30 % opening*:	0.20	0.22
7)	pv with 20 % opening*:	0.15	0.14
8)	pv with 10 % opening*:	0.10	0.07
9)	MicroShades (60 % opening):	table 2.5	table 2.6
10)	LowE with solar control coating:	0.27	0.50
11)	LowE with movable solar screening:	same g and LT-value when not in front of the window. Shading coefficient: 0.3. In front of window: sun above 150 W/m² (hysteresis: 20 W/m²) and/or indoor air temperature above 24°C.	

* according to equation 2.2 and 2.3

The north facing windows and the three east facing window in the north part of the building were in all simulations traditional LowE windows. The 10 other window types was successively applied to the south facing windows and the two east facing windows in the south part of the building.

BSim is not yet capable of calculating the electric demand for a cooling plant. BSim only gives the net cooling demand. In order to determine the electricity demand of the cooling system the net cooling demand calculated by BSim has as hourly time series been transferred to Pack Calculation II (ipu, 2012) and the annual electricity demand has then been calculated by this program when using an appropriate model for a cooling system.

3.1.1. Base case

The above model was used as the base case scenario.

Figures 3.5-8 shows the results from runs with BSim with the 11 window configurations. Different from figures 2.7-8 the unit on the x-axis is not the g-value but the opening degree. The reason for this is while 10 of the window configurations have a fixed g-value the g-value for the MicroShades is varying according the solar height and azimuth as shown in table 2.5, but the opening area of the holes in the MicroShade film is 60 %. The opening area of the solar control film is 100 % but in the figures located at 104 % in order to differentiate it from the curves for the pv windows. Likewise is the LowE window with movable sun screening located at 102 %.

Figure 3.5 shows the net energy demands of the building, - i.e. the demand of the building for heating, cooling and artificial light not multiplied with any primary energy factors or corrected for efficiencies of the heating and cooling system. The net energy demand is the sum of the net heating and cooling demand + electricity for artificial light.

The shape of the curves is quite similar to the curves in figure 2.7:

- increasing heating demand and electricity for artificial light with decreasing opening degree
- decreasing cooling demand with decreasing opening degree
- minimum net energy demand around an opening degree of 40 %, however the curve is rather flat between 20 and 60 %

The performance of: the optimal pv opening degree, MicroShades, solar control coating and movable sunscreening is very similar.

Figure 3.6 show the max needed cooling power dependent on the opening degree of the windows. It is seen that the size of the cooling system may be reduced up to 28 % when introducing solar cell in the windows. However, at an opening degree lower than around 20% the size of the cooling plant increases due to the increase in electricity (= increase in internal heat load). The reduction in cooling system for the three other solar screening systems (MicroShades, solar control film and sunscreening) is up to 24 % and highest for MicroShades. The possibility of a smaller cooling plant will reduce the construction cost of a building.

However, the values in figure 3.5 don’t reflect the real energy demand of the building as they don’t include efficiencies and differences in primary energy of different energy carriers. In figure 3.7 it is assumed that the heating is via district heating with an efficiency and primary energy factor of 1 while the primary energy factor for electricity to artificial light and the cooling system is 2.5 and the efficiency of the cooling system is calculated using Pack Calculation II. When including efficiencies and primary energy factors the energy demand is labelled primary.

Figure 3.7 compares the total net energy demand from figure 3.5 with (the gross) primary energy demand including efficiencies and primary factors. The primary energy demand includes 4.000 kWh of electricity (before multiplying with 2.5) for running fans, pumps, etc. (but not including fans and pumps in the cooling system – this is includes in the electricity to the cooling system). The electricity to the cooling system is multiplied with 2.5.

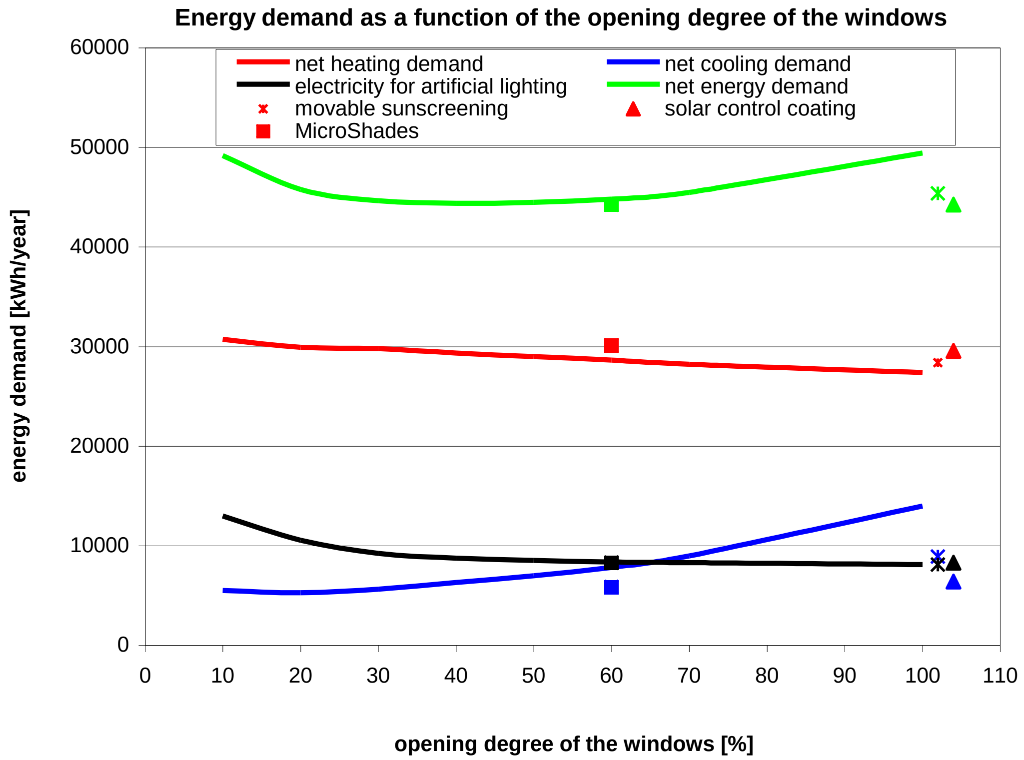


Figure 3.5. The net energy demands dependent on the opening degree.

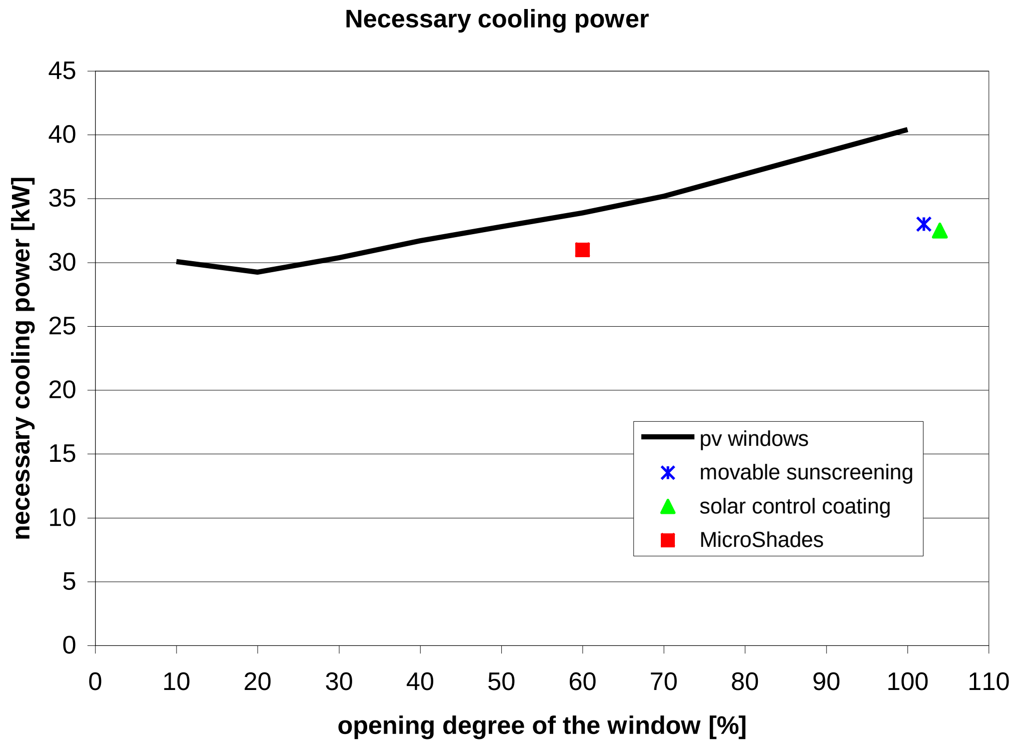


Figure 3.6. The max cooling power dependent on the opening degree.

Figure 3.7 shows that when introducing efficiencies and primary energy factors the minimum energy demand moves to the right in the graph – i.e. towards larger optimal opening degrees of the pv windows. The reason for this is that the primary energy demand of the electricity for lighting is dominant compared to the electricity demand for cooling. This was also seen in figure 2.7.

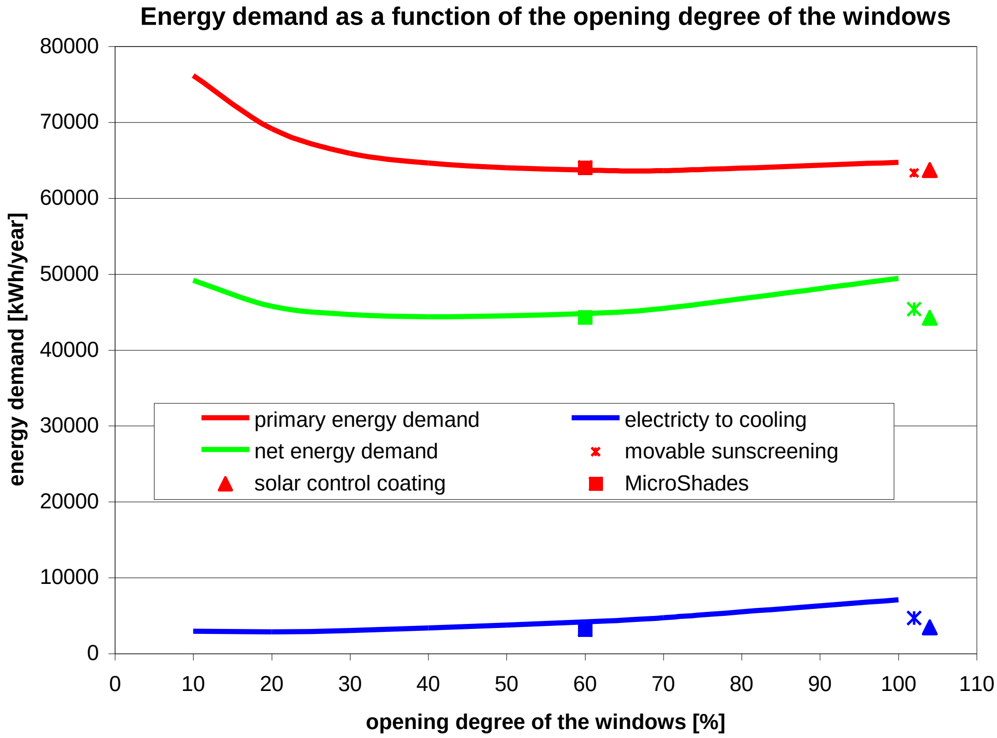


Figure 3.7. The primary energy demand, the net energy demand and the primary energy used by the cooling system.

However, figure 3.7 is not the total story because the solar cells in the windows produce electricity. This is included in figure 3.8.

The electricity production of the solar cells are estimated based on the solar cell panel WS0007 in table 2.8 with an annual electricity production of 60 kWh/m² and an opening degree of 8 %. It is assumed that the electricity decreases linearly to zero at an opening degree of 100 %. This is not the case when looking at WS0007-0009. The reason for this is believed that the spaces between the solar cells are equally increase all around the solar cells in WS0008-0009 which increases the electrical resistance in the window. However, as seen in figure 3.1-2 the here assumed design is where only the horizontal distance is increased not the vertical allowing for no increase in the resistance. The pv production is in figure 3.8 multiplied with 2.5 and subtracted the primary energy demand. It is assumed that MicroShades (PowerShades) have a pv production as a pv window with an opening degree of 60 %, although the 3D structure (holes) of the Microshade may lead to an increased efficiency.

