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PV MOBI – PV MODULES OPTIMISED FOR BUILDING INTEGRATION

B.J. de Boer
W.G.J. van Helden

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Bart J. de Boer and Wim G.J. van Helden
ECN Renewable Energy in the Built Environment, Energy research Centre of the Netherlands, P.O. Box 1, Petten, 1755 ZG, The Netherlands, Tel. +31 224 564 901, Fax +31 224 563 214, E-mail b.deboer@ecn.nl

Abstract – Semi-transparent PV-modules can be seen as multi purpose, synergetic building elements: apart from being electricity generators they fully need to meet the complex of demands to function as light- admitting façade, window, roof or shading elements. For the admittance of sunlight an adequate balance between passive solar gains (heating and lighting) and overheating in summer or heat losses in winter must be found in order to reach useful applications. At the same time electricity output of the PV modules should be maximised. To optimize the design for this type of PV modules the impact of module design parameters on PV-power generation and building physical aspects has been evaluated. For different types of application (atrium, awning and façade) energy related aspects (lighting, heating and cooling demand, power generation) have been simulated. It appeared that building specific design parameters influence the most suited PV module layout largely. Therefore for each project an optimisation of the best PV-module design is still desired. Computerprograms like TRNSYS, WINDOW and Adeline are tools which can succesfully be used for this purpose.

1. INTRODUCTION

The EC funded project 'PV Modules Optimised for Building Integration' (PV-MOBI) deals with research, design, optimisation and manufacturing of prototypes of semi-transparent PV modules. Within the framework of the JOULE program, the project is being executed by the research centres CIEMAT Department of Renewable Energy (Spain), Energy research Centre of the Netherlands ECN and PV manufacturers ASE, PST (Germany) and Isofoton (Spain).
One of the challenges in the design process of buildings is to optimise the indoor comfort level. In Figure 1 a listing is given of all the effects that determine this indoor temperature. Often numerical tools are effectively used in this process. In order to calculate the indoor temperature of a room with transparent glazing systems a large number of parameters have to be included. Like normal transparent glazing systems, semi transparent elements affect the inner climate of the building in several ways. The absorption, reflection and transmission of the modules

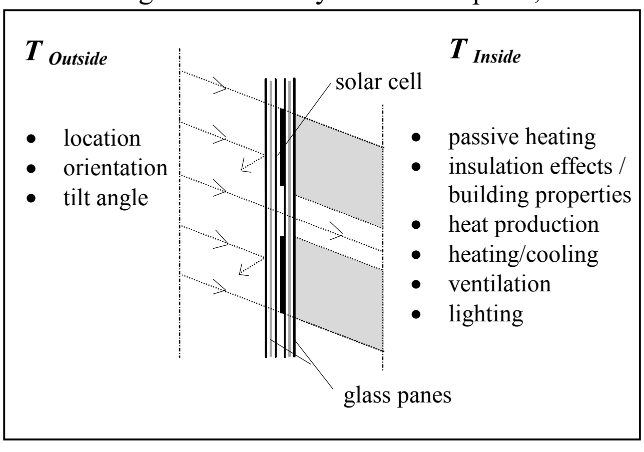

Figure 1. Schematic view of aspects regarding thermal modelling of a semi-transparent PV module

determine the contribution of the solar radiation to the heating of the interior. Furthermore, the heat loss to the exterior on cold days or the heat gain on warm days is partly determined by the module's heat transfer coefficient (U-value). Together with the other transparent elements in a facade (normal windows), the transparency of the modules also determines the share of daylight in the interior lighting level. Both inner temperature and daylight level depend on the type of building or rooms for which semi-transparent PV modules are used. In the present project the effects of semi-transparent PV modules on three different building applications have been modelled: a facade, an atrium and an awning. Special attention was paid to the effects in warmer, Mediterranean climates, in which overheating during the late afternoon can cause serious discomfort. This project is part of an EU-funded research project [1], [7] which is aimed at systematically optimising semi-transparent PV-modules for different buildings applications. The thermal modelling is followed by daylight contribution modelling (Adeline) and by designing, optimising, building and testing of prototypes.

