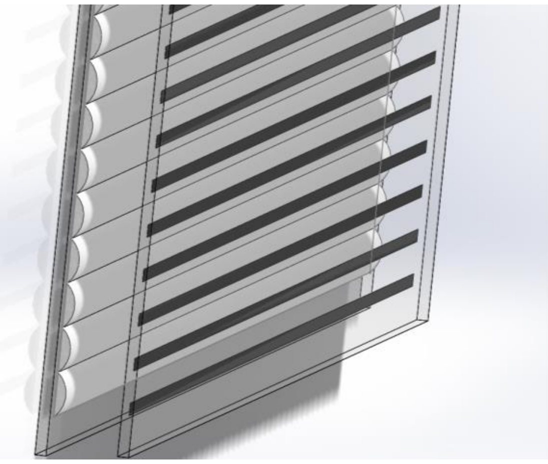
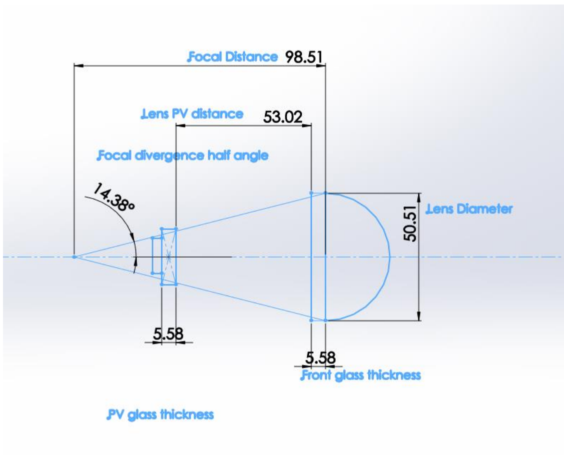
Final Report

ForskEL 12.213 - BICPV

Building integrated concentrator PV window

Feasibility study



WRITTEN BY

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Allan Krogh Jensen, AKJ Inventions

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1.1 Project details

Project title	BICPV – Building integrated Concentrator PV window – Feasibility study
Project identification (program abbrev. and file)	12.213
Name of the programme which has funded the project	ForskEL
Project managing company/institution (name and address)	DTU Fotonik, Frederiksborgvej 399, 4000 Roskilde Peter Behrensdorff Poulsen, ppou@fotonik.dtu.dk
Project partners	AKJ Inventions
CVR (central business register)	DK 30 06 09 46
Date for submission	September 30th 2015

1.2 Short description of project objective and results

1.2.1 English version

The purpose of the project is through applied research and development to demonstrate the feasibility of a building integratable, transparent PV module harvesting concentrated direct sunlight, acting as intelligent venetian blinds and letting in the diffuse lighting into the building. A BICPV system is proposed in this work substituting venetian blinds in a double glass window with semicylindrical lenses and by raising and lowering the lenses with the sun traveling over the sky light the direct light can be focused on lines of solar cell materials on the inside glass towards the building with a thin film solar cell on the inside of a e.g. gas filled double glass window. A composition giving a concentration factor of C=3.5X is shown by optical modelling to use 28% of a flat panel solar cell area to produce 60% the energy thereby production twice the amount of energy pr. Solar cell area under Danish condition vertically oriented south.

1.2.2 Dansk version

Formålet med projektet har været at demonstrere et bygningsintegrerbart PV modul, der kan fungere som dagslyskontrol i bygninger ved at erstatte kommercielle persiennesystemer integreret i termoruder med cylinderlinser, der fokuserer direkte sollys på linier af tyndfilmssolceller og altid lader det diffuse lys passere ind i bygningen. Solens bevægelse over himmellegemet kræver at linserne flyttes maximalt 20 mm vertikalt hen over dagen på danske breddegrader for hele tiden at sikre det direkte sollys fokuseres ned på solcellerne og dermed blokkeres for penetration ind i bygningen. Termoruden med PV koncentratorsystem kan være gasfyldt og fungere som vanlig termisk klimaskærm og samtidig i en konfiguration foreslået i nærværende rapportering koncentrere sollyset 3,5X vist med optisk modellering og dermed udgøre kun 28% af arealet et tilsvarende fladt solcellemodul uden koncentrering producerende 60% af energien af dette. Dyrt halvledermateriale spares herved til fordel for væsentligt billigere optik og solcellerne producerer dobbelt så meget energi pr. areal som et panel uden koncentrering og fungerer yderligere til dagslyskontrol og klimaskærm.

