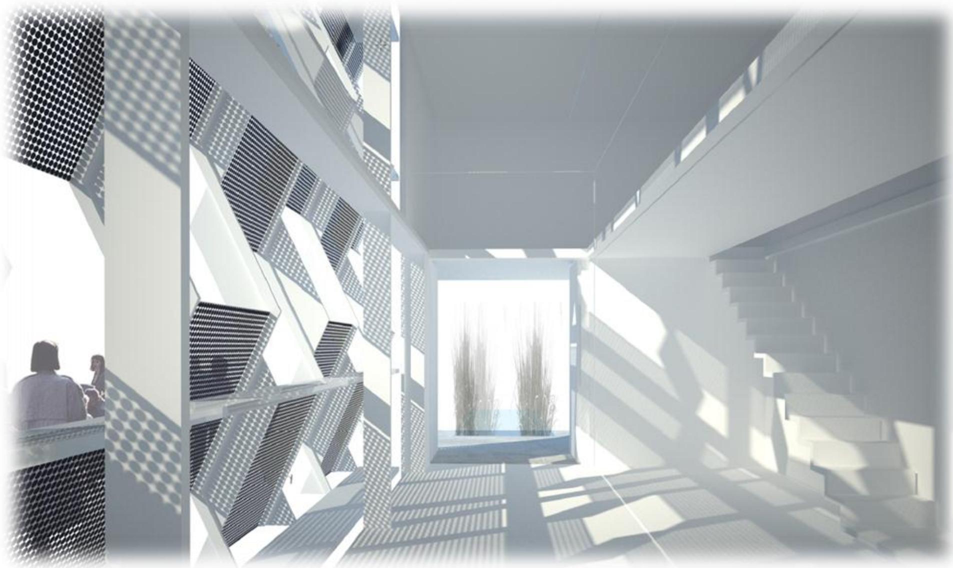
Application of thin-film technology in Denmark

"ThiFiTech"

Summary report



PSO ForskEl project 2008-01-0030

Danish Technological Institute
Energy and Climate Division

Application of thin-film technology in Denmark

“ThiFiTech”

Summary report

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Preface

The report concludes the work on the project ”Application of thin-film technology in Denmark” (ThiFiTech).

The objective of the project is to document and demonstrate the economic, functional and aesthetical potential of thin-film PV (TFPV) installations under typical Northern European conditions.

ThiFiTech is a merger of two project applications:

- Light & Energy – proof of concept
- Systematic introduction of thin film based solar cells in Denmark

The project is documented in the following publications:

- Summary Report
- Feasibility study
- Application and design of light filtering PV-modules (Small-scale demonstration)
- Solar cell pavilion (Small-scale demonstration)
- Medium and large scale demonstration
- Assessment of indoor light and visual comfort when applying solar cells in transparent facades
- Impact on indoor climate and energy demand when applying solar cells in transparent facades
- Performance of roof integrated and free-mounted thin-film photovoltaic modules under Danish climatic conditions
- Product Development

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

ThiFiTech has been realized through a funding of 6.5 MDKr provided by the 2008 PSO ForskEL program administrated by Energinet.dk. The project identification number is 2008-1-0030.

The project has been carried out in the period March 2008 to September 2012 by a team including:

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Energy and Climate Division

Summary

The objective of the project has been to document and demonstrate the economic, functional and aesthetical potential of thin-film PV (TFPV) installations under typical Northern European conditions.

The project was motivated by great expectations that TFPV's would soon have some key advantages over crystalline silicon (X-Si) as a large scale electricity generating technology as well as a building integrated electricity-generating element, the major advantages being lower levelised cost of electricity and greater flexibility and aesthetically attractiveness in regard to building integration.

In order to attain a complete evaluation of the potential of TF-PV in Denmark the project was built upon three cornerstones:

- **A feasibility study** giving a review of the international experience with TF-PV installations and based hereupon a review of the possible advantages of the TF-PV when applied under typical Danish conditions.
- **A series of measurements** designed to characterize available thin-film panels' key performance parameters in various relevant applications, covering both applications with main focus on the energy production and applications where the possible added values given by the PV panels to their surroundings are of equal importance.
- **A demonstration program** focused on gaining practical experience with relevant applications of the TF technology in Denmark, and furthermore to communicate the strengths of this technology to the possible user.

During the project period all of the PV technologies developed and the market changed considerably in favor of X-Si PV. The feasibility was updated regularly in order to keep up with the changes.

In recent years more and more buildings with glass facades have been built. The visual and thermal comfort in the rooms behind the glass is affected by the expanded window areas. Not least the sunlight hitting windows facing south might affect the comfort negatively due to glare and difference in light intensity and temperature in dependence of the position in the room. One way to cope with these problems is to integrate a light filter or sun shading in the pane – or outside the building - ideally in such a way that the negative effects are eliminated without introducing new disadvantages. The pane could become a multi-purpose building-integrated component, if the filter was coated with photovoltaic material thus adding an electricity producing function.

In the project new designs of light filter patterns to be integrated in panes were developed. A few of these were selected to be tested in the daylight laboratory at SBI with regard to visual and thermal comfort. The comfort was tested by letting small groups of test persons work a day in the rooms behind semi-transparent windows while light intensity and temperature in the rooms was measured simultaneously. Afterwards the test persons answered questionnaires. The test persons preferred a design with geometrical micro-structure perforations like the MicroShade pattern designed by the project partner PhotoSolar. A pattern with horizontal lines with the transparency of the pattern increasing towards the window in the middle was preferred over a squared pattern.

Solar radiation is known to may cause considerable discomfort to people in buildings. This discomfort may be divided in three groups: 1) due to elevation of the mean room temperature in the building, 2) due to temperature asymmetry – i.e. because one surface gets warmer than 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, 3) when people are directly hit by solar radiation. The results regarding the thermal comfort of the performed investigations show that solar cells integrated in transparent facades may solve problems with thermal discomfort in buildings. However, utilization of this solution should be examined carefully for each case as integrated PV cells change the visual comfort in the building and are often more expensive than other solutions.

A measurement program was carried out in order to perform a realistic side-by-side comparison of the most promising thin film technologies for on-grid PV power systems in the Danish climate. Some manufacturers of thin film modules claim that their specific technology delivers more energy than crystalline modules with same power due to better characteristics at elevated temperatures or low irradiance. All commercial available TFPV technologies were tested in a side-by-side installation with two modules of each type, one module with open backside and the other with insulated backside to simulate a building integrated module. During the measurement period of one year the modules were running at maximum-power-point. The start of the measurements was delayed much because it was necessary to develop an electronic load (done by the project partner, Danfoss Solar Inverters) and to multiply it with the number of modules. The very limited number of samples made it difficult to draw statistically valid conclusions regarding the performance of each PV module brand. Furthermore a test like this requires very precise measurements to allow the drawing of very firm conclusions. However, some conclusions can be drawn. The open mounted X-Si reference module performed at least as good as any of the TFPV modules, also at low irradiance levels where some TFPV manufacturers claim they have an advantage. The low temperature coefficients of a-Si and CdTe were confirmed, for the other technologies it was difficult to see a clear trend. There is generally a lower production from the integrated modules compared to the open mounted as expected, most pronounced for the X-Si reference module. During the project period the IV curve of each module was measured with regularly and significant degradation of performance was detected for some of the modules, and as expected especially for the a-Si. This is common in the first year of operation for this type.

A spectacular pavilion with TFPV integrated in a 3-D façade construction was designed and the plan was that it should have been built and exhibited at the COP 15 meeting in Copenhagen in 2009. However, despite of many efforts to find the necessary financing, the result was negative. The reason was probably that the global financial crisis had started a few months earlier.

One of the goals of the project was to encourage a number of hosts to install TFPV plants by providing a grant. This goal was achieved only to a limited extent. During the project period the price of X-Si dropped much more than of TFPV making the interest for TFPV very small. Only a few plants were installed.

The conclusion is that it is difficult to pinpoint areas in which TFPV will have obvious benefits over crystalline silicon PV in a Danish context, at least in the short and medium term. Some investors might find the appearance of TFPV more attractive than X-Si. The profitability of TFPV integrated into windows is rather questionable, but for some investors it can have a major symbolic value.

1 Introduction

1.1 Background

The physical principle of photovoltaic (PV) solar cells to convert light energy into electricity has been known for more than hundred years. The presently dominating technology, crystalline silicon (X-Si) PV, was developed more than 50 years ago and has basically not changed much since. Meanwhile several new technologies have emerged. A number of these have the common term thin-film (TF) because of similarities in their construction. Roughly speaking a handful of the TFPV technologies are commercially available. They fight to gain shares from X-Si in a commercial global market for grid-connected systems that has grown 50 to 100 % annually for several years now and has surpassed the wind power business in annual revenue.

X-Si has many advantages e.g.: a proven technology, long service life, robust, reliable, abundant feedstock materials, high efficiency and little or few environmental issues. However, X-Si has one major drawback: a high energy input resulting in a long energy pay-back time.

The TF-PV technologies of which the more important are amorphous silicon (A-Si), Copper-Indium-(Gallium)-Diselinide (CI(G)S) and Cadmium-Telluride (CdTe) have the advantages of a much lower energy input, a lower negative temperature and are considered to have more flexibility when it comes to the aesthetical integration in buildings (BIPV). Furthermore studies indicate that TFPV has a higher electrical yield at low light-conditions Some of the major disadvantages compared to X-Si are: less proven, less efficient, more uncertainty regarding lifetime and degradation, less flexibility regarding custom-designed solutions in building integrated installations.

1.2 Purpose

The following is a quote from the application:

"The objective of the project is to document and demonstrate the economic, functional and aesthetical potential of thin-film PV installations under typical Northern European conditions. The project will pave the way for a generation of TF-PV installations giving a potentially lower cost per unit power produced than typical installations of today which are predominantly based on X-Si. The project will envisage new ways of designing and using PV panels in multi-functional installations.

In order to attain a complete evaluation of the potential of TF-PV in Denmark the project is built upon three cornerstones:

- **A feasibility study** giving a review of the international experience with TF-PV installations and based hereupon a review of the possible advantages of the TF-PV when applied under typical Danish conditions.
- **A series of measurements** designed to characterize available thin-film panels' key performance parameters in various relevant applications, covering both applications with main focus on the energy production and applications where the possible added values given by the PV panels to their surroundings are of equal importance.
- **A demonstration program** focused on gaining practical experience with relevant applications of the TF technology in Denmark, and furthermore to communicate the strengths of this technology to the possible user.

The evaluation will be performed for TF-PV in general and for TF-PV capable of serving more functions in the building than solely energy production. Particular focus will be put on panels capable of filtering daylight.

1.3 Work packages and organization

The group of project partners represents an essential part of the Danish PV knowledge base. Figure 1.1 shows a diagram of the organization of the work in work packages and the partners involved in each of the packages.