2. SEMI-TRANSPARANT PV MODULES

Semi-transparent PV modules are increasingly used as building elements. As such, they combine aesthetics with environmentally friendly electricity generation and with transparency, enabling a more efficient use of daylight. In recent years a number of buildings have been equipped with semi transparent PV modules, forming either facades, roofs, atria or awnings. An example of a facade can be found in Barcelona, in the Mataro public library, or in Aachen, in the building of the Stadtwerke and at the sloped facade of Solar Office in Doxford, England. Roofs of semi-transparent PV modules have been built at, for instance, Rikers Island, New York, and on the HUK Insurance company in Coburg, Germany and Hirne . In De Kleine Aarde in Boxtel, The Netherlands, an atrium has been built with a semi-transparent PV module roof. The Handelshaus A. Wild in Innsbruck, Austria is one of the first buildings equipped with awnings of these PV modules. These are just a few examples of projects that have been realised. More examples and descriptions can be found in, for instance, [2], [3] and [4].
Semi-transparent photovoltaic (PV) modules are created by using transparent material, e.g. glass, for the encapsulation of the cells and for the construction of the module. The module can be constructed in many ways: single, double or triple glass panes, with the position of the PV-cells at the rear of the front pane or in front of the back pane. In figure 2 two possible configurations are depicted. The top-configuration has been chosen for the present modelling

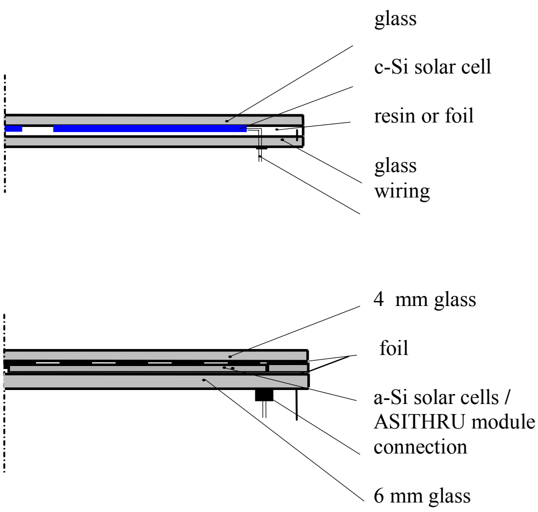

Figure 2. Possible compositions of a semi-transparent PV-module.

3. PV MODULES ASSEMBLED FOR MODELLING

One of the possible geometries mentioned above is chosen for further simulations, in order to constrain the number of calculations to be made. The window structure is composed of two glass panes of 4.8 and 4 mm thickness separated by an air filled 15 mm wide gap. The PV cells are placed at the inner side of the interior glass pane. The optical and thermal characteristics of this module are modelled with the software program WINDOW4.1, developed by the Windows & Daylighting group of the Lawrence Berkeley Laboratory, USA [5]. The spectral data files for the different glazing materials applied form the basis for this program. In these files, the transmission and reflection data per wavelength are specified. The spectral data for the combination of inner glass pane plus PV-cells are constructed from the data of the separate elements. The reflection is found by taking the area-weighted average, while the transmission of the glass parts covered with cells is found by multiplication of the separate transmissions. The transmission for the complete surface finally is computed by area weighted averaging of the transmissions of the covered and uncovered glass parts. With this information and with the geometry of the window, the program calculates the visual and infrared properties of the window, for incident angles varying between perpendicular and 90 degrees and for the complete window system. The latter includes the glazing edges and the framing. In our case, square windows with a total area of 1.5 m^2 and a glass area of 0.8 m^2 are assumed, with a 100 mm wide vinyl frame. The window properties are calculated for 6 windows with transparency ratios of the glass area of 10, 20, 25, 30, 40 and 50%. The main properties are listed in table 1.

Transparency Ratio (%)	U (W/m^2K)	SHGC	T_{sol}	R_{fsol}	T_{vis}
10	1.93	0.37	0.065	0.255	0.068
20	1.99	0.38	0.120	0.248	0.135
25	2.21	0.39	0.148	0.244	0.168
30	2.05	0.39	0.175	0.240	0.203
40	2.10	0.41	0.229	0.233	0.271
50	2.15	0.43	0.284	0.225	0.339

Table 1. Main properties of window systems with different transparency as calculated with WINDOW4.1.

U is the heat transfer coefficient. SHGC is the solar heat gain coefficient, the ratio between interior solar heat gain and the incident solar energy. T_{sol} is the solar transmission, R_{fsol} is the solar reflection off the front of the window and T_{vis} is the visible transmission.