Figure 3.8 shows that when introducing the pv production the minimum energy demand again moves to the left in the graph, - again with a minimum around 40 % opening degree. Figure 3.8 also shows that with the pv production the pv windows (with an opening degree below 80%) incl. MicroShades perform better than the solar control window and the movable solar shading. However, figure 3.8 also shows that the difference in energy demand between the traditional LowE window and pv windows with an opening area of 40 % is less than 7 %.

This means that the decision of introducing solar cells in the windows should mainly be based on other reasons than energy: cost (e.g. cost of pv windows, reduction of cooling plant), visual comfort, signal value, etc.

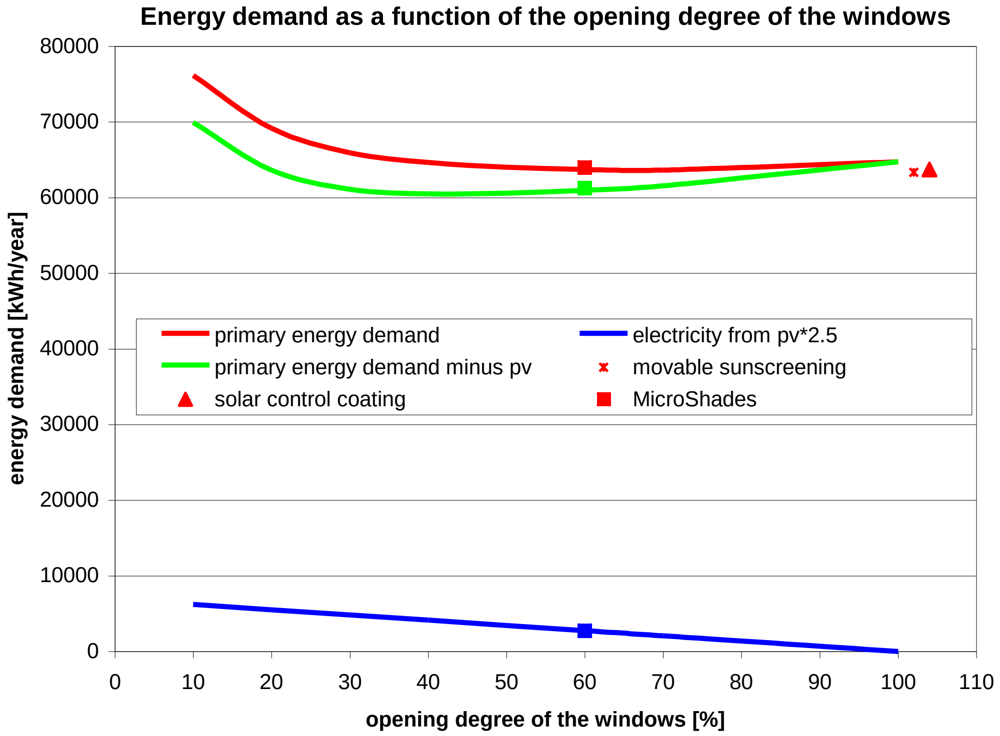


Figure 3.8. The primary energy demand of the building with and without electricity production from the solar cells.

3.1.2. Parametric study

Figure 3.5 shows that the increase in energy demand at low opening degrees mainly is due to the electricity demand for artificial light (which also influence the cooling demand) while the increase of energy demand at high opening degrees is due to the increase in cooling demand. In the following the dependency on the cooling demand is investigated.

A very efficient cooling system was applied in the calculations in section 3.1.1: EER of 4.6-7. Figures 3.9-10 shows the same as figures 3.7-8 the only difference being that the cooling system is half as efficient as the cooling system in figures 3.7-9.

Figures 3.9-10 shows that the minimum energy demand moves slightly to the left in the graphs. This is shown more clearly in figures 3.11-16 where the same cooling system as in figures 3.9-10 have been used. However in figures 3.11-13 the internal load of the equipment has been increased with a factor 4 increasing the internal load from 7.8 to 31.2 kW, while in figures 3.14-16 the office building has been moved to Catania in Italy to allow for more sunshine and a higher ambient temperature. When comparing figure 3.5 with figures 3.11 and 3.14 it is seen that the net cooling load is increased considerably – especially for the Catania case. The electricity demand for lighting remains the same in figure 3.11 and is slightly lower in figure 3.14. But due to the higher internal gain in figure 3.11 and the more solar radiation and higher ambient temperature in figure 3.14 the net heating demand is considerably lower than in figure 3.5. Figures 3.11 and 3.14 shows that the minimum net energy demand for the pv windows move to the left in the graphs and that this curve is less flat around the optimal opening degree of the pv windows. The optimal opening degree is now around 30% and lowest for the Catania case with the highest cooling demand.

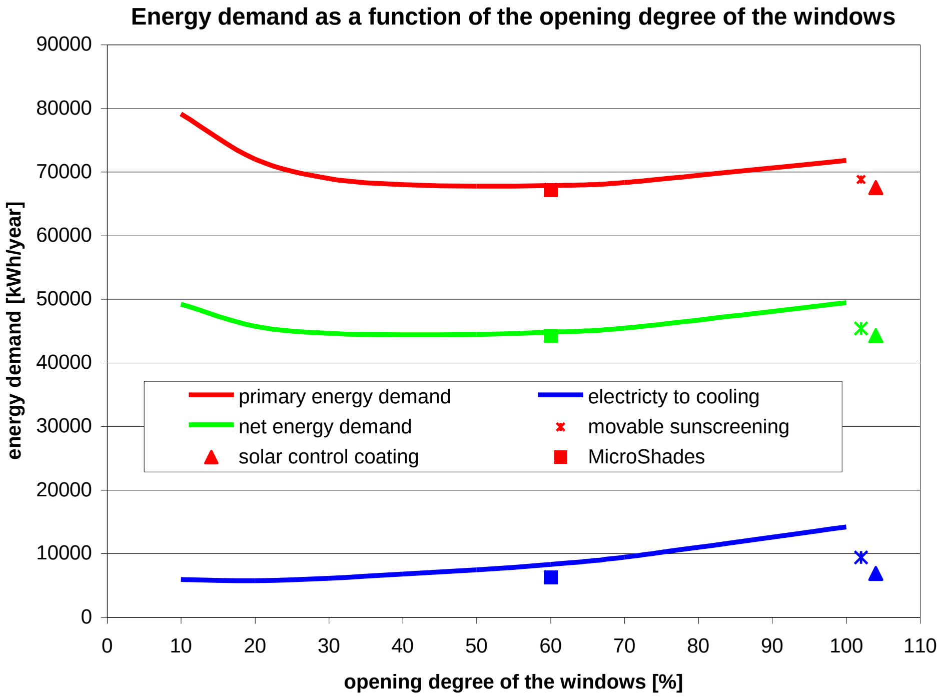


Figure 3.9. The primary energy demand, the net energy demand and the primary energy used by the cooling system with a half as efficient cooling system as in figure 3.7.

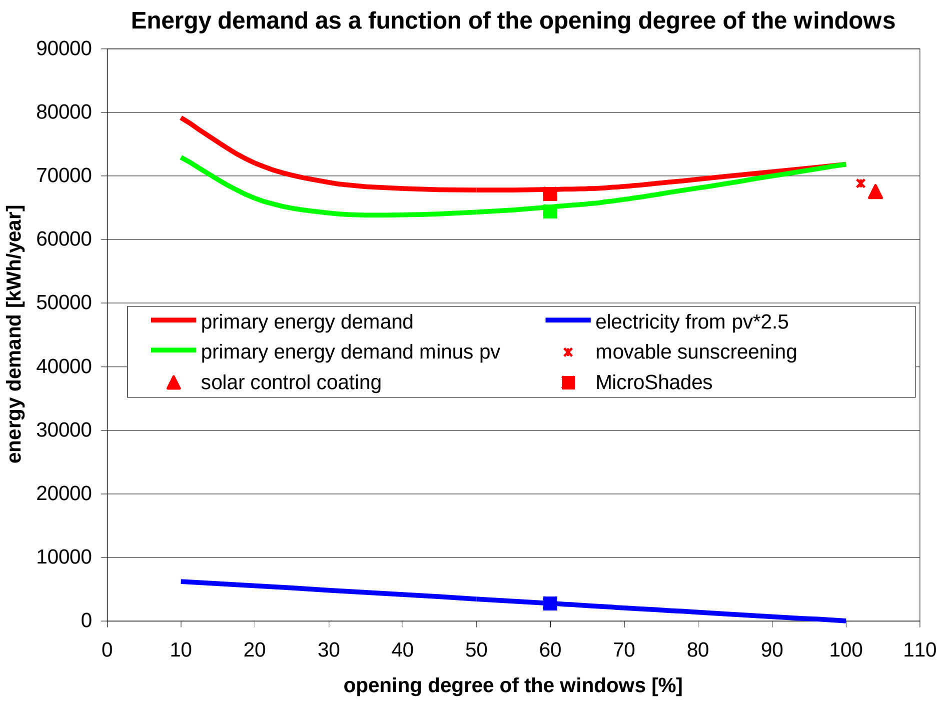


Figure 3.10. The primary energy demand of the building with and without electricity production from the solar cells with a half as efficient cooling system as in figure 3.8.

Different from figure 3.7 the optimal opening degree of the pv windows in figures 3.12 and 3.15 moves very little to the right when introducing system efficiencies and primary energy factors. The small movement to the right compared to 3.7 is because the primary energy demand for lighting has become less dominant due to the much higher electricity demand for cooling. The curves are especially for the Catania case less flat compared to figure 3.7 making the optimal opening degree of the pv windows more precise.

Figures 3.13 and 3.16 include the pv production. The pv production in the Catania case is increased due to the higher amount of solar radiation hitting the south façade. Inclusion of the pv production again moves the optimum opening degree slightly to the left again to an optimal opening degree around 30%. This imply that at high cooling demands the optimal opening degree of the pv windows are less influenced by efficiencies of the energy systems, primary energy factors and the electricity production from the pv windows. However, it is still advisable to take these factors into account when evaluating the energy savings when applying pv windows.

The question is, however, how pleasant it is to sit behind a façade with an opening degree of only 30%. As the openings degree in the graphs is the mean opening degree of the window it means that if areas as in figure 3.1-2 are without solar cells in order to enable look out the other areas need to have an even lower opening degree in order to obtain the mean opening degree of e.g. 30 %. Visual comfort behind pv windows is investigated in (Markvart et al., 2012).

Figure 3.13 and 3.16 show that the larger the cooling demands is compared to the other energy demands of a building the more energy it is possible to save when applying solar cells in the windows. The difference between the LowE window and pv windows with an opening degree of around 30 % is in figures 3.13 and 3.16: 16% and 22% (20% if the pv production is reduced to Danish conditions) respectively.

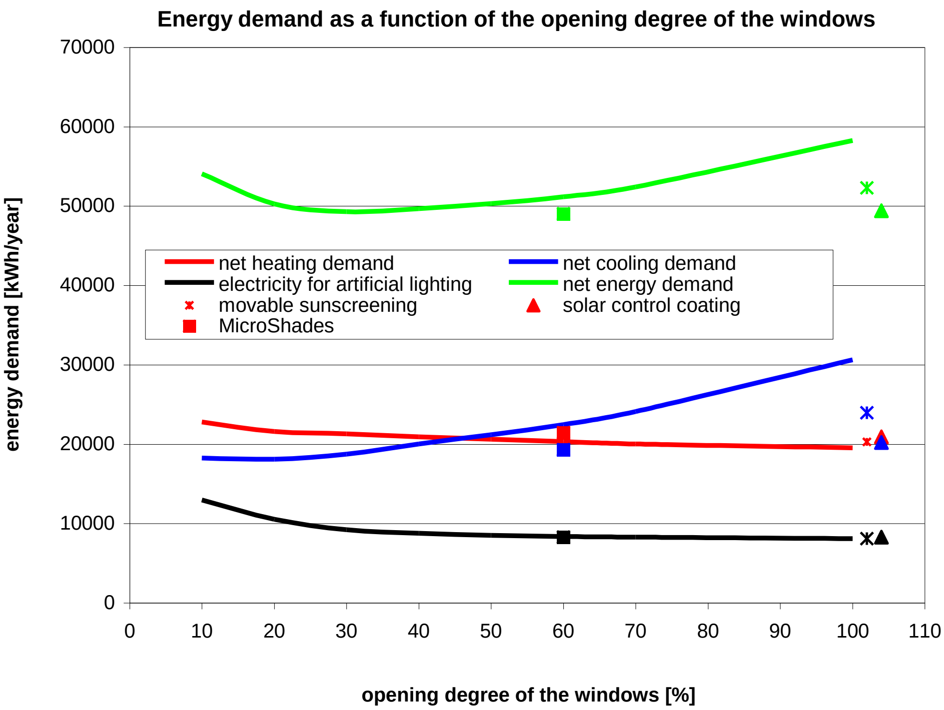


Figure 3.11. The net energy demands dependent on the opening degree as in figure 3.5 but with a 4 times higher internal load from equipment.