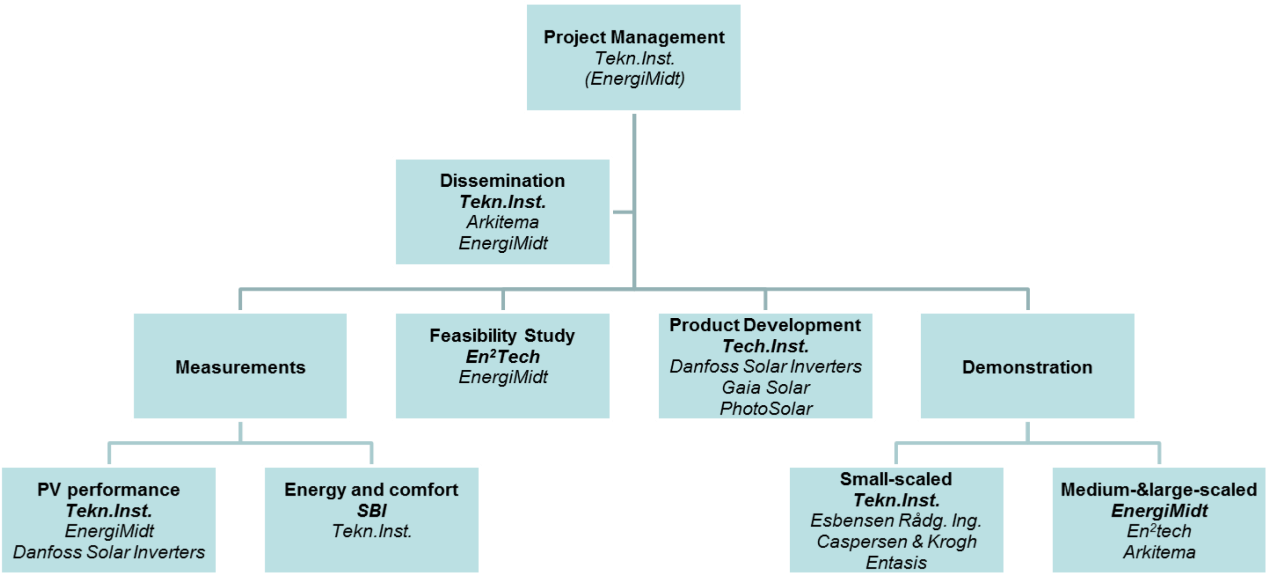


Figure 1.1 Diagram showing the organization of the work in work packages and the partners involved in each of the packages

1.4 Process

The process of the project work is described in brief in order to give a better understanding of the structure of the reporting and of the outcome of the project, which to some extent is different than anticipated. A number of preconditions for the project changed significantly during the project period which necessitated an extension of the period with more than a year.

1.4.1 ThiFiTech, a merger of two projects

ThiFiTech is based on two project applications submitted to Energinet.dk:

1. Light & Energy – proof of concept
2. Systematic introduction of thin film based solar cells in Denmark

The purpose of the first TFPV project was to substantiate the architectural potential of light-filtering semi-transparent TF-PV panels in transparent facades including investigation of indoor comfort aspects.

The purpose of the second project was to investigate the energy performance of TFPV under northern latitudes and to initiate the establishment of a number of demonstration TFPV installations.

The two projects were merged into one entitled ”Application of thin-film technology in Denmark” (ThiFiTech), involving 12 partners.

Due to the merging of two projects with different approaches to thin-film solar cells, much of the work has been carried out in subtasks with little interdependence or exchange of data. It was therefore decided to make a summary report and a number of annex reports each documenting a well-defined part of the work carried out.

1.4.2 Competitiveness of TFPV contra X-Si

Up to the start of the project there had been no significant price reductions of X-Si for some time and the general opinion was that the potential for substantial price reduction was small. At the same time the general expectation for TF-PV was that substantial price reductions waited just around the corner.

Indeed the prices of TFPV have come down since. However, the prices of X-Si have dropped relatively much more. Contrary to the expectation the X-Si has gained market shares in the BIPV-market as the customers generally prefer a proven and reliable technology instead of a new TFPV technology which in best case *might* be cheaper. This trend has been amplified by the financial crisis. As a consequence for the project it has been very difficult to identify hosts for demonstration of TF-PV installations, which was an activity under the Demonstration part of the project.

This is described well in the "Feasibility Study" report and it is also elaborated on in the reports of the demonstration part of the project.

1.4.3 Performance measurements of PV-panels

From the outset it was the intention to purchase panels of all common commercial TF-PV technologies and to equip them with individual electronic loads.

First challenge was to buy a panel of the cheapest TFPV panel type of all, CdTe. This type is very controversial due to the content of cadmium. Despite the fact that this panel type was the most sold of all TFPV technologies globally it was impossible to buy any for test purposes. They were only sold for mega-Watt installations under strict control by the manufacturer. Halfway through the measurement program the project succeeded in getting the first CdTe modules to Denmark, and two panels were immediately included in the measurement program.

Second challenge was to provide electronic loads, one for each panel under test (a total of 12 pieces). They were commercially available but at prohibitive prices for the project. It was then decided that the project partner Danfoss Solar Inverters to develop an electronic load for the project with features making it suitable also for other PV panel investigations. The mission succeeded, however the time consumption was not incorporated in the time schedule from the outset. In order to have a measurement period of at least one calendar year it was necessary to apply for an extension of the project period.

1.4.4 Organization and staff

During the project period several of the key persons left their jobs, among those the project manager. One partner, Aarhus School of Architecture, withdrew from the project. This caused some discontinuity in the working progress and contributed to the need for an extension of the project period.

2 Feasibility study

As part of the ThiFiTech project, a separate activity was launched with the purpose of preparing a Feasibility Study in which the current technical, architectural and market aspects regarding the thin film PV (TFPV) technologies were described.

The original study from 2009 was prepared as a general introduction to the subject with the purpose of collection and transmitting international experience and development trends with respect to the prevailing TFPV technologies.

2.1 Production volume and previous expectations

When ThiFiTech was launched, TFPV had for several years gained marked shares over crystalline PV and at the same expanded production capacity on all the major TFPV technologies.

The general opinion at the time was that this tendency would steadily continue, since the production cost for TFPV modules potentially is very low and thus counterbalance that the efficiency is also lower compared to crystalline PV types.

The reality, however, turned out to be different, since the cost for traditional PV products soon took a very steep decrease, when large production capacities were established mainly in China while at the same time some incentive programmes in some of the most important countries were terminated or reduced.

On account of this, TFPV in many respects lost their potential competitive benefit and thus from 2010 on have not been able to maintain the marked share gained, which is shown in Table 2.1.

2.2 Technological developments

In the ThiFiTech project period some progress with respect to e.g. efficiency and usability were gained.

In Table 2.2, the actual stage regarding efficiency for TFPV as well as crystalline modules is shown. Due to the lower efficiency for TFPV, more areas are needed to obtain a certain installed capacity. Thus in cases where area is a limiting factor, crystalline PV has a benefit over TFPV. Besides the area related costs (e.g. cables, cable trays, man hours) for TFPV are higher.

Another technical point, which has developed over the course of ThiFiTech, is that now several TFPV module manufactures allows their products to be used together with the more effective transformer-less inverter types.

Development in PV-cell production by technology												
Technology	**2006**		**2007**		**2008**		**2009**		**2010**		**2011**	
	MWp	**%**	**MWp**	**%**	**MWp**	**%**	**MWp**	**%**	**MWp**	**%**	**MWp**	**%**
- Mono-Si	1.098	43,3	1.806	42	3.030	38,3	4.711	37,8	9.091	33,2	11.490	30,9
- Poly-Si	1.179	47	1.934	45	3.774	47,7	5.384	43,2	14.485	52,9	21.196	57,0
- Ribbon c-Si	66	2,6	94	2,2	119	1,5	174	1,4	329	1,2	0	0,0
Crystalline	**2.343**	**92**	**3.834**	**90**	**6.922**	**87,5**	**10.270**	**82,4**	**23.904**	**87,3**	**32.686**	**87,9**
- a-Si and a-Si/µc-Si	119	4,7	223	5,2	403	5,1	760	6,1	1.369	5,0	1.264	3,4
- CIS/CIGS	5	0,2	21	0,5	79	1,0	212	1,7	438	1,6	892	2,4
- CdTe	68	2,7	201	4,7	506	6,4	1.122	9,0	1.451	5,3	2.045	5,5
Thin-film	**193**	**7,6**	**445**	**10**	**989**	**12,5**	**2.094**	**16,8**	**3.258**	**11,9**	**4.202**	**11,3**
Other	**0**	**0**	**4**	**0,1**	**0**	**0**	**112**	**0,9**	**219**	**0,8**	**297**	**0,8**
All	**2.536**	**100**	**4.279**	**100**	**7.911**	**100**	**12.464**	**100**	**27.382**	**100**	**37.185**	**100**

Table 2.1 Development in PV cell production by technology

Module efficiency and area needed for thin film and crystalline base PV modules						
Technology	Thin film photovoltaic				Crystalline based	
	Amorphous silicon a-Si	a-Si/µc-Si	CIS - CIGS	Cadmium telluride CdTe	Mono crystalline	Poly crystalline
Module efficiency, %	5 – 8	9 - 10	11-13	8 – 11	14 - 20	12 – 15
Area needed pr. kWp, m²	15	11	8	10	5	6

Table 2.2 Module efficiency and area needed for thin film and crystalline base PV modules

It is, however, very important to observe the requirement from the manufacturer in this respect, since there is a risk that for some modules corrosion of the modules Transparent Conductive Oxides (TCO) layer can occur if there is no galvanic separation between the modules (DC) and the electrical grid (AC), which is the case when transformer-less inverters are used.

In case the guidance from the module manufacturer is not fully observed and complied with, the guarantee will almost evidently be voided, which will leave the owner or the supplier/installer with a serious problem.

2.3 Market aspects and future prospective

Although some benefits regarding architectural conditions are present, TFPV has not yet captured noteworthy marked shares in Denmark and it is difficult to imagine that the outlook for TFPV will improve significantly unless some radical change in market conditions will occur.

The main reason for this is attributable to economic conditions: At the present situation with steadily decreasing cost for traditional PV modules based on crystalline cells, TFPV has a hard time being competitive from a holistic point of view.

Although the crude module price per Wp is often lower, the total cost including BoS will for the Danish situation very often be higher, due to the need for more cables, mounting equipment and manual labour for mounting.

It is thus difficult to pinpoint areas in which TFPV will have obvious benefits over crystalline PV in a Danish context; the most likely areas, however, could be large-scale PV power plants on marginal soils and for multiple-purpose and/or special building integrating solutions, in which the uniform surface and especially the possibility to prepare the transparency of the module can be utilized. However, due to the integrated manufacturing method in one process step of TFPV modules with standard dimensions, custom designed solutions are usually very expensive.

The pictures inserted below give two examples of TFPV utilized for multiple purposes, namely as visually covering of ventilation plants on a rooftop respectively a solar shading device at a new office building.

Figure 2.1 CdTe TFPV modules utilized to covered technical installation at the rooftop of Skive City Hall.

Figure 2.2 a-Si TFPV module used as solar shading device in a moving solar shutter. The picture is taken as the device is closing, whereby the transparency of the device is shown and can be compared with the view without the shutter (EnergiMidt, Silkeborg).

3 Demonstration, Small-scale

This part of the ThiFiTech project is the continuation of the an earlier project entitled “Ligth & Energy – solar cells in transparent facades” (PSO-ForskEL j.nr. 6302) dealing with architectural integration of solar cells in transparent facades and comfort issues related to this integration (Wedel et al, 2008) and (Aarhus School of Architecture et al, 2008).