The U-value and solar heat gain coefficient are comparable to the values for normal 2-pane glass with an air gap. The transmission values, however, are much lower due to the opaqueness of the solar cells in the modules. The U-value for the base-case with 25% transparency ratio is not in line with the other U-values. This is due to the smaller window size used for this transparency. The smaller window has a relatively larger edge and therefore the (higher) edge heat transfer value contributes more to the total window heat transfer. As can be seen from the table, this has no effect on the solar heat gain coefficient or the transmission and reflection values. Next to the set of windows in this table, a second set has been used in the calculations. This set is the same as the previous, but with a filling of Argon instead of air, leading to lower heat transfer coefficients.

4. CHOSEN BUILDING APPLICATIONS

The aim of the project is to find optimal designs for semi-transparent PV modules used in a range of building applications. Initially, three main applications have been chosen: a facade, an atrium and an awning.

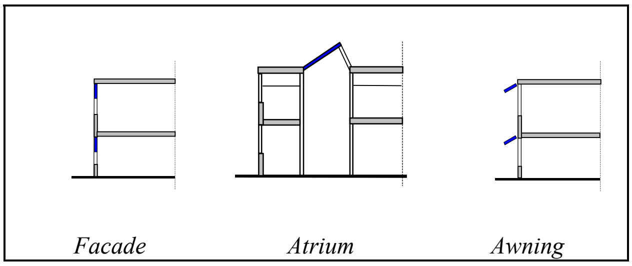

Figure 3. Types of semi-transparent PV applications that have been chosen

For each application the effects on inner temperature, heating demand, cooling demand and lighting level in an office room was studied. In the case of the facade the semi-transparent PV-modules are directly connected to the room and the effects are expected to be larger than in case of an atrium or an awning.
For each application a large set of parameters can be altered, leading to an even larger number of possible situations that can not all be evaluated. In order to identify the most important parameters, a first set of calculations was made with the facade application. The facade forms the outside boundary of an office room. The facade area is divided into three horizontal parts. The lower part is a closed wall, the middle part is normal, fully transparent glazing and the upper part consists of the semi-transparent PV modules. An automatically operated shading device is mounted in front of the transparent window and minimises unwanted solar heating. Two persons work in this office and they both use a personal computer. The list of most important parameters that have been varied in the first set of calculations is given below. One value for every parameter is chosen for the base case that serves as reference for all variations. These values are <u>underlined</u>.

- Orientation of the facade; five orientations are chosen ranging from south-east through <u>south</u> to south-west
- The slope of the facade, from <u>vertical</u> to 60°
- The size of the room. 3 rooms are used with <u>16</u>, 20 and 40 m^2 floor area and <u>12</u>, 12 and 15 m^2 of facade area, respectively
- Level of internal heat production. A low, <u>standard</u> and high level of electricity consumption for PC's and lighting are assumed. The annual internal heat gains correspond with 4.4, <u>5.4</u> and 8.1 GJ, respectively.
- High (50) or <u>low</u> (<u>35</u> m^3/h/person) ventilation level
- Transparency of the PV-modules as listed in Table 1. <u>25%</u> transparency represents the base case value.
- Infiltration of outside air. 3 levels are calculated with 0.06, <u>0.6</u> and 1.7 room volumes per hour
- Colour of the facade with the absorption factor ranging from 0.3 through <u>0.6</u> to 0.9. These values roughly correspond with a white, <u>red/brown</u> and dark brown facade.
- Percentage of PV modules in facade area. If only the module area and not the frame area is taken into account, the percentages are 0, 10, <u>20</u> and 30. The base case represents 30% of the facade area including frame.
- Insulation value of the modules is varied between medium (U=<u>2.21</u> W/m^2K) and high (U=1.55)
- The building mass of floors and ceiling is either high (<u>260</u> kg/m^2) or low (200 kg/m^2)

Apart from this list the influence of some other parameters were investigated but these were found to be of minor importance.

5. THERMAL SIMULATIONS

The numerical modelling has been performed with the transient simulation software package TRNSYS [6]. As boundary condition the climatic situation in Madrid was used, combined with building element properties, ventilation rate and internal heat production as defined above. The modelled heating and cooling equipment are assumed to be ideal. This means that during the time step of one hour the equipment can provide as much energy as needed to keep room temperatures within the limits. The indoor temperature (T_i) is set to an absolute maximum value of 25° C. In one calculation, the hour-to-hour values of a complete climatic reference year is the input. The meteorological data for Madrid (40° North latitude) have been used, with a global annual solar irradiation of 1860 kWh/m^2 on a horizontal surface. It has been assumed that the office room used for the calculation was bounded at all sides by identical rooms at identical temperatures, leading to adiabatic boundary conditions for all walls except the facade. During a calculation all possible temperatures and heat flows can be output. Three of the possible output values are of special interest: the total heating and cooling energy required and the electricity produced by the PV modules.