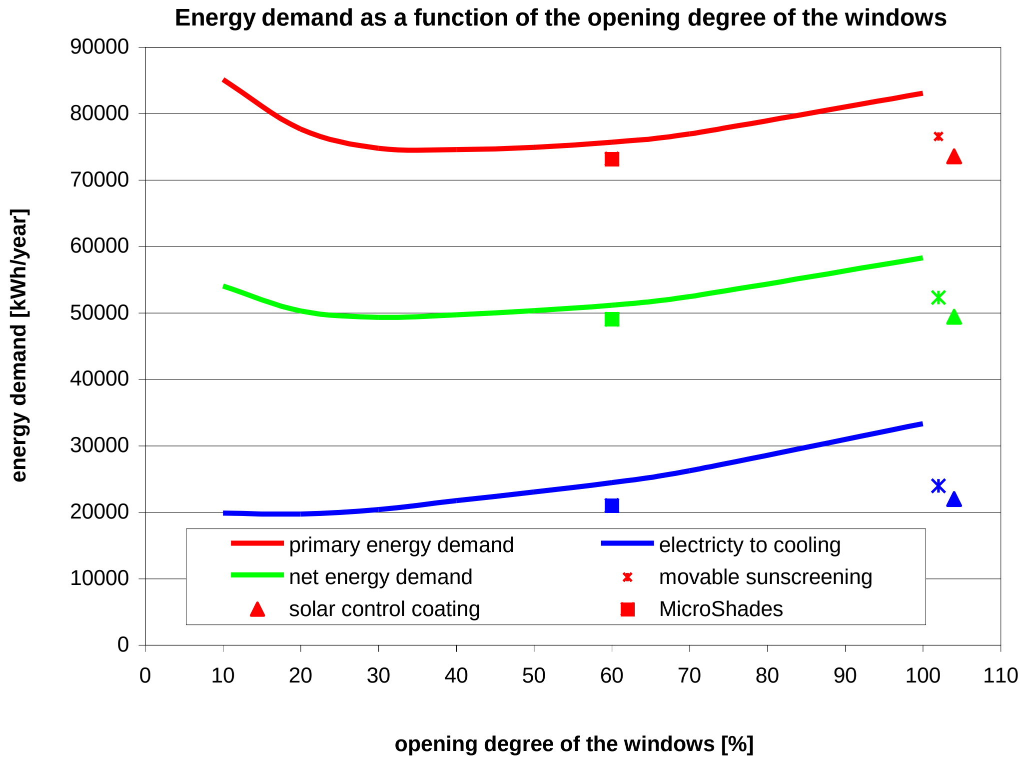


Figure 3.12. The primary energy demand, the net energy demand and the primary energy used by the cooling system as in figure 3.9 (poor cooling system) but with a 4 times higher internal load from equipment.

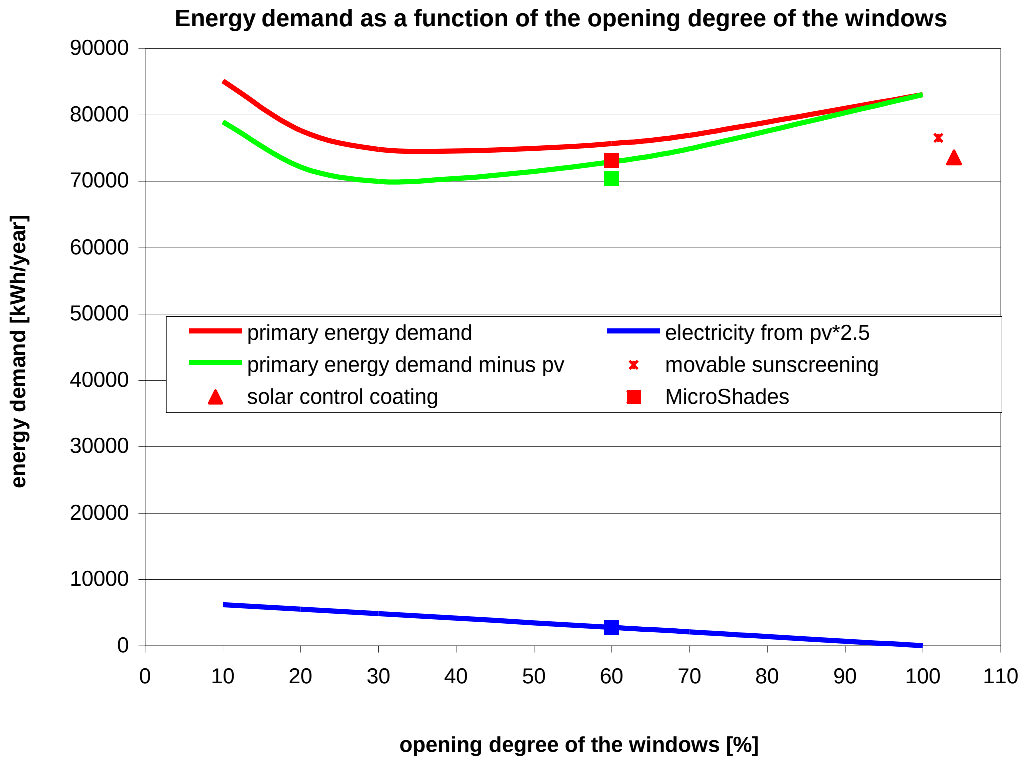


Figure 3.13. The primary energy demand of the building with and without electricity production from the solar cells as in figure 3.10 (poor cooling system) but with a 4 times higher internal load from equipment.

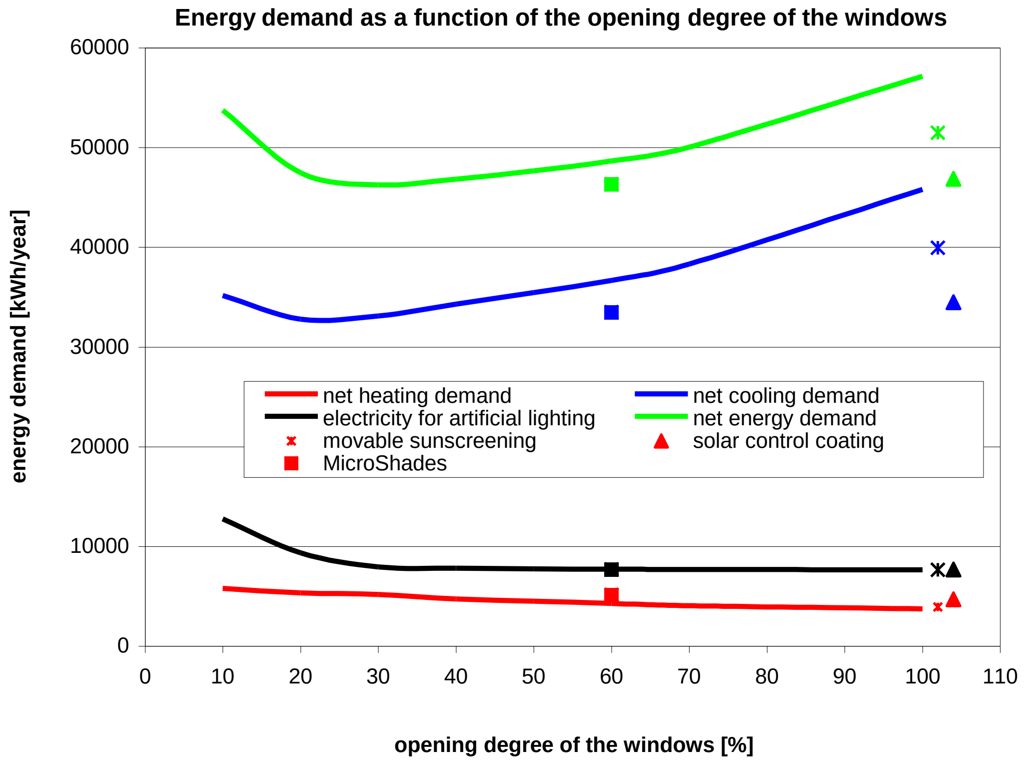


Figure 3.14. The net energy demands dependent on the opening degree as in figure 3.5 but the building is located in Catania, Italy.

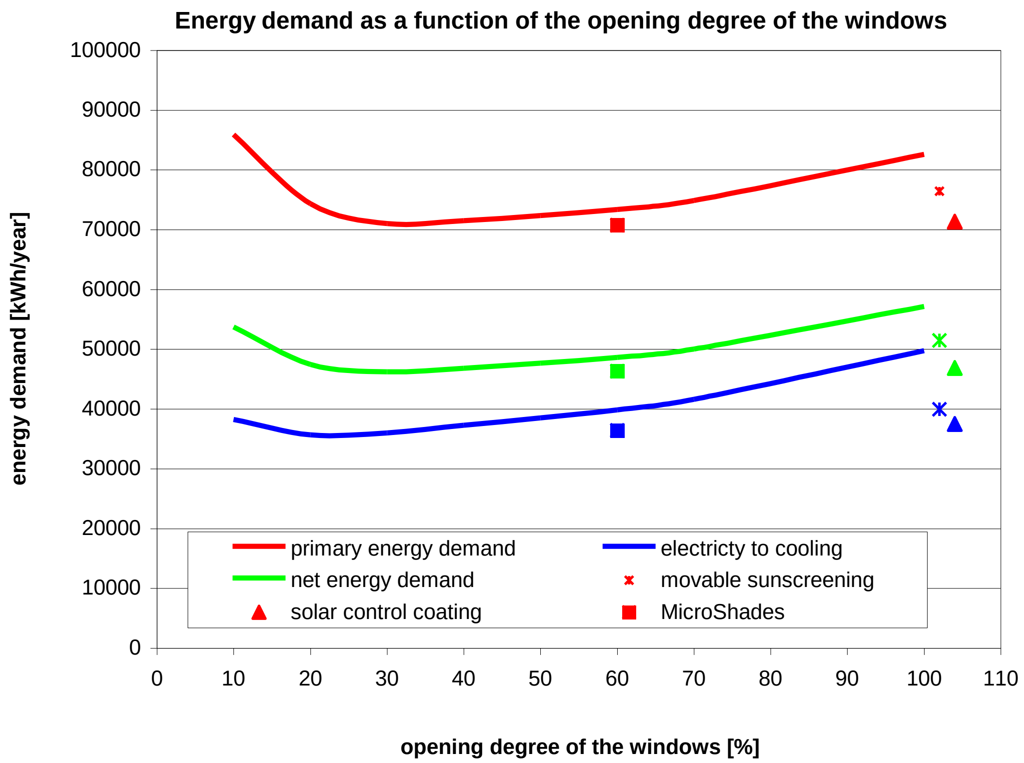


Figure 3.15. The primary energy demand, the net energy demand and the primary energy used by the cooling system as in figure 3.9 (poor cooling system) but the building is located in Catania, Italy.