The present chapter summarizes the findings from the work in ThiFiTech regarding **architectural** issues while issues regarding visual comfort and thermal comfort are dealt with in chapter 4. The focus is on possibilities for design and application of light filtering PV-modules in buildings.

3.1 Objective of small-scale demonstration

In the recent years new types of solar cells have been developed to be integrated as a part of the building envelope. In this context the aim of the work in this part of ThiFiTech has been to give ideas for application of light filtering thin film solar cells through the development and assessment of new designs. A selection of these designs has been tested in the daylight laboratory at Danish Building Research Institute (SBi), see chapter 4.

3.2 Light filtering PV-modules applied in buildings

Solar radiation through a window influences the thermal comfort, the visual comfort through the perception of the view to the outdoor scene and glare, and finally the energy consumption in the building.

The use of light filtering TFPV integrated in windows has many implications. The technology will enable the façade to function both as a combined temperature reducing, energy producing, solar shading and light transmitting element thus affecting the above mentioned parameters. Furthermore it affects the appearance of the building.

The transmission of solar radiation will influence the thermal comfort of a building due to the added solar gain at times where windows in other parts of the building also transmit solar radiation to the rooms. The function as solar shading will reduce the amount of heat gained from solar radiation.

The function of light filtering used as sun protection will also make it possible to vary the light into the room and affect the glare and the view from the room to the outside environment.

In several recent types of building constructions large window areas are used which leads to a significant solar gain to the connected rooms. In order to reduce these gains and to reduce the glare solar shading is needed. For this case light filtering PV-modules can be used to also provide an aesthetic design with a solar and light dampening function.

The light filtering solar cells can have different appearances. Some types have the solar cell material on glazing with different geometries as e.g. patterns where only a part of the glazing is translucent while the other parts are opaque solar cell material. Other types are constructed as a metal mesh with penetrations which transmit light and solar radiation while the solar cell material is placed on the metal mesh. The type of light filtering TFPV can be chosen so as to provide a building with a certain aesthetic appearance.

In this part of the project a number of options for utilizing this technology is described and investigated. The report is organized with first a collection of previous experience, next a development of novel ideas, a discussion of the viability of the ideas and finally a selection of the most promising techniques for further investigations.

The collection of experience is based on different sources, one of the more important ones being the previous project on which ThiFiTech was partly based: "Lys + Energi + Arkitektur" (Light +Energy + Architecture) (Hansen, E. K., et al. 2008). This project provided a survey and collection of light filtering solar cells. The technology was also evaluated in an architectural context.

Some elements from this report showed that it was expected that the market share of TF technology would expand from 10 % in 2008 to 20 % in 2020 and up to 30 % in the future. The TFPV technology will in most configurations block for solar transmission. But some producers have small translucent stripes or areas between the spots or fields of opaque PV-material. (See figure 3.1). Due to the small size of these transparent stripes or areas the visual appearance will at a distance be translucent. The characteristics of some typical light filtering panels was described and evaluated. The opening area of PV-modules investigated was between 4 % and 49 %. The solar heat transmittance was between 0.09 and 0.3. The relative cost per produced kWh varied about a factor 3 between the most and the least expensive modules.

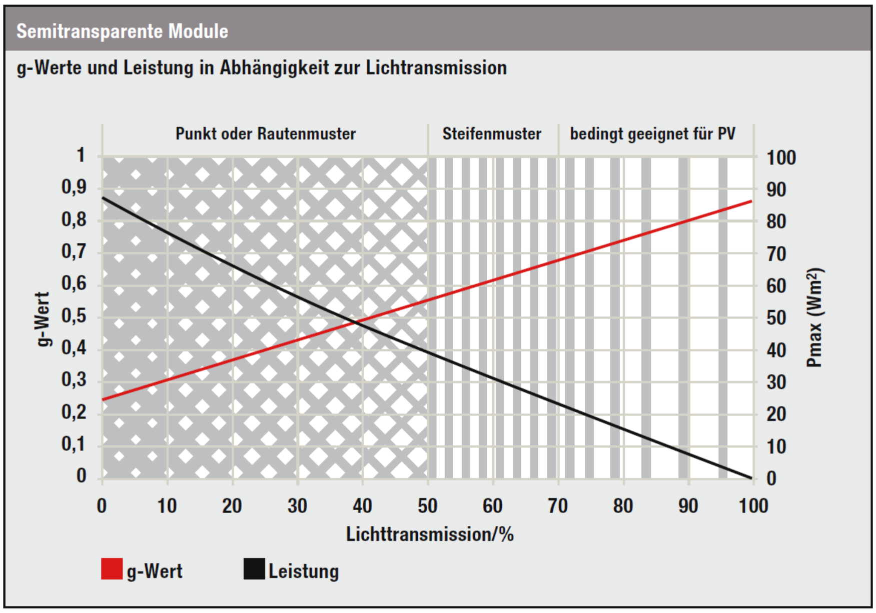


Figure 3.1. Examples of different opening areas. (Würth Solar, 2008)

A workshop was arranged in the beginning of the ThiFiTech project period in order to collect and exchange the experience from the persons involved. Presentation was done regarding the different PV-types, the experience on light and PV-modules, indoor climate and examples of different buildings which already have installed this type of PV-modules.The experience collected gave an inspiration for development of new types and new applications of thin film light filtering PV-modules. Some of the detailed experience from the workshop was:

- Solar shading in general can lead to conflicts in large office rooms due to the different needs and wishes and varying light and heat effects.
- The solar heat transmission (g-value) can normally be calculated in direct dependence of the opening area for light transmission of the PV-modules.

The light filter in the window will lead to an increase of the glazing temperature. The consequence hereof was discussed. The durability of the PV property will probably be reduced and the performance in relation to the production of electricity will also be reduced compared to the nominal power at Standard Test Conditions (STC) due to the negative temperature coefficient of the solar cells. The last influence is dependent on the type of PV-modules since some types of solar cells have less temperature sensitivity.

The design of the different PV-modules was discussed. It will in principle be possible to provide the PV-modules with an individual design but it will increase the costs. It will be less expensive to have PV-modules of a 'standard' size and give them a placement corresponding to a patchwork with a number of modules of the same size.

The output of the work in the group has been the basis for different designs and the selection of the PV-modules to be tested. (See chapter 4).

3.3 Work in project groups

The two architect groups involved in the Small Scale Demonstration part of the project presented two proposals for application of light filtering solar cells. These are described in the following chapters 3.3.1 and 3.3.2.

3.3.1 Utilization TFPV in a shopping center

A proposal for a design with light filtering PV-modules to be installed at a shopping center in Randers was presented by Peter Krogh, Caspersen & Krogh. In the proposal the light transmission was at a maximum at the upper part of the façade and gradually reduced at the lower parts of the façade. See figure 3.2.

Some major points of the possibilities for utilization of semitransparent light filtering PV-modules in this proposal is described, commented and discussed by Peter Krogh below.

The arguments for such a design might be architectural, as in the case of the round shaped building in Haraldsparken, which is a planned business and office building complex located in the southern part of Randers. The building has two wings along two roads and on the corner between these two roads, which will have a pronounced exposure of the road users from both South and Vest.

The corner on the ground and first floor of the building is proposed to be rented to a jeweler with exclusive articles. The sales area, which encompasses half of a circle in the ground floor, is a room with double height, which can be entered through a security gate. As a part of the security measures is the area of the windows at the ground floor limited to the minimum. This is the explanation why the window area, separated in bands each 110 cm in height, has an increasingly larger and larger extent, and on the top, just below the roof, the windows covers a full circle of the building. It is an architectural wish, that the apertures for entering the light shall be distributed in this way so there are natural light sources immediately below the roof in an angle of 180° in the directions from Southeast to Northwest.

This provides, due to the gradual reduction of the window area where the main part is facing in the direction from South to Vest, a risk for over temperatures, which have to be reduced by a cooling system which leads to increased energy consumption.

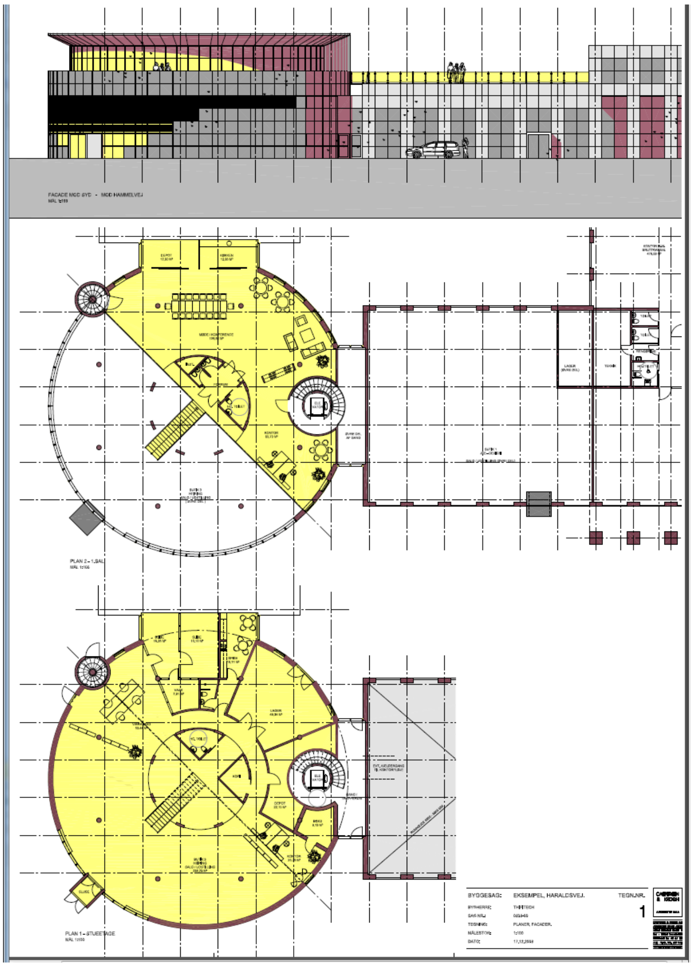


Figure 3.2. Proposal for a shopping centre. Caspersen & Krogh.

It has to be remarked, that the expression of the building facade is intended to be very tight. Closed plane steel panels and window areas with structural glazing, placed with the front of the glazing in plane with the plate covering, all included in a tight module of 110 cm both horizontal and vertical. External solar shading with blinds, venetian blinds, and awnings will in this context be absolutely undesirable.

Due to this a dampening of the light and the solar gain with transparent PV-modules in the double glazed window units will be an obvious possibility. In this measurement project as well as in the proposed large scale project it could be a desire that the percentage of transparency can be graduated from a large to a small opening area.

In the circular shaped building an option could be to have two window bands with panes without PV-modules where there is a need for undisturbed view into the building and where there are the largest problems with overshadowing of the building. In the 3th, 4th and 5th window band it is assumed that the window panes have PV-Modules with a reduced transparency for each window band. This seems to be feasible technically but maybe not economically.

In the proposals for a façade element to be used in the daylight laboratory this graduation of the transparency from high to low is made in the single pane. Generally it is an exciting perspective by TFPV-based modules that the intensity of the day light can be graduated.