6. RESULTS THERMAL MODELLING

The first calculations were performed to identify the most important parameters, as explained in section 3. The base-case is used as a reference for all variations. For this purpose the facade application at an office room has been chosen. The next table gives the base-case results.

Q_h (GJ)	Q_c (GJ)	Q_{tot} (GJ)
0.46	4.75	5.21

Table 2. Base-case results. Annual heating demand (Q_h), cooling demand (Q_c) and total(Q_{tot}).

The annual heating and cooling demand per square metre floor area are 28.75 MJ and 297 MJ, respectively. In many cases the efficiencies of heating and cooling equipment is taken into account when determining the total (primary) energy demand. The efficiencies, however, depend on many specific assumptions: boiler and heat distribution system efficiency, the coefficient of performance of the cooling apparatus and, as the cooling machine normally is driven by electricity, the mean conversion efficiency of electricity generation. These should all be considered to arrive at a complete picture for the primary energy demand. We will make no assumptions for these efficiencies and just take the simple sum of heating and cooling demand for Q_{tot}. As the separate values of Q_h and Q_c are also given, the reader can make his own calculation of the primary energy demand for a given system configuration.
For each variation of the parameters listed in section 3 a calculation of Q_h and Q_c is made. The results are given in table 3, together with the maximum deviation found, relative to the base-case results.
As can be seen in table 3, the variation in orientation has a very large effect on the annual heating demand and a large effect on the cooling demand. If the building is oriented more to the southwest the total energy demand decreases. This is mainly due to the lower cooling demand in the early hours of the day, as with this orientation the morning sun does not enter the office room. As compared to the base-case situation with vertical facade, a smaller slope angle leads to a somewhat smaller heating demand and a larger cooling demand. The base-case room volume is 48 m^3. From the variations in room volume it can be seen that the heating demand is roughly proportional to the room volume, while the cooling demand for small and large room is nearly the same.

The medium-size room has a lower cooling demand because the facade area is equal to the base-case, but the room is deeper and thus has a larger heat capacity. The influence of the level of internal heat production is as expected: an increase leads to a lower heating demand and a higher cooling demand. If the ventilation is reduced from high (50 m^3 air per hour per person) to low (35 m^3/h) the heating demand decreases while the cooling demand increases slightly. A rather large variation in PV transparency, from 10% to 50%, does not have a large effect on heating or cooling demand. This could be explained by the fact that a larger transparency leads to a higher direct solar contribution, and simultaneously to a lower indirect contribution through the absorption of solar radiation by the PV cells.

Parameter	**Value**	**Q_h**	**Q_c**	**Q_{tot}**
Orientation	SW	1.61	3.76	5.37
	SSW	0.88	3.86	4.73
	SSE	0.32	7.1	7.42
	SE	0.31	10.42	10.73
Δ		**248**	**120**	**106**
Slope	60°	0.34	6.8	7.14
	75°	0.38	5.75	6.13
Δ		**-26**	**43**	**37**
Room size (m^3)	60	0.54	4.57	5.11
	120	1.11	4.71	5.82
Δ		**141**	**-4**	**12**
Internal heat prod. (GJ/y)	4.4	0.61	4.2	4.81
	8.1	0.18	6.3	6.47
Δ		**-62**	**33**	**24**
Ventilation	Low	0.31	4.87	5.18
Δ		**-33**	**3**	**-0.4**
PV transparency (%)	10	0.45	4.73	5.18
	20	0.46	4.75	5.20
	30	0.46	4.76	5.22
	40	0.46	4.79	5.25
	50	0.46	4.83	5.28
Δ		**-3**	**2**	**1**
Infiltration (h^{-1})	0.06	0.15	5.59	5.74
	1.7	1.53	3.9	5.43
Δ		**231**	**18**	**10**
Solar absorption of facade	0.9	0.45	4.8	5.25
	0.3	0.47	4.69	5.17
Δ		**3**	**1**	**1**
% PV modules in facade	0	0.54	2.57	3.11
	10	0.46	3.56	4.03
	30	0.48	6.06	6.54
	40			
Δ				
Module U-value (W/m^2K)	1.55	0.37	4.48	4.84
Δ		**-20**	**-6**	**-7**
Building mass (kg/m^2)	200	0.55	4.89	5.44
Δ		**18**	**3**	**5**

Table 3. Annual heating, cooling and total energy demand for variation of the parameters listed in section 3. The symbol **Δ** represents the highest relative deviation with respect to the base-case values.