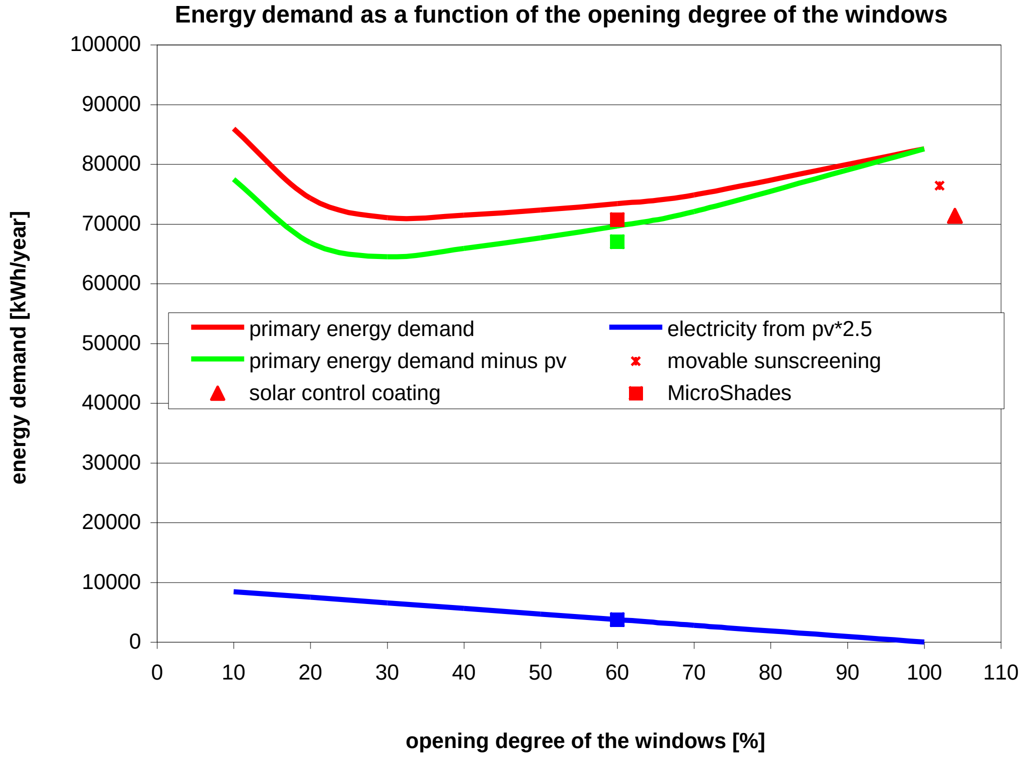


Figure 3.16. The primary energy demand of the building with and without electricity production from the solar cells as in figure 3.10 (poor cooling system) but the building is located in Catania, Italy.

Figures 3.17 show the case where there is no cooling demand. This situation is obtained by removing 2/3 of the windows in the south and north (because there is a rather large heating load through north facing windows during the summer) façade of the building and half of the windows in the east façade. But as the ambient temperature in the Danish Design Reference year used in BSim during the summer often is above 24°C is was also necessary to exclude cooling. This latter leads to occasionally indoor temperatures up to 28°C.

The red curve (primary energy demand without pv) shows that the minimum energy demand is obtained without solar cells in the windows. When introducing the pv production the minimum demand is obtained at an opening area between 50 and 70 % and only slightly better than the traditional windows. As pv windows are considerably more expensive than traditional LowE windows, the use of solar cells in the windows should here, therefore, be based on other reasons than energy and cost. The primary energy demand for the two cases: solar control film and movable sunscreening increases compared to the traditional LowE window because there is no need for reducing the incoming solar radiation and because this reduction in incoming solar radiation leads to an increased heating demand and increased electricity demand for lighting.

A sensitivity study has also been carried out for the electricity demand for artificial lighting. The simulations are identical to the simulations shown in figures 3.5-8 the only difference being that the efficiency of the artificial lighting is only half – i.e. max consumption of electricity for lighting is increased from 1.3 kW task light, 7 kW general light to 2.6 kW task light, 14 kW general light. The result is shown i figures 3.18-19.

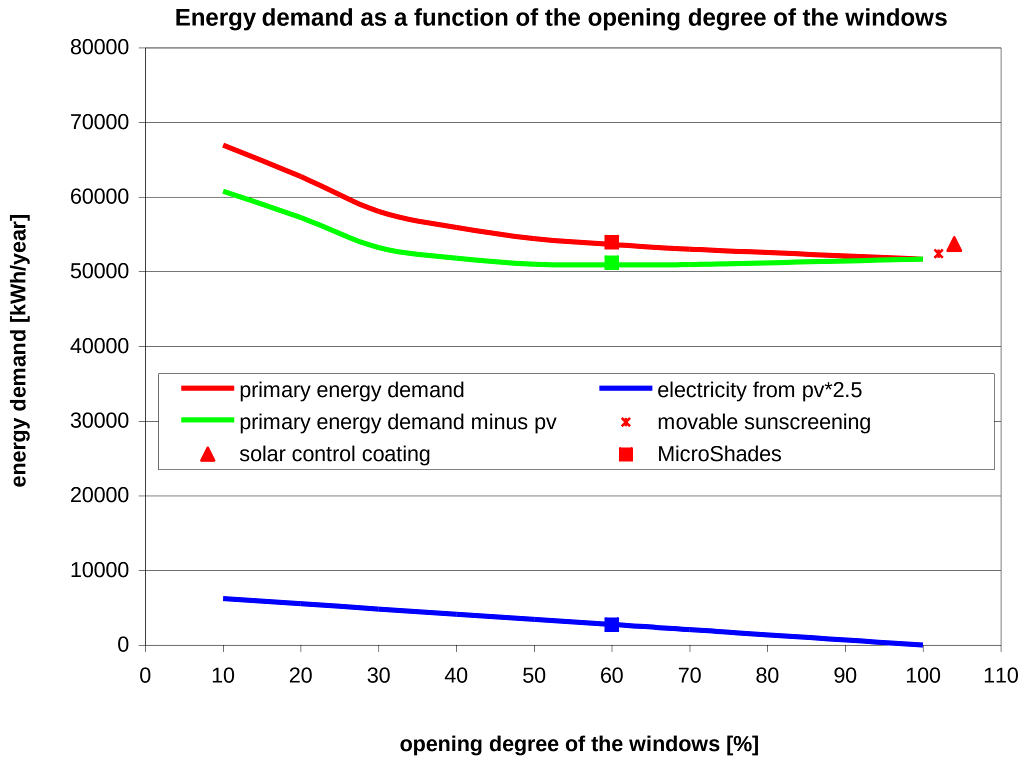


Figure 3.17. The primary energy demand of the building with and without electricity production from the solar cells with no cooling demand.

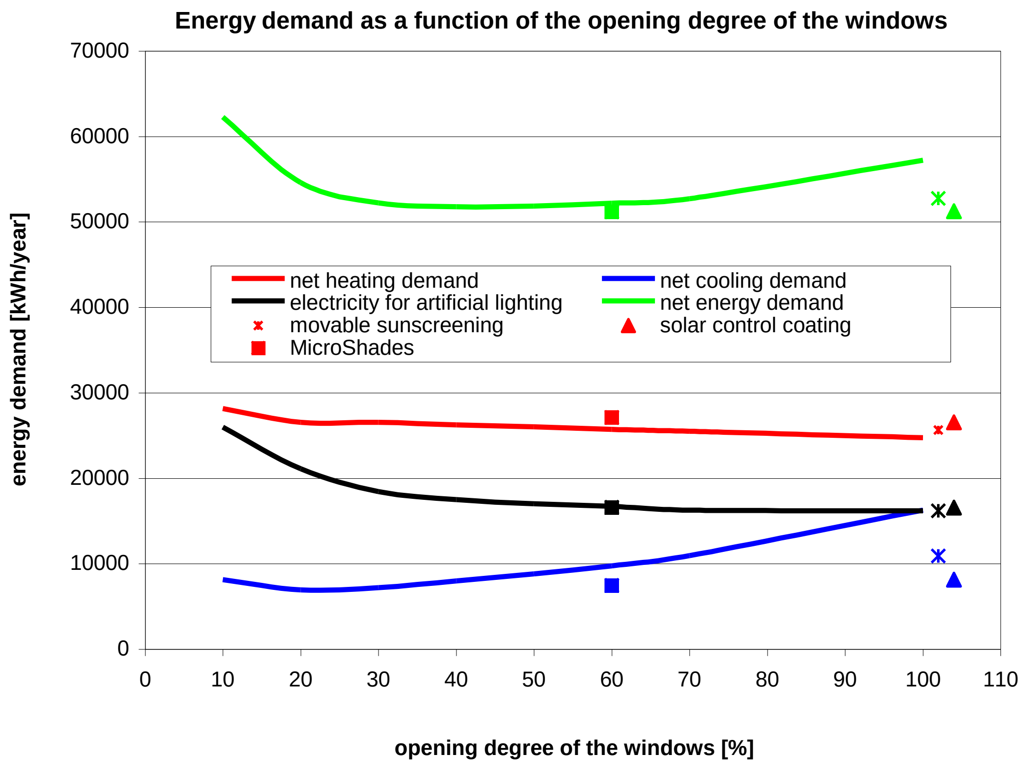


Figure 3.18. The net energy demands dependent on the opening degree as in figure 3.5 but with the twice the power for artificial lighting.

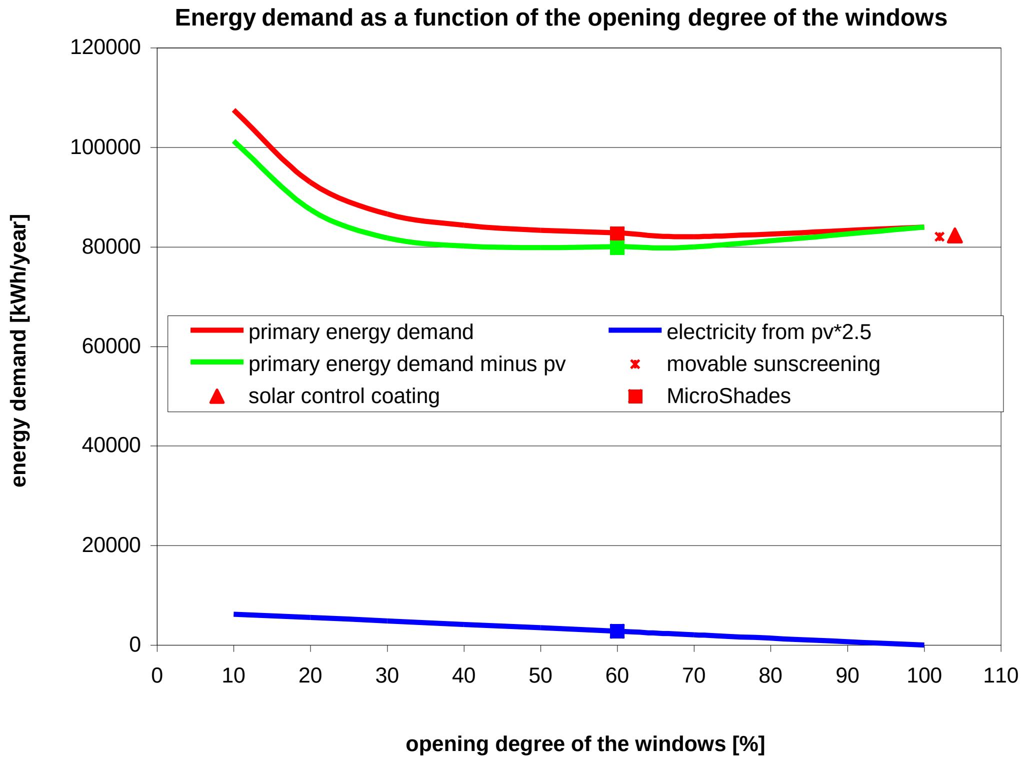


Figure 3.19. The primary energy demand of the building with and without electricity production from the solar cells as in figure 3.7 but with the twice the power for artificial lighting.

When comparing 3.5 with figure 3.18 it is seen that the net energy demand is pushed only slightly to the right because the electricity demand for lighting is rather stable at opening degree above 40% and because the net cooling demand at very low opening degrees increases due to the increase in electricity demand for lighting compared to figure 3.5 where the net cooling demand is almost stable at low opening degrees. This is also seen in figure 3.15.

When introducing the system efficiencies and primary energy factors the curve (red curve in figure 3.19) is pushed rather much to the right. When including the pv production figure 3.19 shows that the optimal opening degree is in the area of 35-75% and that the energy savings by introducing pv windows are quite low.

3.1.1. Conclusion of the parametric studies

When comparing the total net energy demand with the total primary energy demand including the pv production for all above parametric studies it is seen that the optimal opening degree of the pv windows is quite similar in the base case and in the cases of increased internal heat load, more solar radiation (Catania) and no cooling. However, there are large differences in the case of the base case with a poor cooling system and the case with increased electricity demand for artificial lighting. It is therefore important to include the efficiency of the energy supply systems especially for the cooling system, the primary energy conversion factors and the pv production as it is not priory known where these parameters make a major difference.

The parametric studies reveal that:

- the benefit of include more solar cells in the windows increases with increasing cooling demand
- the benefit of include more solar cells in the windows decreases with increasing electricity demand for artificial light
- with increasing cooling demand the benefit of pv windows incl. MicroShades increases compared to traditional solutions as solar control coating and movable sunscreening
- there is really no energy benefit in applying solar cells in the windows if the building has no cooling demand
- however, the decision of introducing solar cells in the windows should most often be based on other reasons than energy: cost (e.g. cost of pv windows, reduction of cooling plant), visual comfort, signal value, etc.