The proposal involves a challenge to introduce solar cells in curved glazing and to control the output of the solar cells with different orientations. There will be an advantage in using solar cells placed at curved glazing since the output will be distributed more evenly during the day than if the solar cells are placed on a single plane surface which will have a larger peak once a day.

3.3.2 Application of TFPV in a high rise building

A proposal for a design with light filtering PV-modules to be installed was presented by Vagn Borlund, Entasis.

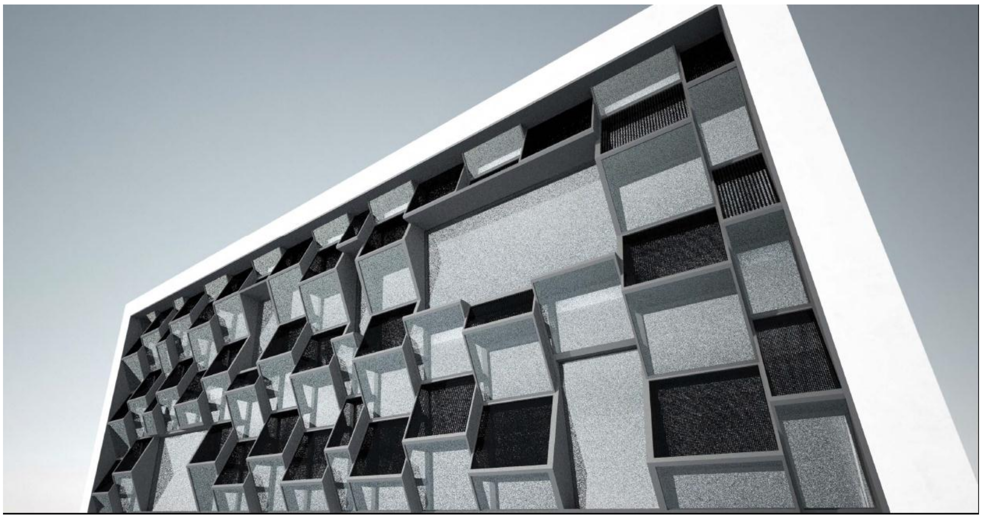


Figure 3.3. Proposal for a structure with PV-modules, exterior view. Illustration from a presentation 14.04.2009 by Vagn Borlund - Entasis Architects.

It is proposed to apply PV-modules on a new development where a number of existing industrial buildings are planned to be transformed to a number of different purposes e.g. hotels or offices.

The design proposal uses large adjoining glazed facades which will be suitable for integration of PV-modules. A possibility is to use PV-modules on roof coverings and light filtering PV-modules on the facades of the planned towers. In the areas where the high rise buildings have an expression of being heavy (and dark), it is proposed to install the glazing elements at a certain limited area of the exposed façade facing south.

The glazing elements are formed as a three-dimensional structure, partly as a contrast to the heavy solid but simple facade expression which dominates the tower house, partly for optimization of the energy producing surface and partly for creating a living and dynamic expression.

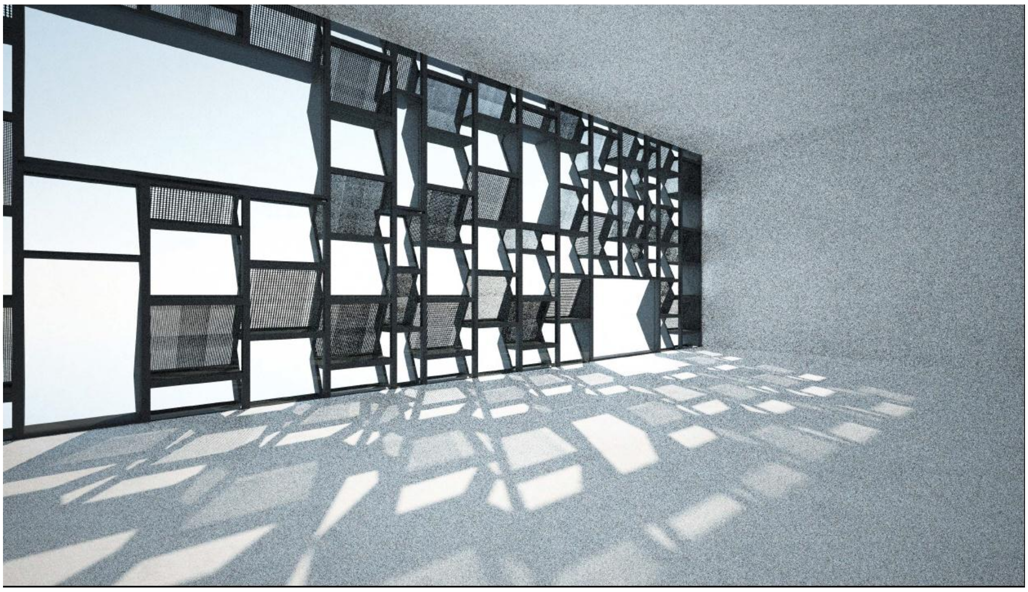


Figure 3.4. Proposal for a structure with PV-modules, interior view. Illustration from a presentation 14.04.2009 by Vagn Borlund - Entasis Architects.

The glazing will form a shape corresponding to a crystal composed of aluminum frames with single layer panes at the outer side and an insulating glazing unit at the inner side. In the intermediate space shading in the form of a blind is placed. The TFPV-modules are placed in the upper angled part of the glazing element, thus having an angle to the sun with an inclination of 66° to horizontal which optimizes the utilization of solar radiation and provides solar shading for the activities in the adjoining rooms.

The other parts of the project will provide information about the performance with respect to both visual and thermal comfort as well as the pleasure with working or living behind such a vivid façade expression. The areas to be investigated in the comfort study should have key words as outlook, experience, inspiration, distraction, overheating, concern and fascination.

The comfort study should also be accompanied by measurements of the energy related performance, since this part is an un-separable part of the proposed principle and should therefore be compared with the resulting economy involved in such a project.

Considerations should also be done concerning reducing the overshadowing of the PV-modules due to the complex shape of the structure.

The design was originally developed for the purpose of testing to investigate the performance regarding visual and thermal comfort and the energy balance on a mock-up. However the structure was complicated which made it expensive and difficult to integrate and test it in the daylight laboratory. Instead the design was modified in order to be built into a pavilion to be used as a show room for an exhibition with different renewable energy solutions on the occasion of the

COP15-meeting held in Copenhagen 2009. This design is shown in a separate document, "Solar cell pavilion (Small-scale demonstration)" to be downloaded, see Preface for link. Work was proceeded on making plans and budgets for such a facility, but it turned out to be impossible to get the necessary external co-funding from sponsors probably due to the newly emerged financial crisis.

3.4 Selection of elements for test in the day light laboratory

The suitability of a number of test patterns was discussed at a workshop. (See figure 3.5). The single patterns were printed on transparent film and mounted at window panes. Three sets of patterns were proposed for further tests, see chapter 4

A sketch of an element to be installed in the day light laboratory was presented. The transmittance can be varied at the different parts of the façade. A problem might be the use of black colored frames (due to the visual glare effect). It should be possible to have undisturbed view to the exterior in an appropriate height over the floor.

Figure 3.5 Discussion concerning the different sets of patterns.

3.5 Conclusion

The project demonstrated that there exist a number of possibilities for application of light filtering solar cells.

Some buildings have already designs and features today which can be exploited by integration of solar cells on the surfaces e.g. patterns printed on windows or transparent solar shading. The performance of solar cells can be increased, if the light filtering surfaces have a slope. The slope can be varied at certain sections of the facades.

If the light filtering is obtained by patterns of solar cells on windows the size of the patterns should not be too large due to potential glare problems from bright and dark areas placed close to each other. It is expected that a gradual change of translucency due to varying density (per area) of patterns will be more acceptable than abrupt changes in density. It will also be convenient to have an undisturbed visual outlook in the parts of the windows which gives a view to the surroundings of the building. The patterns can be used as a tool for controlling the light and solar transmission for glazed areas where there might be overheating or other discomfort due to glare.

Some of these aspects are investigated in the measurement program “Light and Comfort” described in chapter 4.

4 Measurement program: "Light & Comfort"

This part of the ThiFiTech project is, like the work package "Demonstration, small-scale" described in chapter 3, a continuation of the an earlier project entitled "Ligth & Energy – solar cells in transparent facades" (PSO-ForskEL j.nr. 6302) dealing with architectural integration of solar cells in transparent facades and comfort issues related to this integration (Wedel et al, 2008) and (Aarhus School of Architecture et al, 2008).

The present chapter summarizes the findings from the work in ThiFiTech regarding **visual comfort** and **thermal comfort** while architectural issues are dealt with in chapter 3.

4.1 Visual comfort

The aim of the study of the visual comfort was to demonstrate how the integrating transparent TFPV in glazed facades in building with large glass areas influences the users' perception of the daylight in the room and the view to the outside

4.1.1 The tests

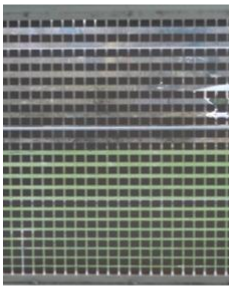
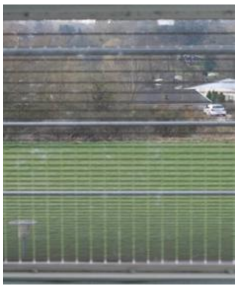
Panels with various patterns were constructed representing façade-integrated thin-film, both for collecting solar energy, to filter the daylight and reduce solar loads in the room. Four different dummy thin-film panels were selected for test, two of which designed in the "Demonstration, small-scale" work package. The selected panels (Table 1) were evaluated at the daylight laboratory facility at the Danish Building Research institute in two different tests and periods, i.e. in each test there were two different panel patterns at the time in two equally arranged test rooms (Figure 4.1).

After working half a day in a test room office having a large glass area where the upper and lower part was covered with an integrated transparent dummy thin-film panel, the test persons evaluated the daylight in the room and the view to the outside by answering questionnaires. Each of the four panel patterns were evaluated by 19 test persons. Besides, the illumination levels in the test rooms were measured at various strategically places and analysed.

During test 1 the Pattern 4 and 6 were tested against each other as they resemble a similar structure, with the transparency of the pattern increasing towards the window in the middle. The difference between the two patterns is the geometry of the cells and the transparency. Pattern 4 was having opaque cells as lines with a cell dimension of 5.15 mm x 39.10 mm and a transparency of 72 %, whereas Pattern 6 had quadratic cells with a cell dimension of 27.64 mm x 27.55 mm and a transparency of 38 %.

During test 2 the Pattern 3 and MicroShade pattern were tested. Pattern 3 was very similar to pattern 4 with the transparency of the pattern increasing towards the window in the middle and having opaque cells as lines with a cell dimension of 4.96 mm x 39.10 mm and a transparency of 74 %. MicroShade is a special type of solar shading constructed of transparent strips of stainless steel bands with micro-structure perforations being angled so that they shield to direct sunlight, while the clear view is maintained (Figure 4.2). MicroShade is specified having a shading coefficient by normal radiation of approx. 0.63, and on a summer day approx. 0.25.