The effect of a change in infiltration level is as expected: an increase in unwanted ventilation leads to a higher heating demand and a lower cooling demand. A decrease in both heating and cooling demand could be achieved by realising a very low infiltration, leading to a lower heating demand and combining this with a higher ventilation level in summer, resulting in a lower cooling demand. The solar absorption factor of the facade has only small effect on the energy demand. A variation of the share of semi-transparent PV modules in the facade area from 0% to 40% leads to a minimum value of the heating demand and a constant increase of the cooling demand. Using high-performance glazing for the semi-transparent module results in a decrease of both heating and cooling demand. This is caused by the lower infra-red emissivity of this kind of glazing, keeping radiative heat outside in summer. The last parameter that was varied is the mass of floor and ceiling. A lighter construction leads to an increase in energy demand, as expected. The absolute increases of both heating and cooling demand are comparable, but as the cooling demand is much higher its relative increase is rather small. Therefore, an increase in building mass will have more effect if the base-case cooling demand is already low.
It can be concluded that the orientation of the building, the infiltration and the internal heat production are of large influence on the annual heating and cooling demand of this office room. A first minimisation procedure should attend these parameters.

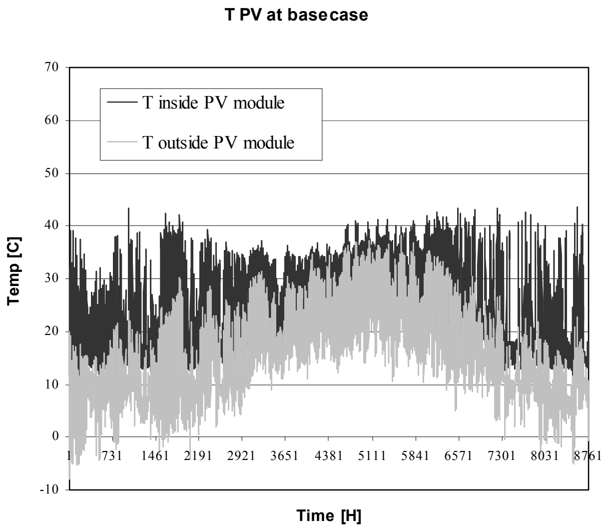

Figure 4. Temperatures of the inner (upper curve) and outer glass layer of the semi-transparent PV-module in the base-case calculation.

Figure 4 gives an impression of the temperatures of the inner and outer glass layer of the semi-transparent PV modules in the base-case configuration. As the PV cells in this case are connected to the inner glass pane the temperatures can become as high as 65 °C. The PV gain would be higher if the cells were placed at the back side of the outer glass layer.
If the area of PV modules in the facade is fixed and the proportion of clear glass varied, a minimum annual heat demand is found. The cooling demand, however, increases with increasing transparent part of the facade. This is depicted in Figure 5.

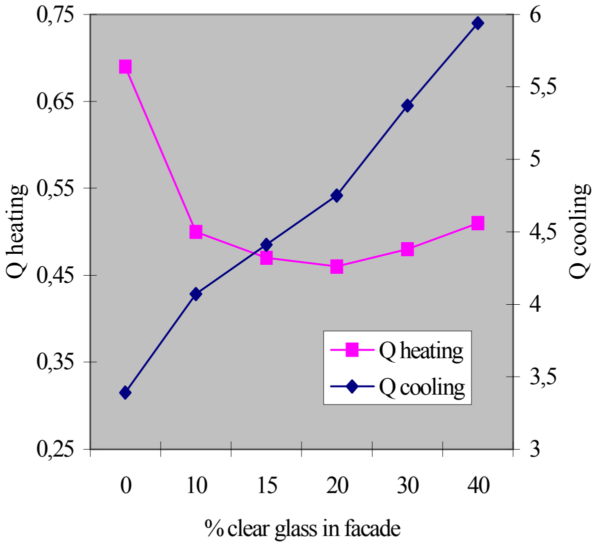

Figure 5. The annual heating and cooling demand for varying proportion of clear glass in facade area.