3.2. Comparison with previous work

It is not possible directly to compare the figures in this chapter with figures 2.7-8 due to the fact that the units of the x-axis are different. In figures 3.20-21 the unit on the x-axis of 2.7-8 is change to be the opening degree instead of being the g-value.

The net cooling demand in figure 3.5 is at an opening degree of 20 % 15 kWh/m², which is similar to figure 3.20. But the electricity demand for lighting is in figure 3.5 30 kWh/m² at an opening area of 20 %, which is almost three times as high as in figure 3.21. This imply that the minimum energy demands in figures 3.5 and 3.7 would lay to the right of the minimum energy demands in figures 3.20-21, - which also is the case when comparing these figures.

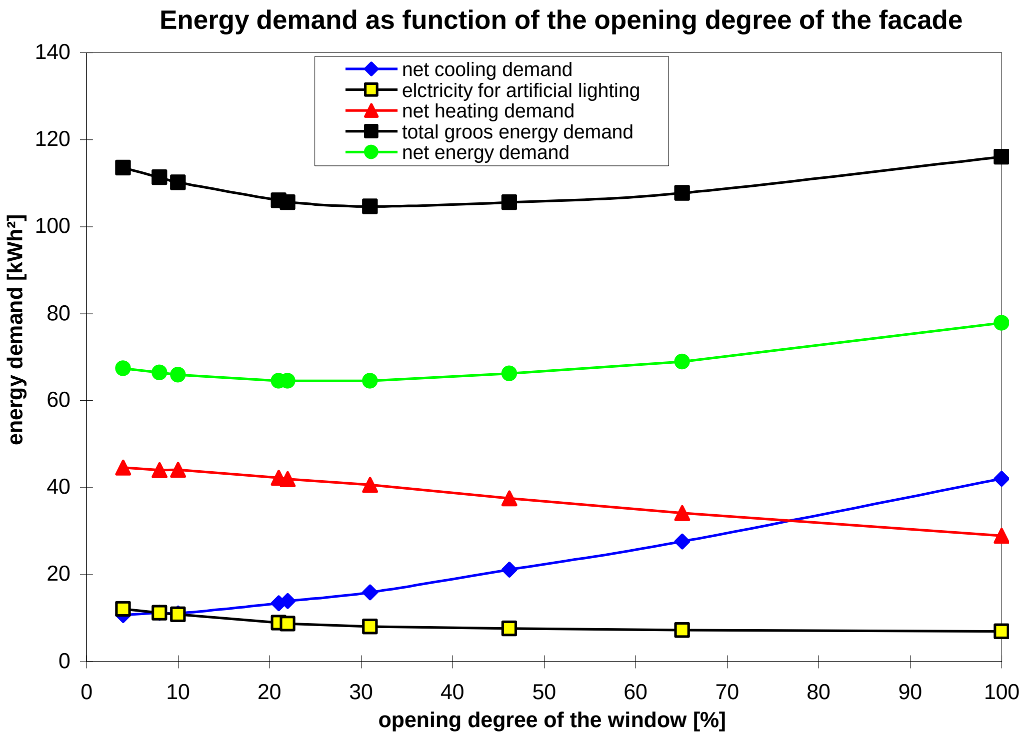


Figure 3.20. Figure 2.7 with the unit of the x-axis changed to opening degree.

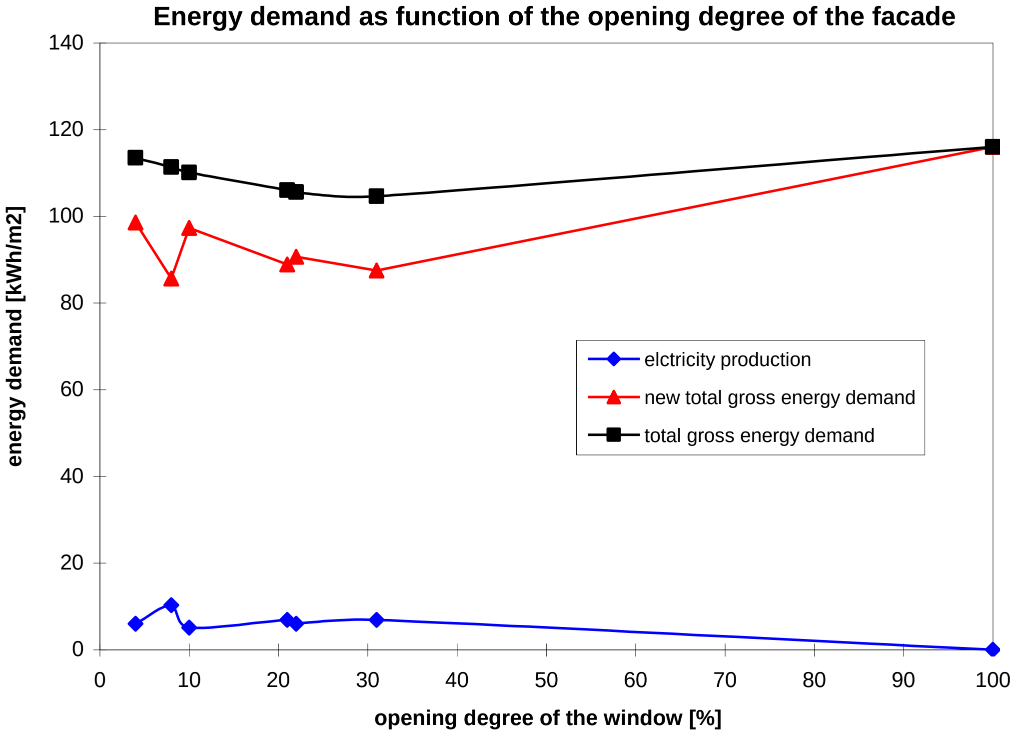


Figure 3.21. Figure 2.8 with the unit of the x-axis changed to opening degree.

Based on this it may be concluded that Be06 (now Be10) may be used to determine the optimal opening degree of pv windows. The benefit is that Be10 is more easy and quicker than the combination of BSim and Pack Calculation II. However, it is important to underline that real conditions should be used in Be10 – especially the real internal gains and temperature set points for especially cooling should be used and not the standard values used when investigating if the buildings energy demand comply with the building regulation.

3.2. Conclusion

Based on the above work it is possible to draw some general conclusions, however, calculations should always be performed for the actual case. When calculating the benefit of applying solar cells in transparent parts of the facade it is important to include the efficiency of the energy supply systems especially for the cooling system, the primary energy conversion factors and the pv production. At the moment BSim doesn't include the efficiency of cooling systems, however, BSim is at the moment being combined with Pack Calculation II, so that this will be possible in the future. Be10 may be used but it is important that real conditions are used in Be10 – especially the real internal gains and the temperature set points for especially cooling should be used and not the standard values used when investigating if the buildings energy demand comply with the building regulation.

Some general conclusions from the investigation are:

- the benefit of include more solar cells in the windows increases with increasing cooling demand

- the benefit of include more solar cells in the windows decreases with increasing electricity demand for artificial light
- with increasing cooling demand the benefit of pv windows incl. MicroShades increases compared to traditional solutions as solar control coating and movable sunscreening
- there is really no energy benefit in applying solar cells in the windows if the building has no cooling demand
- however, the decision of introducing solar cells in the windows should most often be based on other reasons than energy: cost (e.g. cost of pv windows, reduction of cooling plant), visual comfort, signal value, etc.

4. The effect of solar radiation through windows on local thermal comfort

Dependent on the level of solar radiation hitting a person - and the perception of solar radiation of that person - direct solar radiation through a window may create discomfort. Some people cannot get enough solar radiation while for others gets very annoyed being hit by solar radiation when working by a window.

Only little research has been performed on the relationship between comfort and solar radiation hitting people in buildings. Some studies have however been carried out concerning comfort and solar radiation in cars as the view here is mandatory and people therefore are hit by solar radiation.

The aim of this chapter is to investigate if the results from one study concerning cars (Hodder and Parsons, 2006) can be transferred to buildings.

4.1. Hodder and Parsons – discomfort in cars

(Hodder and Parsons, 2006) investigates the effect of solar radiation hitting a person in a car in the form of different radiation levels, different spectral distributions of the solar radiation at the same radiation level and different glazing exposed to a identical exterior radiation level.

The tests were carried out in two test rooms as shown in figure 4.1. The test persons were exposed to solar radiation on the torso, arms and thighs. But not at the head as cars have measures to protect the head against solar radiation.

Several values were measured and calculated and the test persons filled in questionnaires each five minutes. For a detailed description of the tests see (Hodder and Parsons. 2006). Here will mainly be dealt with PMV (predicted mean votes), AMV (actual mean vote), PPD (predicted percentage of dissatisfied) and APD (actual percentage of dissatisfied). PMV and PPD are calculated using the comfort equation (Fanger,1982) while AMV and APD are based on the questionnaires filled in by the test persons.

The main result is that:

- when exposed to a solar radiation of 400 W/m² the spectral distribution has no effect on the comfort level. This is in the present chapter further extended to conclude that it doesn't matter if the solar radiation is direct or diffuse if the radiation level is identical
- an increase of one scale unit (AMV) per increase of 200 W/m² solar radiation hitting the person
- the type of glass influence the comfort due to the level of transmitted solar radiation

Table 4.1 shows two PMVs and PPDs. The values with "a" are calculated with a mean radiant temperature equal to the air temperature: i.e. without solar radiation. The values with "b" are calculated with the measured mean radiant temperature: i.e. with solar radiation. From table 4.1 it is seen that the persons would have been in thermal comfort if no solar radiation was hitting them – PMV^a is between -0.5 and 0.5.

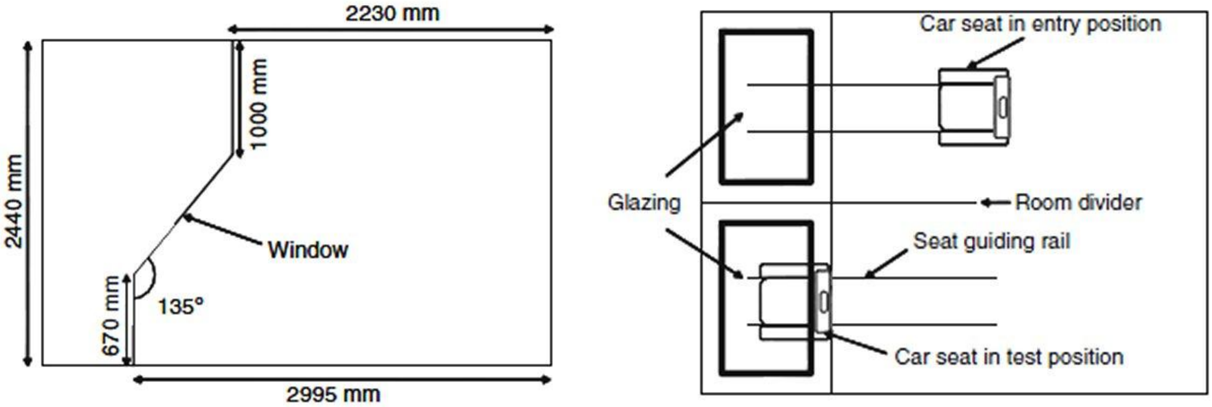


Figure 4.1. The test rooms in (Hodder and Parsons, 2006).

The below table shows the result of the study with different levels of radiation hitting the test persons.

Simulated solar radiation	600 Wm^{-2}	400 Wm^{-2}	200 Wm^{-2}	0 Wm^{-2}
t_a shielded (°C)	24.0	23.4	23.4	22.8
t_r (°C) derived from t_g	44.0	41.8	37.7	24.2
Air velocity (m/s)	0.1	0.1	0.1	0.1
Relative humidity (%)	49.6	51.0	51.4	48.3
PMV^a	0.2	0.1	0.1	−0.1
PPD^a	6.8	8.8	7.1	6.2
PMV^b	2.8	2.3	1.9	0.2
PPD^b	96.5	79.8	70.6	12.8
AMV	3.1	1.9	1.1	0.2
APD	100	75	62.5	12.5

t_a air temperature, t_g globe temperature, t_r mean radiant temperature derived from globe temperature (Parsons 2003 p 97), *PMV* predicted mean vote, *PPD* predicted percentage of dissatisfied, *AMV* actual mean vote, *APD* actual percentage dissatisfied
^{a}PMV calculated with t_r=t_a
PMV^b calculated with t_r=measured t_r

Table 4.1. The result from a study of (Hodder and Parsons, 2006) with different levels of solar radiation hitting the test persons.