1.3 Executive summary

At present, the use of solar concentrator systems is limited in scale and the majority of existing installations employ devices of considerable size like:

- Solar power towers
- Parabolic trough concentrators
- Parabolic dish concentrators
- Large Fresnel concentrators with two-axis tracking systems

Producers of solar concentrator systems for small scale building integrated installations must develop reliable systems which are adequate for their application. Single axis tracking design are suitable for building integration. Building Integrated Concentrating Photovoltaics (BICPV) need to be designed in such a cost optimized way allowing them to compete with the flat panels technology which manufacturing costs are declining rapidly. Furthermore, BICPV apt for architectural integration must fulfil the requirements generalized by IEA PVPS Task 7 - Photovoltaic power systems in the built environment [1].

- Natural integration.
- Architecturally pleasing design.
- Good composition of colours and materials.
- Dimensions that fit the gridula, harmony and composition.
- Conformity to the context of the building.
- Well-engineered and innovative design.

Building integrated concentration systems may be installed either on the building façade or on the roof. Depending on the type, the system may be integrated in such a way that it is unseen, plays some role in the architectural aesthetic or that it constitutes in itself an architectural concept [2]. The integrability of a concentrator, being it reflective or refractive, depends on its concentration factor, C (defined as the ratio between the aperture area of the primary concentrator and the active cell area) [1] as illustrated in Figure 1.

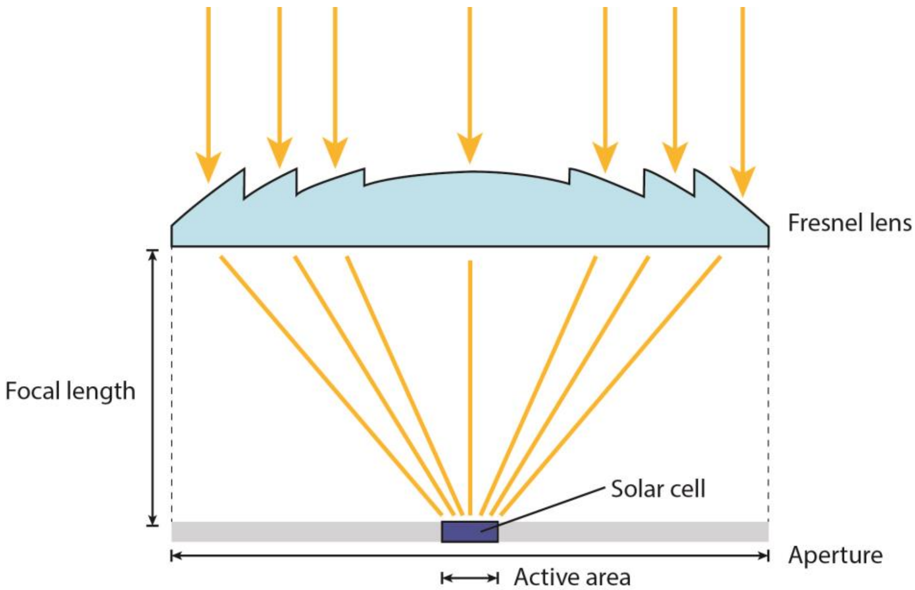


Figure 1 – The concentrator factor, C, is defined as the ratio between the aperture area and the active solar cell area, here illustrated by an optical system with an fresnel lens.

Concentrating systems with C > 2.5 generally use a system to track the sun, whereas systems with C < 2.5 can be static. However, in the long term static concentrators with higher ratios which make use of luminescence and photonic crystals may appear [1]. Low concentrating ratio systems (C < 10) usually called low concentrating photovoltaic (LCPV) are of particular interest for as they are of linear geometry and thus one tracking axis is sufficient for efficient operation which is the topic of this project.

Even though the prices have dropped considerable on PV panels the last 5 years with the most dramatic decline in 2011/2012 [3] the cost of energy from PV is still high compared to the fossil fuel sources. Price development of mc-Si modules from 2010-2015 can be seen in Figure 2.