Because the cooling demand is much higher than the heating demand it is also not possible in this case to find a minimum for the total energy demand.
If we consider a facade without semi-transparent PV modules and make the same variation in proportion of clear glass in the facade, a minimum total energy demand can be found. From Figure 6 it can be seen that the minimum demand moves towards larger values of transparency of the facade area if the heat transfer value of the window panes decreases.

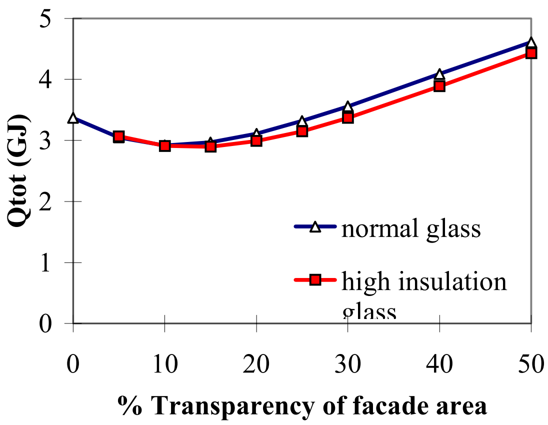

Figure 6. Total annual energy demand as a function of the percentage transparent facade area. No semi-transparent PV modules situated in facade.

6. MODELLING OF ELECTRICITY OUTPUT

For the PV electricity output a per square metre module area it is assumed that the PV module efficiency is 10% at reference conditions (1000 W/m^2, AM 1.5 and 25° C). The photovoltaic conversion efficiency decreases with increasing temperature. For multi-crystalline silicon cells the relative decrease in efficiency is set at 0.04 K^{-1}. The temperature of the inner glass pane with cells was calculated in TRNSYS and this value is used to determine the actual PV efficiency. The electricity generation per m^2 is found by multiplying the PV gains with (1-ε), with ε being the transparency. For the office room application the electrical gains of the PV modules have been calculated. The gains were corrected for the local temperatures of the PV cells in the module. The temperatures were obtained with the building simulation program. It was found that due to higher temperatures for PV modules with lower transparency the annual gain decreased with approximately one percent. This is much lower than the increase in PV gain per m^2 module surface area caused by the higher proportion of cells in this area. The calculated PV cell temperatures can reach maximum values between 35 and 45 °C, depending on the amount of transparency.

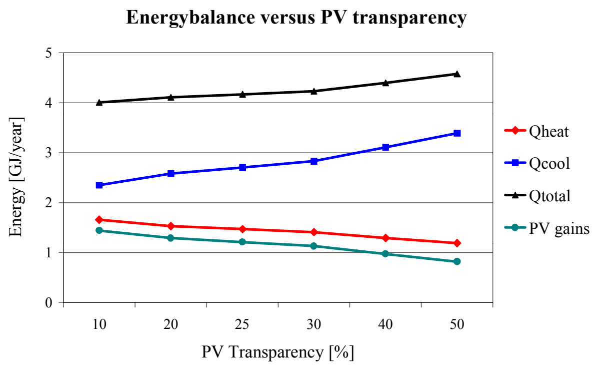

Figure 7. Energy balance and PV gains at different PV-module transparancies.

In the facade application the room size was fixed at 5 meters wide, 8 meters deep and 3 meters high. The PV-modules are integrated on a vertical façade, facing south. The façade area consists of three horizontal zones. The first meter of this façade was opaque, the next meter is clear glass with 90% transmittance and the third meter is the PV layer with a variable transmittance. Elaborated modelling has been done by Ciemat on this subject [8]. Here, the effects of PV with a different transparency is illustrated by the following examples.

To study the effect of PV light transmittance the same simulations were carried out with a PV transparency of 10% and 30%. The picture in figure X presents the result of a simulation in kLux for diffuse and direct daylight, calculated for a horizontal plane at a height of 1 meter (working surface).