Figure 4.2 shows a graphical representation of PMV^b and AMV dependent on the solar radiation level hitting the test persons.

PMV^b over predicts the discomfort at 200 and 400 W/m². This is in (Hodder and Parsons, 2006) explained with the fact that some people enjoy being hit by the sun up to a certain level after which these persons also start to feel uncomfortable.

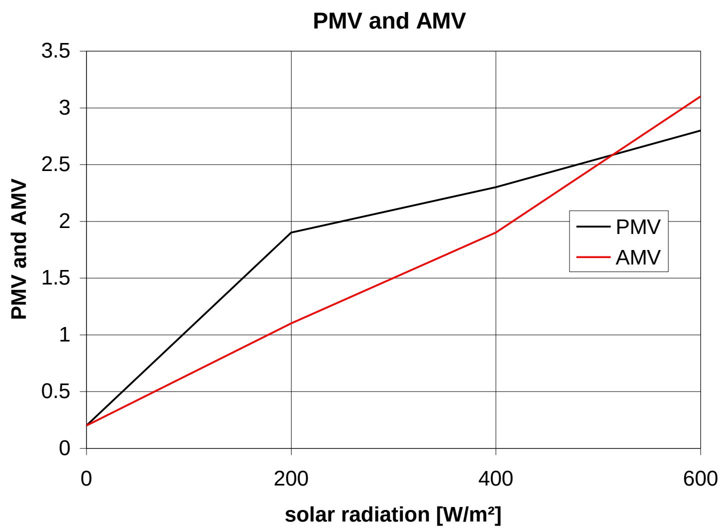


Figure 4.2. PMV[b] and AMV dependent on the level of solar radiation.

Figure 4.3 shows a graphical representation of PPD[b] and APD. Although PMV[b] and AMV are quite different at 200 and 400 W/m² this is not the case for PPD[b] and APD.

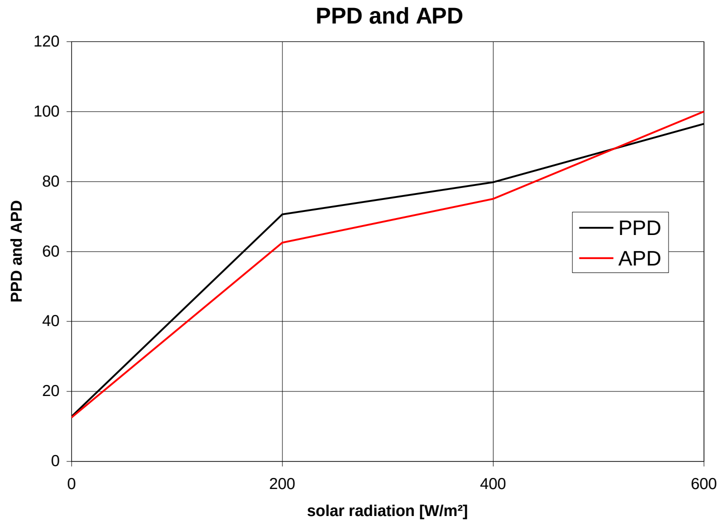


Figure 4.3. PPD[b] and APD dependent on the level of solar radiation.

The solar transmittance for a normal low-E window is around 0.65 which means that a person behind such a window may be hit by 500-700 W/m² dependent on the time of the year – highest during wintertime. So figure 4.2 and 4.3 are within the range of what may be experienced in buildings.

Figure 4.2 shows that the conclusion in (Hodder and Parsons, 2006) "an increase of one scale unit (AMV) per increase of 200 W/m² solar radiation hitting the person" is based on AMV and not PMV.

4.2. Discomfort when being hit by solar radiation in buildings

The following described work was initiated as part of the research on PowerShades and Microshades (Jensen, 2008b and Jensen, 2010) as it in test installations was noticed that it during the summer during clear sky conditions was more comfortable to sit next to a window with MicroShades than next to a window with solar control film. The reason is that MicroShades during the summer especially around noon lets less direct solar radiation through the window.

A prototype of MicroShades was investigated in [Jensen, 2008b]. The reduction of the direct incoming solar radiation through a MicroShade window compared to a solar control window (g-value of 0.37) is shown in figure 4.4. At low solar heights during the winter (11°) the two windows let in the same amount of solar radiation while the solar control window lets twice as much solar radiation in during the summer (solar height: 57°).

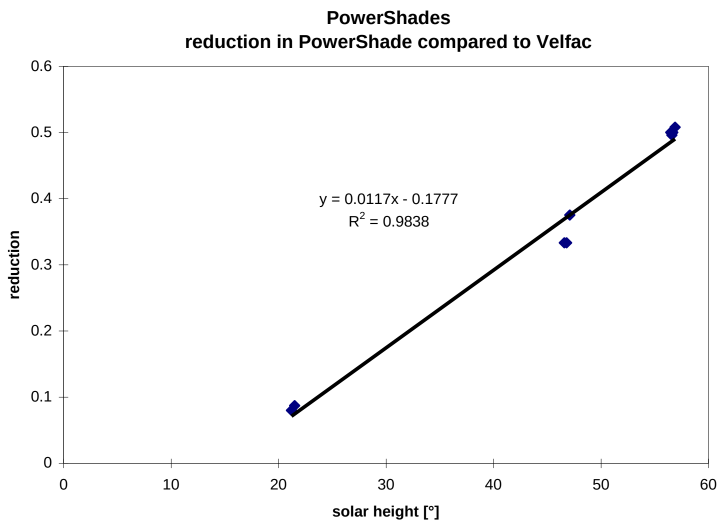


Figure 4.4 The reduction of the direct incoming solar radiation at noon through a MicroShade window compared to a solar control window at an azimuth of 0° (Jensen, 2008b).

The measured transmitted solar radiation at noon was:

	solar control window	MicroShade window
	W/m²	W/m²
Winter	280	280
Summer	170	85

The increase in AMV (PMV) according to (Hodder and Parsons. 2006) - the numbers above divided with 200 – is then:

	solar control window	MicroShade window
Winter	1.4	1.4
Summer	0.85	0.43

Figure 4.5 shows the relationship between PMV and PPD. The equation for the curve in figure 4.5 is:

$$PPD = 100 - 95 \cdot \exp(-(0.03353 \cdot PMV^4 + 0.2179 \cdot PMV^2)) \qquad \text{(Olesen, 1996)}$$

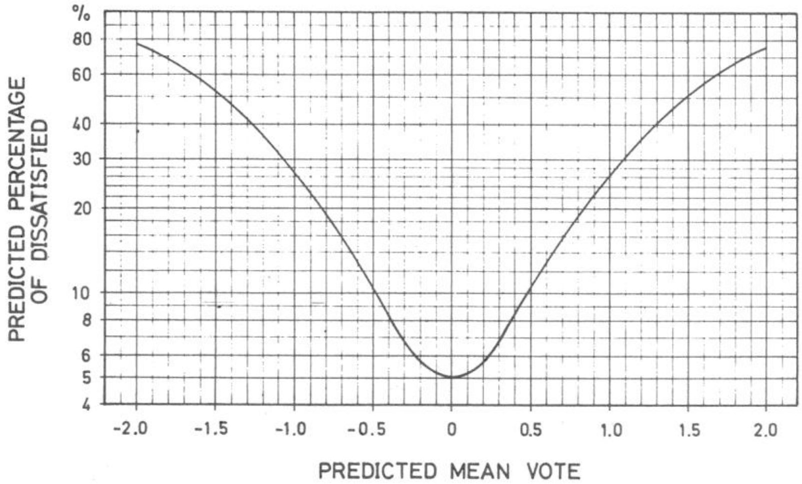


Figure 4.5. The relationship between PPD and PMV (Fanger, 1982).

If prefect comfort in the room – i.e. PMV is 0 - the solar radiation will give 45% unsatisfied if hit by the solar radiation during the winter for both window types. During the summer a room with MicroShades will be inside the comfort range of ±0.5 while 20% will be dissatisfied in a room with the solar control window if hit by the sun.

This explains what was experienced in relation to the test installations in rooms. However, the relationship: an increase of one scale unit (AMV) per increase of 200 W/m² solar radiation hitting the person was found for cars. But does this also apply for buildings?

4.2.1. Experiments in test rooms

Based on the above it was decided to verify if the findings in (Hodder and Parsons, 2006) also apply for buildings.

As a central part of the research work on PowerShades/MicroShades two almost identical test rooms was erected at the Danish Technological institute (Jensen, 2008c). Figure 4.6 shows the dimensions of the two test rooms while figure 4.7 shows the sensor set in and around the test rooms.

Each test room has as shown in figure 4.8 a window consisting of two parts. The smaller of the window can be opened while the larger is fixed. The hole in the wall for the window is 1.57 x 1.58 = 2.48 m² while the total transparent area is 1.98 m².

In order to replicate the test of (Hodder and Parsons, 2006) the two test rooms were equipped with globe temperature sensors as shown in figure 4.9. The globe temperature sensors had a mat black globe with a standard diameter of 150 mm. The globes were made of thin plastic in order to increase the thermal response to variation in the solar radiation level.

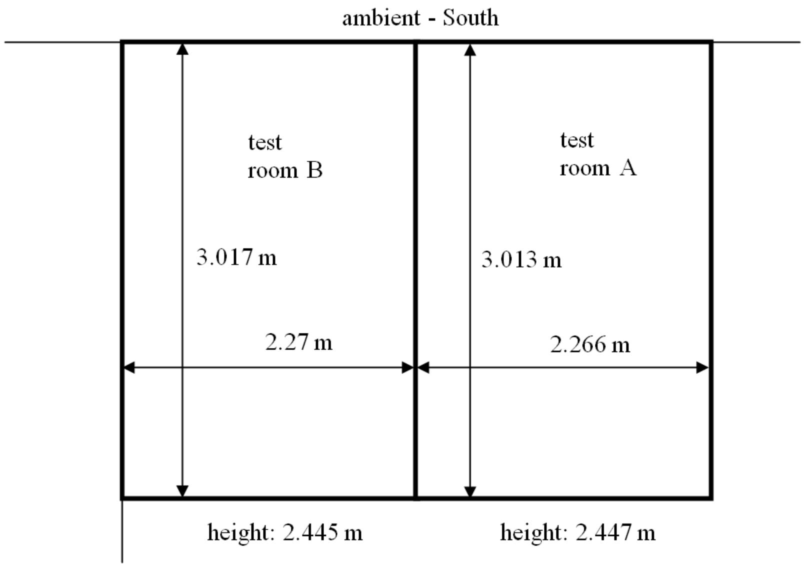


Figure 4.6. The dimension of the test rooms (Jensen, 2008c).