Table 4.1. The different test panels being evaluated by tests persons in the daylight laboratory in Hørsholm, Denmark

Test period	Room A	Room B	Comments
Spring 2010 26.4 – 10.5 Test 1	PV pattern 6  ✓ *Quadratic cell* ✓ *Transparency of 38 %*	Pattern 4  ✓ *Opaque cells as lines* ✓ *Transparency of 72 %*	Pattern 4 and 6 were tested against each other as they resemble a similar structure, with the transparency of the pattern increasing towards the window in the middle. The difference between the two patterns is the geometry of the cells and the transparency. The difference in cell geometry influences the transparency of the two patterns.
Spring 2012 12.3 - 23.3 Test 2	PV pattern 3  ✓ *Opaque cells as lines* ✓ *Transparency of 74 %*	MicroShade (MS)  ✓ *Q Steel bands with micro-structure* ✓ *Transparency of ?*	The MS has a very open and see through structure. Therefore it was chosen to test the MS against pattern 3 as pattern 3 resembles the most transparent pattern

		%	

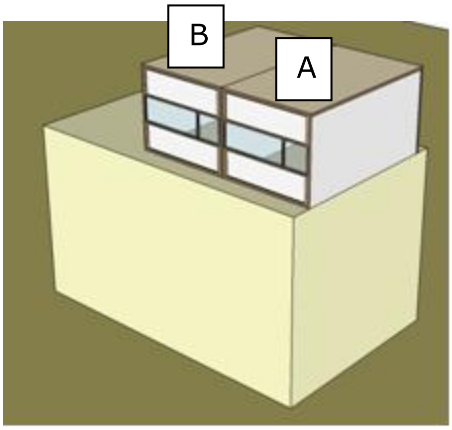


Figure 4.1:

Model of the test facility at SBi with the two identical test rooms facing South. The rooms are named A and B as indicated. The upper and lower part of the glass area in the front façade was partly shielded with selected test panels during tests. The two rooms are characterized by identical photometrical properties (R_{wall} = 0.62, $R_{ceiling}$ = 0.88, R_{floor} = 0.11) and geometrical features (3.5 m wide, 6.0 m deep, 3.0 m high).

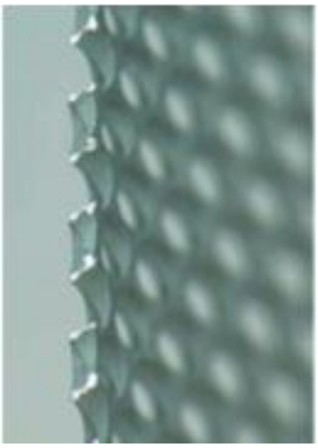


Figure 4.2:

Microscopy- photography of the structure of MicroShade micro-fins.

4.1.2 Results

During test 1 the test persons preferred the striped pattern 4 opposed to the square pattern 6. MicroShade was evaluated more positive compared to the striped pattern 3 (being very similar to the striped pattern 4 used in the first experiment). The lowest overall average illumination was found in the room with MicroShade. The variation in the light intensity in the room with MicroShade was less than what was found in the room with Pattern 3, in which higher illumination levels were measured. The measured light intensities were corresponding well to the transparency of the panels and test persons perception of the illumination levels. Since higher illumination levels was preferred during test 1 and the lowest illumination levels preferred during test 2, there was no link between the test persons' evaluations being positive and a high illumination level of the room.

However, much higher light intensities were measured during the 2nd test vs. what was measured during the 1st test.

Both the view through the pattern and the appearance of objects outside was evaluated negatively for the room with the square pattern 6 unlike the striped pattern 4.

4.1.3 Conclusion

We found that if structures of the transparent PV panels cannot be very small as for the MicroShade panels, then patterns, where the horizontal line and an undisturbed view to the outside is somehow maintained, seems to be preferred. We conclude that the horizontal striped patterns tested in these tests were preferred over squared patterns. Moreover, MicroShade seems to influence the light environment positively compared to the three other test panels. The view through the MicroShade panels is maintained except from the color perception of objects outside which was evaluated as being changed unlike the other test panel results. In the room with MicroShade the light intensity fluctuations and light intensity differences seemed to be reduced caused by the geometrical micro-structure perforations in the MicroShade panels.

4.2 Thermal comfort

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. The aim was to investigate if solar cells integrated in the transparent facades of buildings may solve the above problems.

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 characterizing the impact of solar cells in windows on comfort has been investigated in ThiFiTech:

- 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.

The investigations and the results of these investigations are fully described in (Jensen, 2012. Link for download, see Preface). The following is only a brief summary of this report.

4.2.1 Discomfort due to hot windows

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 un-comfortable to sit next to a surface which is considerable warmer than the air temperature.

Based on the detailed measurements of the thermal and optical properties of a standard Danish two pane LowE windows with and without integrated solar cells (center U-value: 1.2 W/m^2K) it is possible to simulate the temperature conditions of the two glasses during a Danish standard year. The simulations revealed that although the external glass with the pv cells gets very hot the internal glass get slightly less warmer than in a standard LowE window. The reason for this 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. And further due to the Argon filled air space and the LowE coating only little heat is transferred from the external glass with pv cells to the internal glass.

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 influenced 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.

4.2.2 Discomfort due to directly being hit by solar radiation

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 results from investigations in cars have in ThiFiTech been compared to investigations carried out in two well-defined and highly monitored test rooms. The monitoring system of the test rooms were extended with two globe temperature sensors in each room as seen in figure 4.3. One at the window being hit by solar radiation and one in the shade in the back of the rooms.

Based on the measurements it was possible to calculate the change in PMV (Predicted Mean Vote) dependent on the solar radiation for a person being in comfort if not being hit by solar radiation. This result was further compared with the result from the investigations in a car. The combined result of these two investigations is shown in figure 4.4.

Figure 4.3 Globe temperature sensors in one of the test rooms.

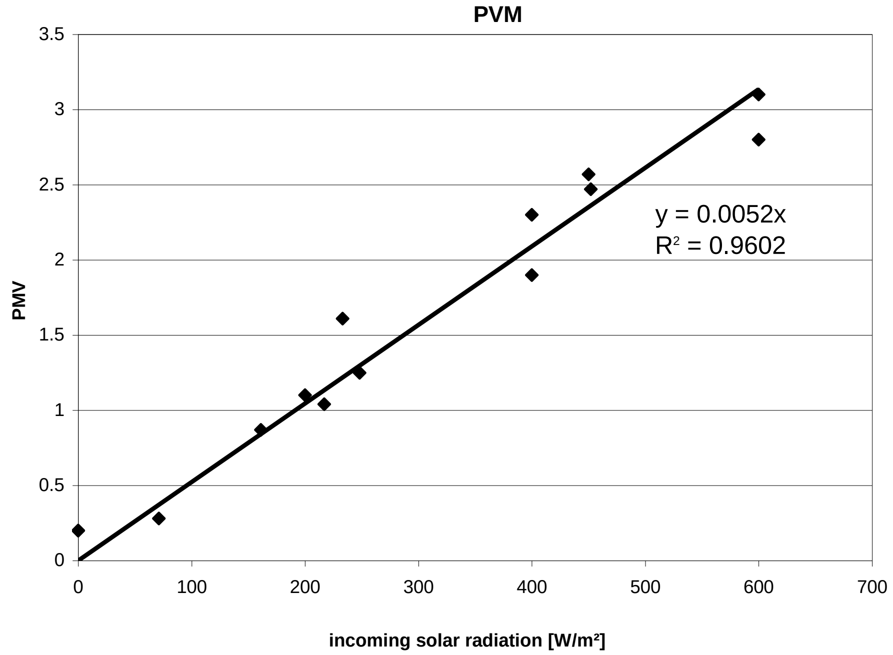


Figure 4.4 The result of the two investigations and a linear regression based on the values.

The discomfort of being directly hit by solar radiation may be described by the following equation:

$$PMV = I/200 \qquad [4.1]$$

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

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

Equation 4.1 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 LowE coating. However if the PV cells are small and/or the distance between the solar cells are small the solar radiation hitting the person may be considered as evenly distributed.

The PMV may be transformed to PPD (Predicted Percentage of Dissatisfied) by using the equation:

$$PPD = 100 - 95 \cdot \exp(-(0.03353 \cdot PMV^4 + 0.2179 \cdot PMV^2)) \qquad [4.2]$$

A radiation level of e.g. 200 W/m² which often occurs behind a traditional LowE window will lead to a PMV of 1. Which according to equation [4.2] means that 20% of a population will be dissatisfied.

4.2.3 Method for evaluation of the impact on indoor climate and energy demand when applying 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 the simulation program BSim. The office building is a two floor building with both south and north facing offices as seen in figure 4.5. The gross floor area of the building is 345.5 m².

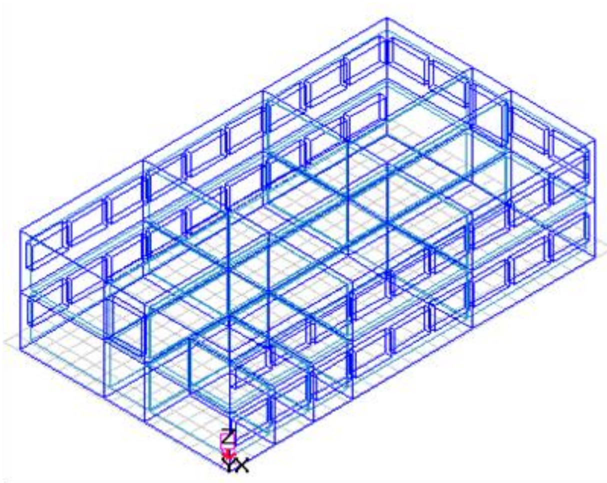


Figure 4.5 The office building considered in the simulations.

Based on simulations with different opening degrees of pv windows (opening degree = the percentage of the window which is not covered by pv cells) a method for determination of the optimal opening degree was developed. The different opening degrees were further compared with a standard LowE window with and without solar control film/movable solar shading + PowerShades. PowerShades are MicroShades coated with thin film solar cells. MicroShades are thin metal sheets with intelligent holes with the same function as venetian blinds, however, not visible to the eye if not standing very close to the window.

Figures 4.6-7 show an example of the method. Figure 4.6 shows the net energy demand for heating, cooling and electricity demand for lighting + the sum of these three values. The conclusion from this graph is:

- increasing heating demand and electricity for artificial light with decreasing opening degree
- decreasing cooling demand with decreasing opening degree

However figure 4.6 is not the whole story as the values do not include the efficiencies of the heating and cooling system, the primary factor for the different energy carriers (here district heating and electricity) and the electricity production from the pv cells in the windows. The influence of this is shown in figure 4.7. While figure 4.6 shows an optimal opening degree (minimum energy demand) around 40% figure 4.7 shows an optimal opening degree of around 30%.