The graphics of a PV-facade with 10% transmittance have been compared with a PV-facade with a transmittance of 30% for the two sky configurations. From the pictures only some general conclusions may be drawn:

- 30% transmittance leads in all situations to a higher mean value on the worksurface and also to a slightly deeper penetration of light into the room.
- 30% transmittance leads also to slightly larger illuminance variations in the vicinity of the window on desktop level.
- The maximum values at 30% transparency are somewhat higher than at 10% for all data. The differences are relatively small, probably due to the window below the PV facade, which takes care of circa 75-90 % of the transparency of the total facade. Changing the PV

transparency from 10 to 30 % results in a total façade transparency change from 33% to 40% respectively. The maximum levels of illuminance occur near the window. For all configurations they are well above the required workspace illuminance level of 500 lux.

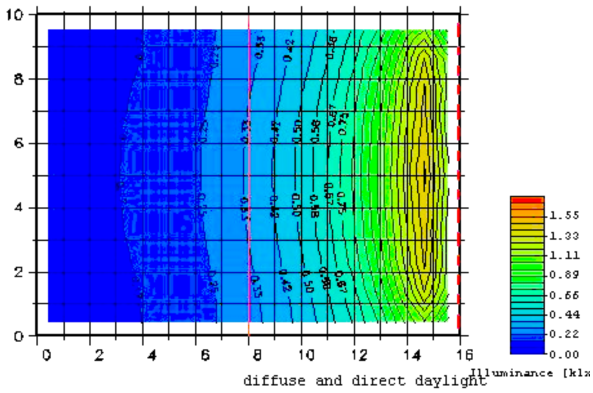

Figure 8. Illuminance at 21st of September at 13.00 hours, overcast sky and 30% transmittance of PV modules

8. CONCLUSIONS

From a first variation of the parameters at the office room application, it was found that changing the module properties (transparency and thermal insulation) in this configuration only has little effect on the thermal behaviour. Other parameters relating to the geometry and physical properties are more important, for instance the orientation of the building, the slope of the PV surface, the internal heat production, the percentage of clear glass in the façade and the infiltration rate of fresh air into the building. Therefore the best approach to design the semi-transparent PV-module is to firstly determine the right building mass, orientation and angle of surfaces and determine their optimum total amount of transparency.
The losses due to insulation values and gains due to passive use of solar energy determine what zone of the façade, or roof should be clear (based on needed view, aesthetics, economic aspects) or filled with semi-transparent PV. Secondly choose PV-modules which fulfil the requirements regarding size, insulation and transparency. For this (second) optimisation the contribution of daylight and the PV gains should be submitted as well. In this way the passive and active use of solar energy can be used to the maximum. A suitable existing PV module type can be chosen or possibly a custom made solution for the PV application can thus be manufactured.

For the office room application the electrical gains of the PV modules have been calculated. It was found that due to higher temperatures for PV modules with lower transparency the annual gain decreased with approximately one percent. This is much lower than the increase in PV gain per m^2 module surface area caused by the higher proportion of cells in this area. The calculated PV cell temperatures at an office application in Spain can reach maximum values between 35 and 45 °C, depending on the building and module properties.
For the façade application that has been modelled here, changing the amount of transparency of the PV module only has little effect on the energy balance. Increasing the insulation values helps to decrease the energy demand for heating as well as cooling. In chapter three it has already been concluded that the presence of a clear glass zone plays an important role here. For thermal optimisation only the total transparency of the façade should be about 15%. This is much lower than the chosen 25% transparency of the base case wall.

For the awning application it can be seen that increasing the transparency of the PV-awning from 0% to 50% e.g. creates a shift from the energy needed for heating to energy needed for cooling. The total amount does not change much, in fact it stays the same at the situation of a small window and even increases the total amount of energy at a larger window if a higher transparency is given. For these applications, from a thermal perspective, the transparency should be low. For other reasons (daylighting and aesthetics) a certain degree of transparency might well be more desired.

A software tool has been built with WINDOW4.1 and TRNSYS with which the heating and cooling demand of building equipped with semi-transparent PV modules can be successfully calculated. The case of an office room with semi-transparent PV modules as part of the facade is used for detailed analysis of the parameters influencing the energy demand. With the meteorological data of Madrid, a total annual heating and cooling demand per square metre floor area of 29 MJ and 297 MJ were found, respectively. The calculated annual PV gains for a 25% transparent module with 10% reference condition efficiency on a vertical, south-facing facade was 45 kWh/m^2. This is a reduction of 6% compared to the gains of the same module at a constant temperature of 25°C.

For a Mediterranean country like Spain a cooling strategy is dominant. If semi-transparent PV-modules are used in stead of glass they can contribute as a tool for the cooling strategy.

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