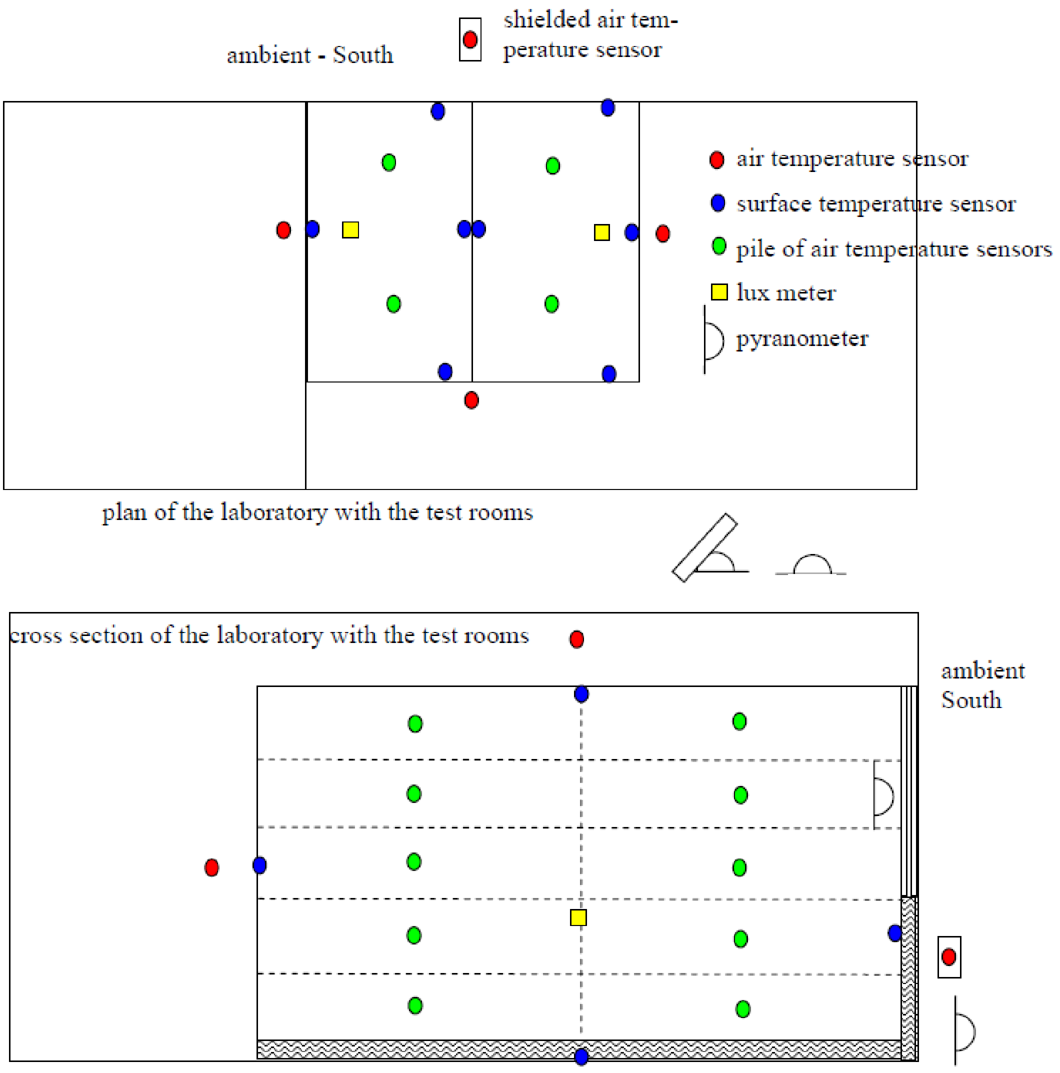


Figure 4.7. The sensor set in and around the test rooms (Jensen, 2008c).

Figure 4.8. The window of the test rooms.

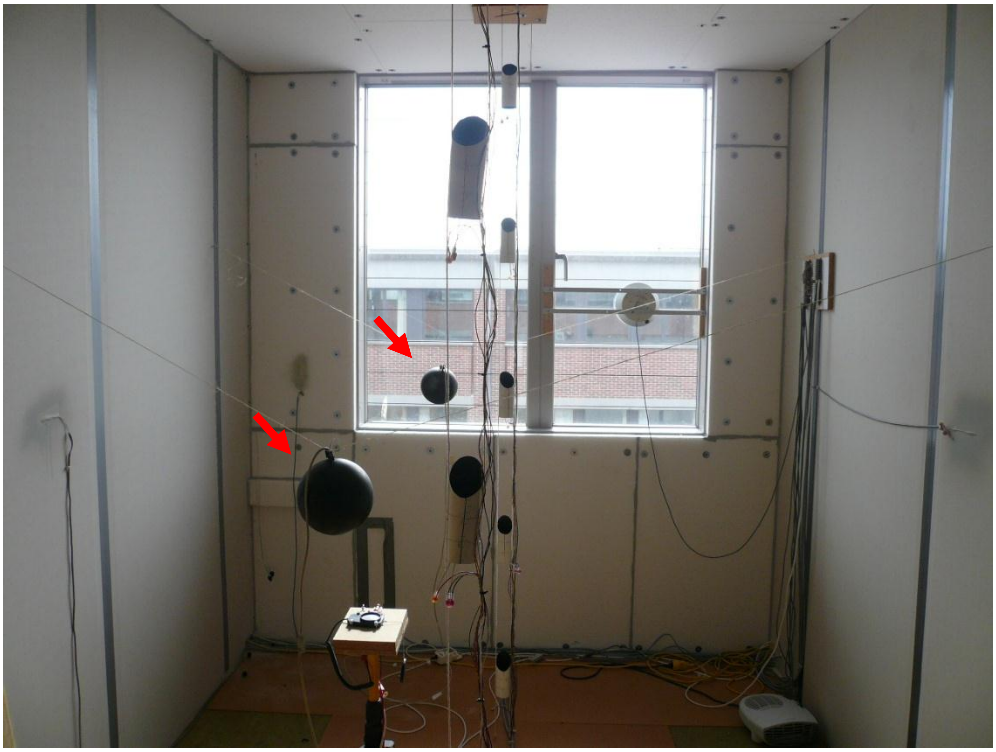


Figure 4.9. Globe temperature sensors in a test room with MicroShades in the window.

Based on the globe temperature and the room temperature is it possible to determine the mean radiation temperature which is necessary to know in order to calculate the comfort. The mean radiation temperature may be calculated using the below equation if the air speed along the globe is low which is assumed as the rooms were sealed:

$$t_r = ((t_g + 273)^4 + 0.4*10^8*|t_g - t_a|^{0.25}*(t_g - t_a))^{0.25} - 273°C \text{ (Olesen, 1996)} \quad [4.1]$$

where: t_g is the globe temperature [°C]
t_a is the room temperature [°C]

Two globe temperature sensors were located in each room – both in the middle compared to the not open able window (see figure 4.9). One 380 mm from the façade in a height so that solar radiation did hit the globe at an azimuth of 0° of the sun. The other globe was located 2 m from the façade in order to prevent it from being hit by the sun.

The measurements demanded clear sky conditions but this turned out to be difficult to obtain. Only 9 days of measurements from the first half year of 2010 are included in the investigations: 6 days in the period March 25-April 15 (in the following called Spring 2010) and June 3rd. 4th and 6th (in the following called Summer 2010). During spring the original Velfac sun 1/clear with solar control film (Jensen. 2008c) was still mounted in test room B. This window was in the beginning of May 2010 replaced with a traditional low-E window without solar control film in order to allow more solar radiation into the room. However, unfortunately clear sky conditions were first obtained a month later resulting in a less difference in incoming solar radiation between the two periods than hoped. The experiment was, therefore, repeated in the start of 2011. Clear sky conditions were obtained during four days between January 27 and February 20 (in the following called Winter 2011) and four days again between March 5 and March 16 (in the following called Spring 2011). The windows in the two test rooms were the same as during the summer 2010 experiment.

The measurements Spring and Summer 2010 were carried out in the PSO ForskEL project PowerShades II - optimization and validation of highly transparent photovoltaic project no. 2008-1-004 and reported in (Jensen, 2010) but as these measurements remained inconclusive the measurements were repeated in the present project: Winter and Spring 2011.

The test rooms do not have air-conditioning so it is not possible to control the air temperature and further the air temperature continued to incline after the solar radiation had peaked. So the measuring conditions were not stable. This is illustrated in table 4.2 containing the measurements from all the above days where for each day are shown two sets of measurements: one when the room temperature (troom) peaked and one when the incoming solar radiation (radiation) peaked. The mean radiation temperature (Tr) was calculated using equation [4.1].

If the values in table 4.2 are used in Fangers equation where the clo (level of clothing) and met (metabolism – ie level of activity) were adjusted in order to obtain thermal comfort at the measured room temperature and Tr equal to the room temperature a very scattered result is obtained as shown in figure 4.10 (only data from spring 2010).

However. the difference between the mean radiation temperature and the room temperature is very stable not depending on the air temperature as seen in figure 4.11 (only data from spring 2010 – data from the three other periods shows similar results). This has been utilized in order to compare with the findings in (Hodder and Parsons, 2006):

- room temperature 23.4°C from table 4.1
- met was kept at 1.2 while clo adjusted to create thermal comfort at 23.4°C
- mean radiant temperature: 23.4°C + the difference between the mean radiant temperature and the room temperature from the measurements

Room A (with a MicroShade window)					Room B (with traditional windows)				
	Troom	Tr	radiation	ΔT		Troom	Tr	radiation	ΔT
Spring (March-April) 2010									
day 84	26.3	33.27	170	6.97	day 84	27.84	38.61	244	10.77
	24.42	31.56	187	7.14		25.36	37.01	223	11.65
day 93	24.88	31.76	158	6.88	day 93	26.76	39.83	230	13.07
	23.79	31.17	184	7.38		26.13	39.28	254	13.15
day 97	24.86	31.77	156	6.91	day 97	26.08	38.65	232	12.57
	24.18	30.75	169	6.57		25.49	37.91	239	12.42
day 100	24.76	31.83	129	7.07	day 100	26.53	40.16	206	13.63
	23.55	30.34	163	6.79		26.27	39.68	243	13.41
day 104	28.61	35.51	148	6.9	day 104	30	43.34	227	13.34
	27.1	33.37	160	6.27		28.48	41.94	236	13.46
day 105	28.49	35.27	145	6.78	day 105	30.3	43.3	218	13
	27.42	34.02	162	6.6		28.94	42.12	241	13.18
Summer (June) 2010									
day154	25.91	28.31	51	2.4	day84	31.88	51.53	239	19.65
	25.58	28.02	79	2.44		29.33	49.55	280	20.22
day155	27.17	29.62	71	2.45	day 93	33.5	52.51	243	19.01
	25.67	27.53	86	1.86		30.4	50.25	277	19.85
day157	29.22	31.43	65	2.21	day 97	34.9	51.2	240	16.3
	27.96	29.82	76	1.86		33	49.46	274	16.46
Vinter (January-February) 2011									
day27	23.55	33.77	244	10.22	day27	28.08	46.16	425	18.08
	21.58	32.34	258	10.76		24.66	44.65	440	19.99
day43	25.43	35.64	260	10.21	day43	31.64	51.53	467	19.89
	24.06	34.44	267	10.38		29.36	50.18	477	20.82
day50	22.91	31.92	226	9.01	day50	28.06	47.49	437	19.43
	20.5	30.43	244	9.93		25.54	46.67	450	21.13
day51	22.99	32.19	234	9.2	day51	28.22	48.03	445	19.81
	20.31	30.57	250	10.26		25.94	47.2	462	21.26
Spring (March) 2011									
dag 64	22.31	31.54	238.6	9.23	dag 64	28.64	48.86	474.3	20.22
	24.63	33.07	211.7	8.44		31.76	50.96	451.6	19.2
dag 65	21.8	30.53	241.3	8.73	dag 65	27.52	47.55	483.5	20.03
	25.3	33.65	218.1	8.35		32.76	51.72	443.4	18.96
dag 67	22.85	31.3	226.7	8.45	dag 67	29.11	48.72	459.1	19.61
	25.56	32.62	198.2	7.06		32.84	51.19	426.2	18.35
dag 75	23.93	32.54	215.4	8.61	dag 75	31.25	50.66	454	19.41
	25.57	33.09	188.8	7.52		32.18	51.31	441.3	19.13

Table 4.2. Measurements from March 2010-March 2011.

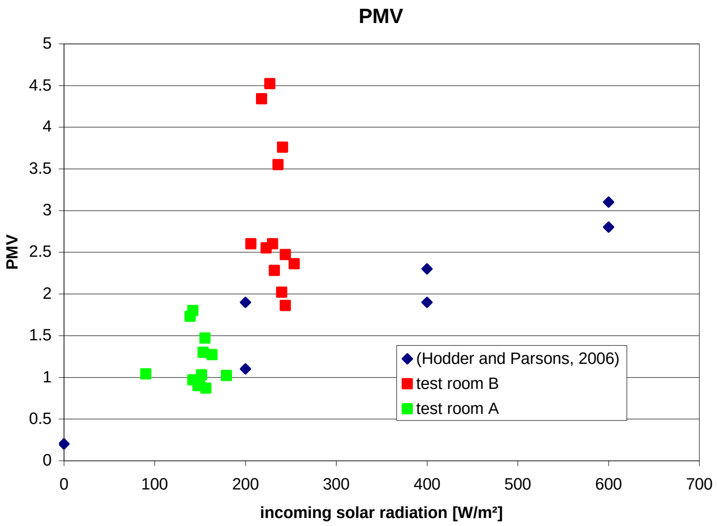
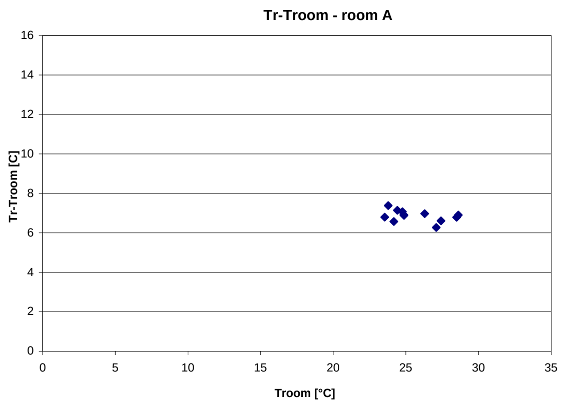


Figure 4.10. PMV when the values in table 4.2 (only from spring 2010) are put in directly in Fangers equation.