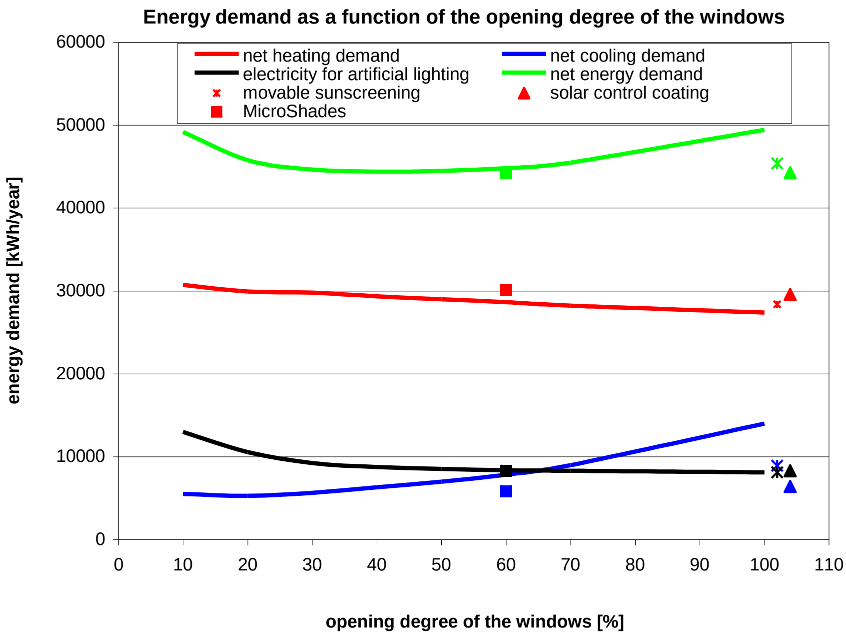


Figure 4.6 The net energy demands dependent on the opening degree.

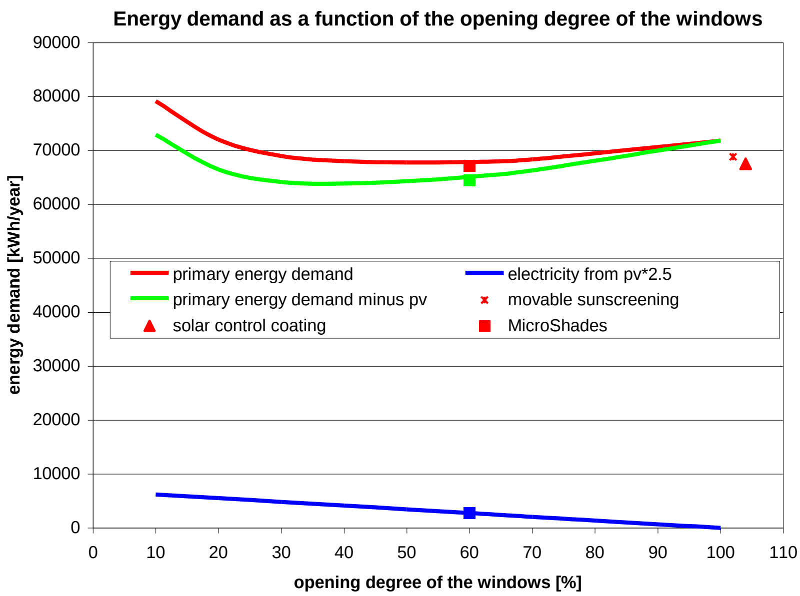


Figure 4.7 The primary energy demand of the building with and without electricity production from the solar cells.

Several parametric studies have been performed with the model leading to the following conclusions:

Based on the parametric study 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.

Some general conclusions from the investigation are:

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

4.2.4 Conclusion

The results of the performed investigations show that solar cells integrated in transparent facades may solve problems with thermal discomfort in buildings. However, utilization of this solution should be examined carefully for each case as integrated PV cells change the visual comfort in the building and are often more expensive than other solutions.

5 Measurement program: "PV performance"

In recent years there has been a rapid development within the area of thin film photovoltaic modules with respect to increased life time, efficiency and power. However, the market is still dominated by traditional crystalline PV modules, mainly because they have proven their performance and reliability for decades. Thin film PV comes in a variety of materials and visual expressions, and could be an interesting alternative in many applications, in particular BIPV. For this to happen, the lifetime and performance under realistic operating conditions must be well-documented.

5.1 Objective

The main objective of the current measurement and demonstration project has been to perform a realistic side-by-side comparison of the most promising thin film technologies for on-grid PV power systems in the Danish climate. Some manufacturers of thin film modules claim that their specific technology delivers more energy than crystalline modules with same power due to better characteristics at elevated temperatures or low irradiance. The project could hopefully reveal this.

5.2 Method

The samples of different modules have been mounted on outdoor racks at Danish Technological Institute, and each module equipped with its own maximum power point tracker. The PV modules have been set up in pairs, where one has an open back side, and the other completely blocked by insulation material, thus simulating the thermally worst possible case of roof integration. The resulting operating temperatures have been recorded, together with the electrical performance.

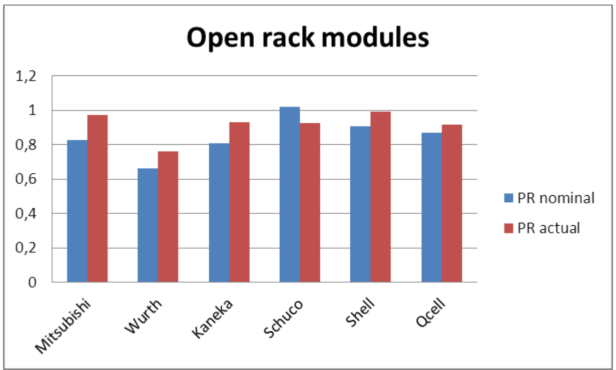
The measurement period was from July 2011 – August 2012, however IV curves have been recorded since March 2009 where the modules were installed.

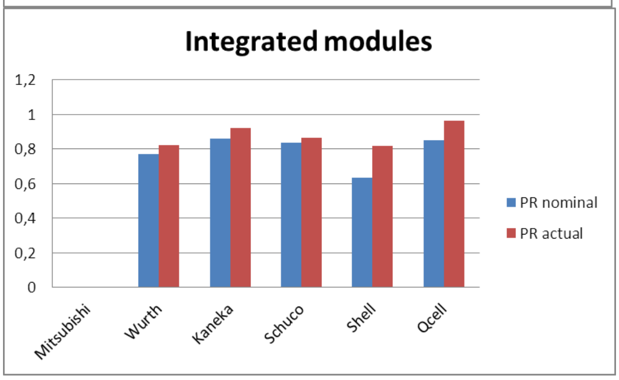
The basic idea of the side-by-side test was to measure the annual performance of as many different thin film modules as possible, representing the most commonly used PV materials such as amorphous and microcrystalline silicon, CI(G)S and CdTe. For practical reasons, the test had to be limited to two modules of each type, where one is mounted with open back side, the other on an insulated surface without any ventilation at all.

The two module racks seen from behind.

The modules are mounted on fixed racks with an inclination of 45° and facing due south. Each module had to run on its own electronic load in order to be able to measure the instantly available maximum power during the entire measurement period. This was one of the most difficult challenges in this project. The reason for this was that it was necessary to develop a new electronic load in the project, because the only one, which was commercially available, was very expensive. It took much time to develop (by Danfoss Solar Inverters) and to fitting it to all the different modules. For a description of the electronic load, which will be very useful in future tests, see chapter 6, "Product development".

A key result from the long term evaluation is the performance ratio i.e. the real efficiency during the operational period compared to the nameplate efficiency:





Performance ratio calculated for either nameplate or measured STC data

The graphs show there are significant differences when the nameplate value is used for comparison, while the differences are quite small when the measured STC data are used. The bad performance of certain modules is thus rather a result of wrong power rating and not the technology as such.

A lot of lessons have been learned from this project that was quite ambitious regarding the open air measurements. The data acquisition and analysis revealed the real practical difficulties with such a comparison of PV modules:

- When measuring small differences in module performance, measurement accuracy becomes very demanding
- Several factors have uncontrollable influence on the measurements and may be difficult to filter later on, such as shadows, cabling problems, EMC noise etc.
- When comparing the efficiency and energy output from different module technologies it is important to define the nominal power values, and that is a problem if the modules are not stable during the period.
- The very limited number of samples makes it difficult to draw statistically valid conclusions regarding the performance of each brand.

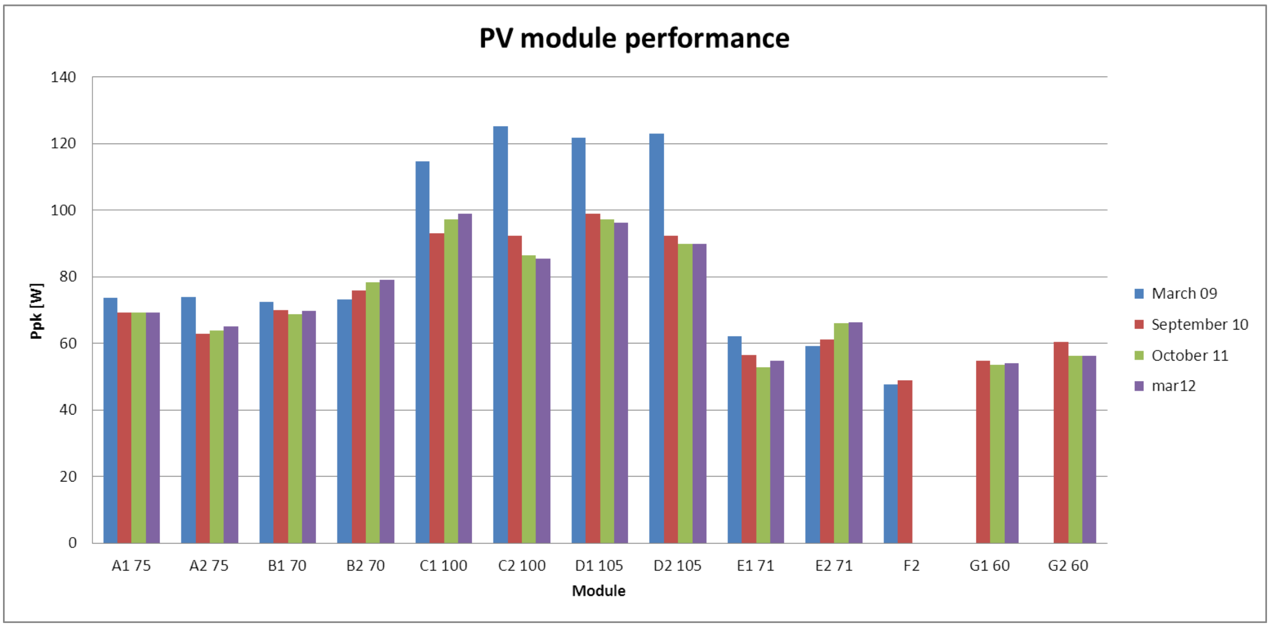
Despite the difficulties, the project succeeded in developing the special measurement equipment needed, and this will subsequently be used in other projects and tasks.

The overall conclusion of the energy performance of the tested modules can be summarized as:

- It is not possible to see any <u>significant</u> difference in specific annual energy yield or performance ratio when the actual peak power is used as base.
- If the <u>nominal power</u> is used as base for the calculations, there are large differences, but no systematic variation related to a specific module technology.
- The open mounted crystalline reference module performs at least as good as any of the thin films, also at low irradiance levels where some thin film manufacturers claim they have an advantage.
- The low temperature coefficients of amorphous silicon and CdTe were confirmed, for the other technologies it was difficult to see a clear trend.
- There is generally a lower production from the integrated modules compared to the open mounted as expected. The difference is 0-10% for the thin films but 19% for the crystalline reference modules. This result is possibly caused by a bad connection.