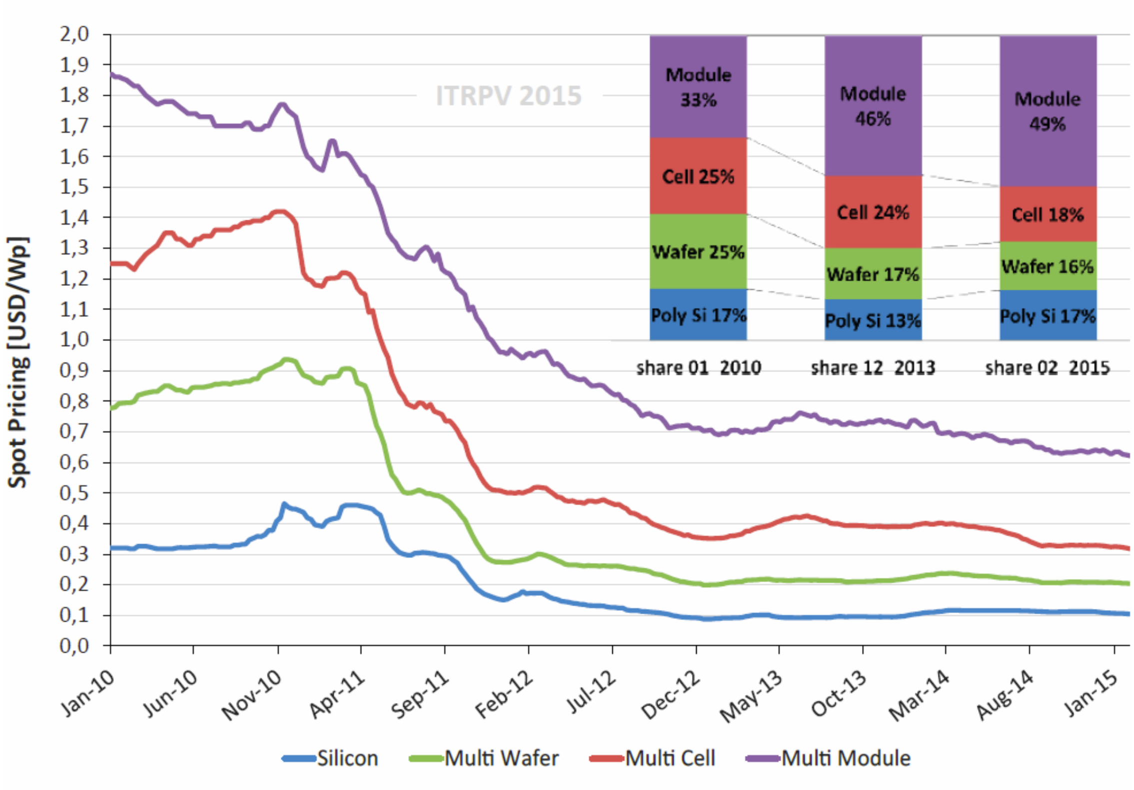


Figure 2 - Price development of mc-Si modules from January 2010 to February 2015 with separate price trends for poly-Si, multi crystalline (mc) wafers, and cells. [3]

Concentrator photovoltaics is feasible method to reduce the rather high initial cost of PV solar energy by diminishing the area of semiconductor devices used replaced by a cheaper element (the concentrator). BICPV is interesting since further functionality can be implemented into the system, not just giving savings on the semiconductor material, but also on the façade element the BICPV system is replacing. Added value of the BICPV system comes on top of this if it can e.g. shade away direct sunlight and gives savings on the energy budget of the building etc.

In this project the feasibility of a special BIPCV system has been evaluated with the purpose of filtering direct light from diffuse light, and harvesting the direct part as electrical energy in a photovoltaic systems and transmitting the diffuse part of the light into the building. The principle is shown in Figure 3 below.

Figure 3 - BICPV principle evaluated in the project. Direct light is concentrated by cylindrical lenses onto solar cells and blocked/harvested while the diffuse light penetrates into the building.

The developed concept is shown below.