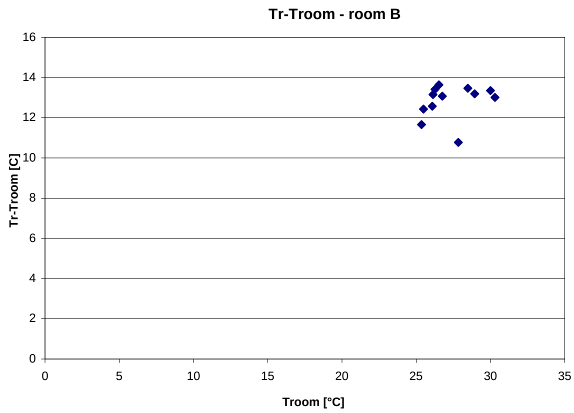


Figure 4.11. Tr minus Troom for the values for spring 2010 in table 4.2.

Figure 4.12 shows the result from these calculations. The 6 days in spring 2010 was averaged into one mean day which also was the case for summer 2010, winter 2011 and spring 2011.

All values except the summer 2010 value from room B fall within the measurements/calculations by (Hodder and Parsons. 2006). Except for (Hodder and Parsons, 2006) PMV at 200 W/m² and the summer value from room B the values in figure 4.12 shows a linearly tendency. Using all data in figure 4.12 in a linearly regression gives a line with a slope of 0.0055 as seen in figure 4.13.

A slope of 0.0055 means an increase of one scale unit PMV per increase of 182 W/m² solar radiation hitting the person. This is very close to the findings of (Hodder and Parsons, 2006): an increase of one scale unit PMV per increase of 200 W/m² solar radiation hitting the person. If however the two main outliers – red circle in figure 4.13 (summer 2010 in test room B and one from (Hodder and Parsons, 2006)) - may contain measuring errors and if therefore excluded from the regression, the slope of the curve will decrease to 0.0052 as seen in figure 4.14 – one scale unit PWW per increase of 192 W/m².

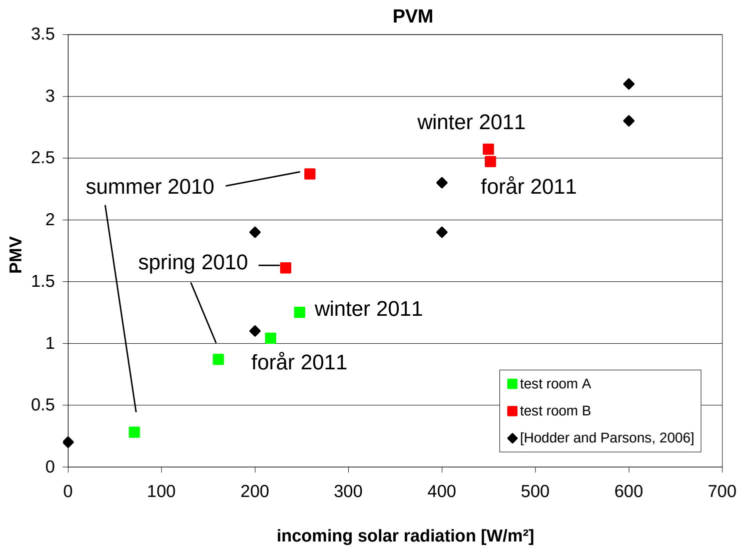


Figure 4.12. The PMV's dependency on the incoming solar radiation.

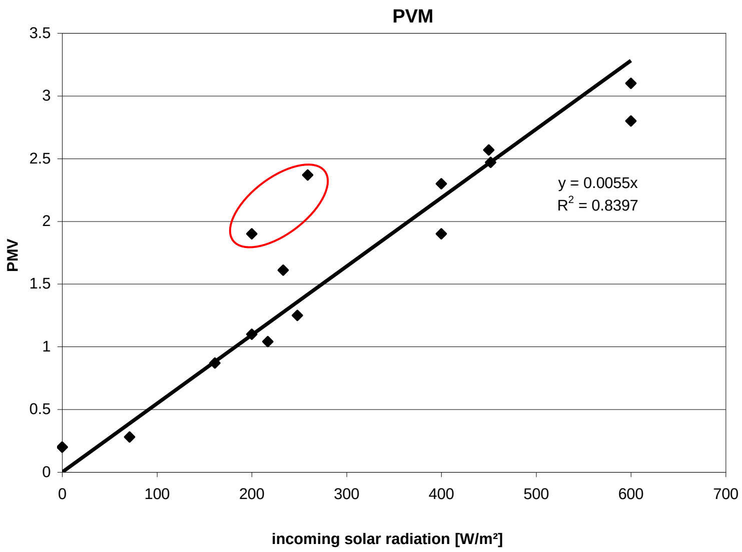


Figure 4.13. Linear regression performed on all points in figure 4.12.

With or without outliers the results from (Hodder and Parsons, 2006) and from the test rooms at the Danish Technological Institut are so similar that it may be concluded that: the influence of solar radiation hitting a person behind a window in a building is the same as in cars.

It could be discussed if the dependency of the PWV on solar radiation should be: PMV = I/200 (where I is the solar radiation hitting the person [W/m²]) as suggested in (Hodder and Parsons, 2006) or PWV = I/182 as indicated in figure 4.12. However, the uncertainty of the measurements is believed to be at least ± 10% so each of the equations are valid. It is therefore suggested for the time being to stick to the relationship: PMV = I/200.

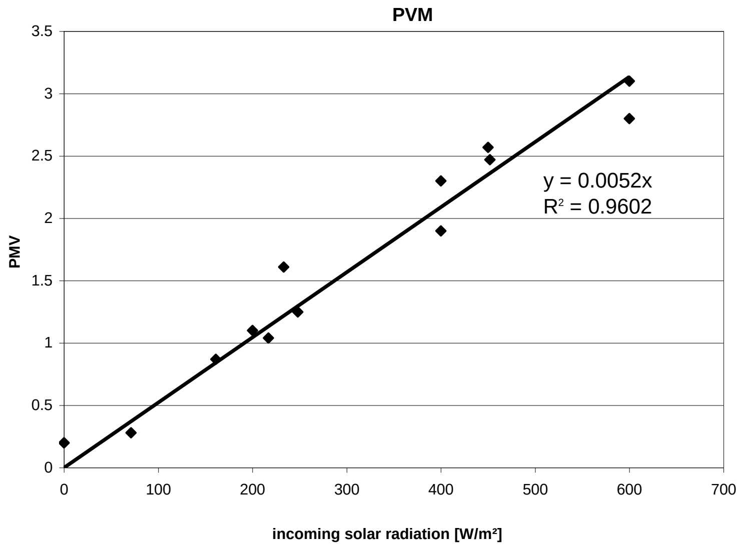


Figure 4.14. Linear regression performed on all points in figure 4.12 except the two outliers indicated in figure 4.13.

The values of PPD shown in figure 4.15 does not show a linearly tendency which is not a surprise as the dependency of PPD on PMV is not linearly as seen in figure 4.5. The values in figure 4.15 show correctly a tendency more like the curve in figure 4.5.

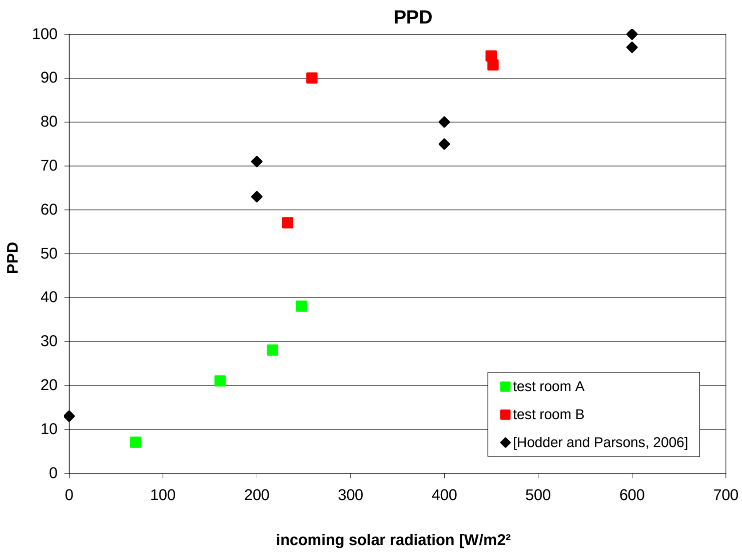


Figure 4.15. The PPD's dependency on the incoming solar radiation.

The measurements from the globe temperature sensors at the back of the rooms showed that if a person is in thermal comfort the solar radiation through the window will not create discomfort while if a person is not in comfort (too hot) the radiation through the window will only increase the discomfort slightly.

This means that the radiation not surprisingly only/mainly influences the comfort level if the person is directly hit by the radiation.

4.3. Conclusions

The result of the experiment in the two test rooms is in agreement with (Hodder and Parsons, 2006). The discomfort of being directly hit by solar radiation may be described by the following equation if the person without being hit by the sun would have been in thermal comfort:

$$PMV = I/200 \tag{4.2}$$

where: I is the incoming radiation through the window hitting a person [W/m²]
if the person would have been in comfort without being hit by the radiation

When combining equation 4.2 with the equation for PPD on page 48 table 4.3 can be generated.

I [W/m²]	PMV [-]	PPD [%]
100	0.5	10
200	1	26
300	1.5	51
400	2	77
500	2.5	93

Table 4.3. Correlation between the incoming solar radiation through a window and the predicted percentage of dissatisfied (PPD) when being hit directly by the sun.

The comfort level of persons not being hit by the radiation is not influenced by the radiation.

Equation 4.2 is only valid if the person is hit by an evenly distribution of solar radiation as is the fact for normal windows with and without low-E coating. The holes of Microshades and the distance between the holes are that small that the solar radiation hitting the person also may be considered as evenly distributed.

But this is not necessarily the case for traditional solar cells integrated in windows – se figure 1.1. It is however supposed that if the solar cells are small the incoming solar radiation may be regarded as evenly distributed both if the distance between the solar cells as small as a) in figure 1.1 or larger compared to the size of the solar cells as shown in figure 3.1.

Equation 4.2 may not be valid where the solar cells are large (eg. 0.1 x 0.1 m² - e.g. d) in figure 1.1) and the distance between the solar cells are in the same order of size as the solar cells.

5. Conclusion

The aim of the present report is to investigate how the thermal conditions including thermal comfort in buildings will be influenced when solar cells are introduced in transparent parts of the facade. The reason is that solar radiation especially in office buildings are known to may cause both discomfort and increased energy demand.

Solar cells in transparent parts of a facade facing the sun will act as sunscreening while at the same time produce electricity.

The conclusion from the work is:

Comfort

- the internal window pane of a window with solar cells filling out most of the transparent area will be less warm than traditional windows leading to less discomfort due to temperature asymmetry
- the heating up of a person being directly hit by the sun is less when located behind a window with solar cells filling out most of the transparent area. An equation for the discomfort of being hit directly by solar radiation has been developed

In order to decrease the discomfort for the persons sitting just behind the glazed facades it is necessary that only little solar radiation can hit the person directly or warm up the window. This calls for windows with a very large degree of solar cells, - i.e. with a small opening area. In order to decrease the closeness of the transparent facades it is possible to work with differentiated degrees of opening area of the windows, - i.e. having some windows almost filled out with solar cells while others are with only a small degree of solar cells or without solar cells.

Energy

If there is a cooling demand in a building it may be beneficial from an energy point of view to include solar cells in the transparent parts of the facades. However, often the decision of introducing solar cells in the windows should be based on other reasons than energy: cost (e.g. cost of pv windows, reduction of cooling plant), visual comfort, signal value, etc.

Calculations of the benefit of applying solar cells in windows should always be performed for the actual case. When calculating the benefit of applying solar cells in the transparent facades it is important to include the efficiency of the energy supply systems especially for the cooling system, the primary energy conversion factors and the pv production.

Applying solar cells in the transparent part of the facades should mainly be considered in buildings with a large cooling demand compared to the heating demand and demand for electricity to artificial light. There is no energy savings if the building has no cooling demand.

At high cooling demands: pv windows incl. MicroShades (PowerShades) performs from an energy point of view better than traditional solutions as solar control coating and movable sunscreening.

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