- All the modules survived the test without any visible defects (except the melted junction box in a reference module) and stabilized at a power level lower than the nameplate value.

During the project period the IV curve of each module was measured with approximately 6 month intervals, and significant degradation of performance was detected for some of the modules, especially a-Si types where 15-20% reduction was measured. This is normal for this type of modules. The IV curves show that series resistance increased, the parallel resistance decreased, or both. This leads to lower fill factor (FF) and thereby lower peak power values in all of the modules. There was no systematic bias that could show if the modules without back ventilation are more prone to degradation than their ventilated twins.



A,B = CIS	C = a-Si	D = a-Si/µX-Si	E= poly-X	F=CIS(excluded)	G = CdTe

The numbers below the bar graph shows the nameplate ratings in Wp. Index 1 refers to the integrated modules. The uncertainty is about 5% in these measurements, so smaller deviations should not be interpreted as degradation.

6 Product Development

In order to transfer knowledge of TF-PV to the Danish PV-industry the private PV-companies, Danfoss Solar Inverters Ltd, Gaia Solar Ltd and PhotoSolar Ltd, were involved as partners. The following is a summary of the findings during the project. These findings are only documented in this chapter and not in a separate report for which reason the main contributing person(s) from each company is mentioned in the following sections.

6.1 Danfoss Solar Inverters

Contributor: Frerk Haase

DSI's motivation for entering the project was primarily to gain more knowledge about some potential induced degradation phenomena (often referred to as PID) observed in many TF-PV panels. The problems were related to the properties of the inverters used and the electrical potential to the ground of the PV modules, though not fully understood.

However, DSI chose to investigate the PID-problems at their own facility. Instead DSI contributed to the ThiFiTech project in another very valuable way by developing an electronic load to be used in the PV-performance measurement work package.

Each of the 12 modules to be tested in the "PV Performance Measurement" work-package had to be loaded in the maximum-power-point (MPP) during the long-term testing in order to reflect real-life conditions for PV modules in grid-connected systems. To carry out this activity each of the modules had to be connected to an electronic load. However the market price for an electronic load appeared to be prohibitive for the project. DSI suggested to develop a much cheaper general purpose load, and thus made. The load can be controlled by analogue signals from e.g. NI Labview.

DTI is benefitting from the new loads, because having finished ThiFiTech, DTI can use the units for general investigations of PV modules or in R&D projects.

The electronic load can also be beneficial for other R&D institutions and PV-companies. For instance it can be used for PV simulators on which MPP algorithms for specific module types are tested. In this case the module is exposed to a controlled artificial light enabling the PV generator curve to be scanned (calibrated) using the electronic load. Subsequently an MPP algorithm under test can be evaluated on the ability to find the MPP of the module under the controlled parameters such as irradiance, shadows or temperature. Especially complex shadow effects on different module types can be simulated with such a tool. The developed tool can also be useful for demonstration purposes on exhibitions for module and inverter manufactures

Figure 6.1 Electronic load connected to solar modules

6.2 Gaia Solar

Contributors: Anders Sørensen
Dennis Aarø

As an X-Si manufacturer the motivation of Gaia Solar to join the project was to get a verification and documentation of allegations of TF-PV's higher annual electrical yield per kWp than X-Si.

As can be seen from the conclusions of the "PV Performance Measurement" work package (in a separate annex report) there can't be drawn firm conclusions confirming these allegations.

At the beginning of the project TFPV were increasingly winning market share from X-Si mainly due to falling prices on TFPV and stagnating prices on X-Si However during the project period this movement reversed, and as X-Si is a much more proven technology, Gaia Solar lost the incitentive to go into the TFPV business.

Gaia Solar listed the strengths and weaknesses of TFPV, in their own opinion:

Strengths:

1) Can be produced in larger dimensions than X-Si modules making them cheaper per square meter and making them more suitable for roofing or façade cladding of large buildings or roofing of e.g. parking lots

Weaknesses:

1) Content of hazardous and rare materials (e.g. CI(G)S and CdTe)
2) Non-tempered glass

3) Probably shorter lifetime
4) Non-flexible and difficult to use in custom designed solutions
5) Difficult to produce

6.3 PhotoSolar

Contributor: Claus Barholm-Hansen

The motivation of PhotoSolar to enter ThiFiTech project was to further develop the understanding of user acceptance of semi-transparent PV in windows in terms of indoor lighting comfort. The experience gained from marketing and selling of the MicroShade™ solar shading product clearly shows that it is important to have an appearance that is acceptable to a large variety of users.

The reason to integrate solar shading in a window is to reduce the influx of solar energy into the building, which is frequently leading to indoor lighting and thermal discomfort. The traditional design of semi-transparent windows often has the drawback that besides being not very aesthetic it is uncomfortable to look through.

The MicroShade design is based on a finely perforated steel-plate integrated in a window and attached to the outer glass (figure 6.2). The perforation is angled relative to the window surface normal in such a way as to reducing incoming light more in summer than in winter, very much like in a venetian blind, and yet providing an excellent view of the exterior scene.

The development of the MicroShade™ Power product has to meet a broad range of requirements. Among these are technical issues around PV manufacture, technical issues relating to varying module size and system integration and issues relating to customer acceptance.

The investigation of user acceptance regarding lighting and the perception of the view to the exterior scene was carried out in SBI's daylight laboratory with test persons working in the room, see paragraph 4.1. MicroShade was compared to other more traditional semitransparent designs of solar shading with a pattern of sun blocking elements. MicroShade was rated the most favorable and generally accepted by the test persons.

MicroShade is purely a solar shading product. Parallel to the work with introduction of MicroShade to the market research is going on to develop a solar active version, named PowerShade. The aim is to make a multi-purpose product with the ability to provide sophisticated solar shading and at the same time providing PV-functionality by depositing solar active material on the perforated steel plate. By depositing the PV-material not only on the plane of the steel plate but also into the holes the product will get a 3-dimensional structure and will obtain an active area comparable with a traditional PV-module with the same outer dimensions.

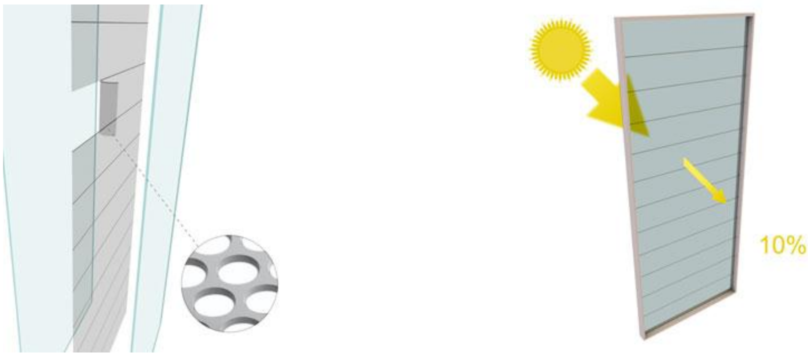


Figure 6.2 Construction of MicroShade™ solar shading

7 Medium- and large-scale demonstration

This chapter concerns one specific activity of the ThiFiTech-project, namely medium and large-scale demonstration. In the context of ThiFiTech, plants below 6 kW are defined as medium scale, whereas plants larger than 6 kW are denoted large-scale plants.

By this division, medium scale plants mainly are for single-family houses that are allowed to use the net metering scheme, whereas large-scale plants are for commercial and public buildings. This part of the ThiFiTech project has been carried out by Arkitema, EnergiMidt and En2tech.

When ThiFiTech was launched both the knowledge and availability of TFPV in Denmark was almost non-existing. Thus the purpose of the medium and large-scale demonstration part of ThiFiTech was to establish a number of plants, which could serve as examples on how TFPV could be realized.

Also the plants established through ThiFiTech should demonstrate if - and how - unique features of TFPV could be exploited. In this way ThiFiTech should provide practice examples of utilization and thereby contribute to further dissemination of PV in general and TFPV in particularly.

7.1 Setting up demonstration plants

To be able to attract hosts for demonstration plant a financial support of 40 % of installation expenditures were offered, but in spite of this, it has proven quite difficult to find relevant installation sites.

For the large plant part, the project partner Arkitema had some initial discussions with costumers whom were planning new commercial buildings and had expressed interest in including PV plants. Eventually, however, none of these contacts ended up with actual TFPV plants, either because the buildings were not constructed or crystalline PV were used in order to obtain as much production as possible with the purpose of meeting the energy frame requirements in the building directive.

In order to include some large scale plants, a cooperation with the ForskVE project Photo Skive was established. The purpose of Photo Skive is to implement PV on a significant part of the building owned by Skive municipal, and for some of these TFPV were then used. Since Photo Skive already received support from ForskVE, no grants for these plants were provided from ThiFiTech.

For the medium scale demonstration EnergiMidt used various information channels to reach potential hosts. For instance a number of people has previously expressed interest in receiving news and offers when available.

Based on this, approximately 15 people expressed initial interest in receiving a quotation for a plant, and as a result of this, 3 plants on private houses were eventually established. The predominant reason why the main part of offers were rejected, were due to the fact that the cost for a TFPV plant – in spite of the 40 % support – were not competitive with a comparable crystalline PV plant due to the steep decline in the cost for traditional crystalline modules that occurred almost immediately after launching of ThiFiTech.

In table 7.1 the basic data regarding the TFPV plants established through ThiFiTech is presented.

As can be seen from the table, all the major TFPV technologies are represented in the demonstration plants. In the specific reporting regarding the medium- and large-scale demonstration, further information regarding the plants is given. (See link to download of the report in Preface).

PFPV plants established through ThiFiTech				
Site	**Technology**	**Producer**	**No. of modules**	**Plant size**
Large scale plants at public buildings				
1. Skive Rådhus	CdTe	Calyxo	377 stk. @ 60Wp	22,62 kWp
2. Skive Bibliotek	CIGS	Solyndra	176 stk. @ 182 Wp	32,03 kWp
3. Brårup Skole	CIGS	Solyndra	36 stk. @ 182 Wp	6,55 kWp
4. Plejecenter Marienlyst	a-Si	Schüco	642 stk. @ 90 Wp	57,78 kWp
Medium scale plants on private households				
5. Sønderborg	CIGS	Schüco	58 stk. @ 75 Wp	4,35 kWp
6. Gjern	a-Si/µc-Si	Inventux	42 stk. @ 130 Wp	5,46 kWp
7. Ulstrup	a-Si/µc-Si	Inventux	32 stk. @ 130 Wp	4,16 kWp

Table 7.1 Data regarding the TFPV plants established through ThiFiTech

7.2 Experience gained

When looking at the installed plants in a general perspective, some aspects can be drawn forward:

- Some of the modules utilized were frameless laminates that benefit from the fact, that dust etc. will not built up near the edges on account of the frame. These modules, however, have to be handled with great caution during transportation and installation since the glass easily brakes when no supporting frame is present.
- Another point worth to mention, is that TFPV typically have higher output voltage compared to crystalline modules which means that the fitting of a given TFPV module type to a given inverter type in some cases can cause problems.
- As the efficiency of the TFPV modules are lower than the X-Si modules, the costs related to the area are higher. The number of connection points and length of DC cables increase and thus the mounting time needed usually rise.
- The a-Si, a-Si/µc-Si and CdTe modules utilized in the demonstration plants established, has a relatively reflective surface, which can give rise to annoying reflection from the sunlight striking the modules. Since this aspect has recently become the subject of interest for e.g. planning departments of certain municipalities, it is highly recommendable to address separate consideration hereto, for instance by making simulations and/or calculations of the reflection pattern during the course of the year.
- Module manufactures always circumscribe under which condition their product may be used and still benefit from the warranty giving. With respect to TFPV, very often it is stated, that only inverters with transformers may be utilized. These devices usually not have as high efficiency as the case is for inverters without transformers and therefore a lower specific annual yield often has to be expected.
- As described for the TFPV plant established on Skive Rådhus, a PV plant can in some cases serve multiple purposes. If the value of these additional purposes is taking into account, the marginal expenditures for adding power production may not be very high.

7.3 Barriers and potentials for TFPV in Denmark

When ThiFiTech started in 2008 it was generally expected, that TFPV – although more modules and mounting equipment were needed due to lower efficiency – would in a short time gain an economic benefit over crystalline PV giving a significantly lower production cost.

The reality, however, turned out to be different, since the cost for traditional PV products soon took a very steep decrease, when large production capacities were established mainly in China while at the same time some incentive program were terminated or reduced.

Although some benefits regarding architectural conditions are present, TFPV has not yet captured noteworthy marked shares in Denmark and it is difficult to imagine that the outlook for TFPV will improve significantly unless some radical change in market conditions will occur.

The main reason for this is attributable to the fore mentioned economic condition: At the present situation with steadily decreasing cost for traditional PV modules based on crystalline cells, TFPV has a hard time being competitive from a holistic point of view.

Although the crude module price per Wp is often lower, the total cost including BoS will for the Danish situation very often be higher, due to the need for more cables, mounting equipment and manual labour for mounting.

It is thus difficult to pinpoint areas in which TFPV will have obvious benefits over crystalline PV in a Danish context; the most likely areas, however, could be large-scale PV power plants on marginal soils and for special building integrating purposes, in which the uniform surface and especially the possibility to prepare the transparency of the module can be utilized.

8 Dissemination

During the project period there have been several dissemination activities. Each of the presentations, reports and papers in the following list has had a strong relation or association to or has been a direct outcome of the ThiFiTech Project.

The following activities report results from ThiFiTech as well as from 2007-1-7353 "Customized PEC modules. Accordingly the activities are included in the interim reports for both projects:

- Lauritzen, H. (Danish Technological Institute): "Solceller'', iNANO, Aarhus Universitet, 25 April 2008 (2 lectures)
- Lauritzen, H. (Danish Technological Institute): "Lysfiltrerende solceller og intelligente facader", Workshop on sustainable building, Gromtmji Carl Bro, Glostrup, May 2008 (oral presentation)
- Lauritzen, H. et al (Danish Technological Institute): "Light and Energy - Solar Cells in Transparent Facades", 23rd European Photovoltaic Solar Energy Conference, Valencia, Spain, 1-5 September 2008 (poster)
- Lauritzen, H. et al (Danish Technological Institute): ''Integration mellem solcelier og dansk arkitektur", Strategies for sustainable building, Taastrup, 13-14 November 2008 (oral presentation)
- Lauritzen, H. et al (Danish Technological Institute): "The battle of light – semi-transparent PV panels in glass facades", 3rd International Conference on the Industrialization of DSC, Nara, Japan, 22-24 April 2009 (oral).
- Nørgaard, K. et al (Danish Technological Institute): "Semi-transparent PV in Glass Facades", 3rd Nordic PV Conference, Tallin, Estonia, 18-19 May 2009 (oral).
- Lauritzen, H. et al (Danish Technological Institute): "The battle of light – solar cells in glass facades" in Proc. of Glass Performance Days, Tampere, Finland, 12-15 June 2009, p. 557.
- Presentation of the projects by poster and orally at the joint Danish exhibition stand at the world's largest solar technology trade fair (Danish Technological Institute), Intersolar 2009, Münich, 27-29 May, 2009.

Poulsen, S. (Danish Technological Institute): Seminar about Energy optimization, photovoltaics of the future and new light sources, IDA-Sydsjælland, SEAS-NVE, Haslev, 28 October 2009 (oral presentation).

Poulsen, S. (Danish Technological Institute): Seminar about PV-technologies, projects & products, Solar City Copenhagen, Copenhagen, 3 December 2009 (oral presentation).

Cold, S. (Entasis Architects): Proposal for a mobile pavilion with PV-modules, exterior view. Illustration from a presentation 27.08.2009 by Signe Cold -

Stephansen, C. et al (EnergiMidt): A poster describing the TFPV for the city hall of Skive Municipality, 24th European Photovoltaic Solar Energy Conference and Exhibition", Hamburg, September 2009.

(Energimidt): A poster describing the projected TFPV plant on the rooftop of the city hall of Skive was presented at various occasions in the city of Skive. One of these events was the official inauguration of the currently largest PV plant in Denmark, which is situated on a public school in Skive, carried out by minister for employment, Inger Støjberg., 2010

Andersen, A. R et al (Danish Technological Institute): "Solceller – en naturlig del af bygningen", oral presentation at a local meeting in Energiforum Danmark in Næstved, 14 April 2010.

Christiansen, J.; Sørensen , M. Brorholt; Andersen, A. Rand; Fyenbo, J (Danish Technological Institute): "DSC solar cells in progress" (poster) CASE-Helios workshop, DTU, 17-18 May 2010

Andersen, A. Rand (Danish Technological Institute): "The diffusion/reaction model applied on mesoporous TiO2 based dye solar cell", AMAS/CCS spring seminar on Photocatalytic TiO2 based technologies, DTU, 17-18 May 2010

Andersen, A. Rand (Danish Technological Institute): "The diffusion/reaction model applied on mesoporous TiO2 based dye solar cell", AMAS/CCS spring seminar on Photocatalytic TiO2 based technologies, DTU, 17-18 May 2010

Christiansen, J.; Sørensen , M. Brorholt; Andersen, A. Rand (Danish Technological Institute): Poster presentation of novel methods in experimental studies of thermal degradation patterns for the Dye Solar Cell (DSC). Especially a method based on a combination of Electrochemical Impedance Spectroscopy (EIS) and Mass Spectroscopy (MS) was described. The International Conference on Photochemical Conversion and storage of energy (IPS-18) in Seoul, South Korea, 25-30 July 2010.

Christiansen, J.; Sørensen , M. Brorholt; Andersen, A. Rand (Danish Technological Institute): Poster presentation of novel methods in experimental studies of thermal degradation patterns for the Dye Solar Cell (DSC). Especially a method based on a combination of Electrochemical Impedance Spectroscopy (EIS) and Mass Spectroscopy (MS) was described. Dye Solar cell Industrialization Conference (DSC-IC 2010) in Colorado Springs, US, 1 October 2010.

(EnergiMidt) ThiFiTech was presented in connection with PV theme arrangements open for the public in Skive and Silkeborg, spring 2011.

(EnergMidt) Conference and study tour for 70 potential hosts for TFPV installations. The TFPV plants established at the city hall and the library in Skive were visited. 24th May 2011, Skive.

(ThiFiTech group of partners). External conference and study tour to visit some thin-film systems with the aim of presenting the main results obtained in ThiFiTech project and to mark the end of the project. There were 35 participants representing inter alia energy companies, architects, consulting engineers, municipalities and production companies. 18 September 2012, Skive.

Presentation of the results of the ThiFiTech-project. 18 September 2012, Skive.

Skive Townhall, CdTe-modules. 18 September 2012

East-West installation with a-Si modules on the roof of Marienlyst old peoples home. Skive 18 September 2012

Installation with the unique tubular Solyndra PV modules (CIS).
Skive Library, 18 September 2012

9 Conclusion and future outlook

From the start of the project there were great expectations that TFPV's would soon have some key advantages over X-Si as a large scale electricity generating technology as well as a building integrated electricity-generating element.

It was generally felt that the price of TFPV would decrease significantly, while X-Si did not have the potential to get much further down in price. Moreover, results from previous projects indicated that TFPV integrated into windows as sun shading element had significantly better properties regarding visual and thermal comfort and architectural opportunities. It was generally felt that TFPV had greater flexibility for adaptation into the building construction both in terms of integration into the windows and to contribute positively to a building's architectural appearance. Finally, there was a perception that the TFPV technologies would produce relatively more electrical energy through better lowlight response, less shadow sensitivity and reduced temperature sensitivity.

These expectations were met only for a rather small part.

Primarily the price of X-Si modules dropped approx. 50%, completely against expectations. This was partly due to technological advances in the form of larger and more efficient solar modules and more rational production methods. And partly due to the financial crisis and subsequent cuts in domestic support programs in several significant countries, which coincided with the start of many new factories, increased competition and reduced profit margins. Furthermore during the project period aesthetically attractive X-Si modules were introduced on the market with completely black appearance, both mono-and polycrystalline.

TFPV did not see the same price drop. Production lines for TFPV are very expensive and a high throughput is required to make profit. This is a tough challenge in a declining market. The real-life accumulated experience with TFPV is much smaller than with X-Si, which has made PV-plant owners turning to X-Si.

Along with the increasing efficiency, both for X-Si and for TFPV, the PV-plant owners have had increased focus on area related costs, e.g. labor for mounting, cables, conduits, etc. More and more owners with a limited area also want as high electrical yield as possible, giving X-Si an advantage through the higher efficiency.

In the project it was attempted to prove the allegations claimed from several sources that TFPV has better characteristics in terms of low light performance, temperature sensitivity and sensitivity to shade. Only the lower temperature sensitivity was verified, however with some uncertainty.

During the project it has also become clear that TFPV all in all, is not a more flexible technology than X-Si. The above mentioned requirement for a very high throughput in the manufacturing of TFPV modules to recoup the expensive production lines means that the modules comes out in a few standard sizes. Manufacturing of custom designed modules with different dimensions is very expensive. X-Si has much greater flexibility in this regard.

TFPV has a clear advantage over X-Si regarding light filtering and sun shading integrated in the windows. Much more attractive designs can be produced from a user's perspective. However, coating the filter with photovoltaic material results in additional costs which should be counterbalanced by the value of the produced electricity. Not only will the filter material be more expensive, but there will be additional costs for cabling, mounting, inverter etc. (BOS). The electricity production will be very low due to the fact that: 1) the active area is small, 2) the window is installed vertically (in most cases) which is not an optimal angle to the sun, 3) TFPV has a lower efficiency than X-Si. When a PV version of MicroShade once is developed (PowerShade), it might have an advantage over other TFPV technologies because the structure of the embedded light filter material is three-dimensional, resulting in a higher light-sensitive area in relation to the proportion of the pane, that the material covers.

The conclusion is that it is difficult to pinpoint areas in which TFPV will have obvious benefits over crystalline silicon PV in a Danish context, at least in the short and medium term. Some investors might find the appearance of TFPV more attractive than X-Si. The profitability of TFPV integrated into windows is rather questionable, but for some investors it can have a major symbolic value.

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