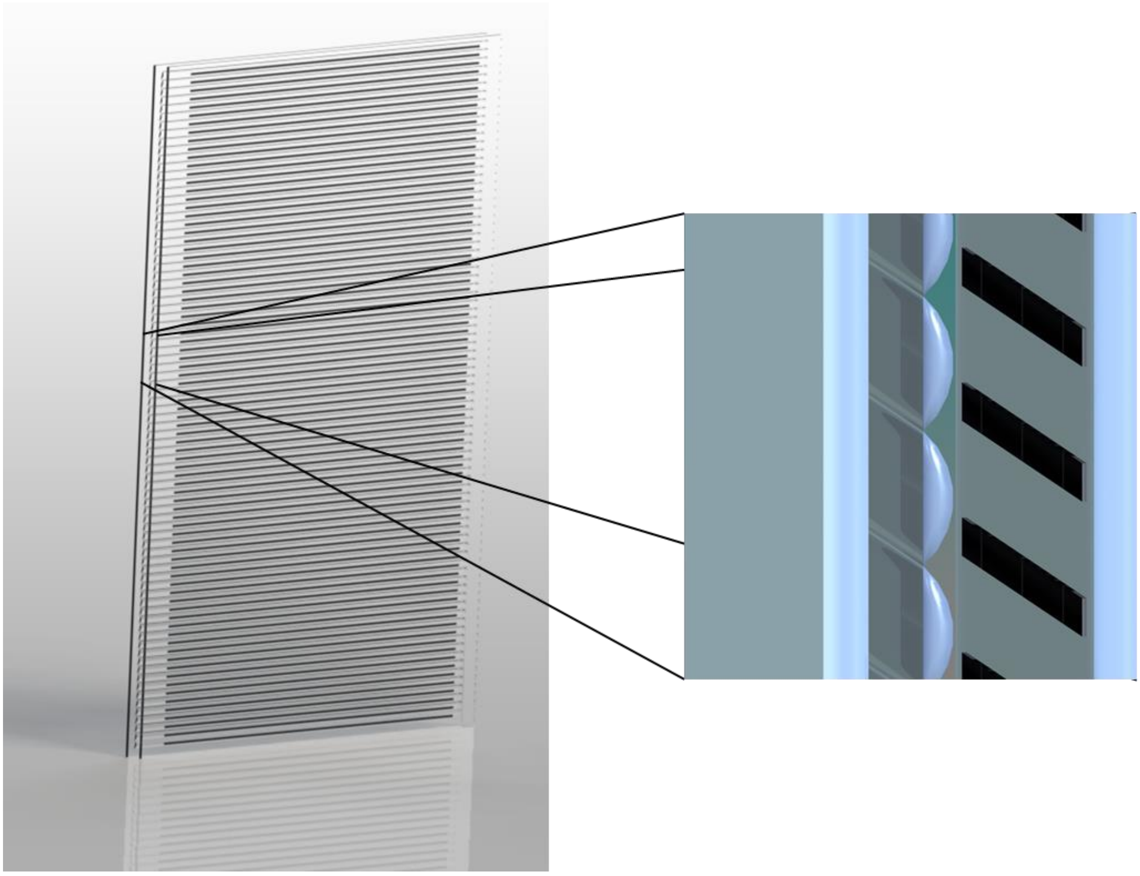


Figure 4 – Final concept developed in the project.

A composition giving a concentration factor of C=3.5X is shown by optical modelling to use 28% of a flat panel solar cell area to produce 60% the energy thereby production twice the amount of energy pr. Solar cell area under Danish condition vertically oriented south. The concept is patent pending and a go-to-market strategy will be executed by the partners if granted. The concept is seen as a platform with many development and adaption possibilities, since the lenses can have other properties than the proposed for other purposes or optimization of the system for cost, size, advanced daylight control or other relevant parameters.

1.4 Project objectives

The project objectives have fallen within the following scientific work packages:

- WP 0. Project Management
- WP 1. System Research
- WP 2. Development of optical system
- WP 3. Development of PV system
- WP 4. Thermal management
- WP 5. Mechanical system design
- WP 6. Building a Demonstrator
- WP 7. Market potential research
- WP 8. Evaluation and reporting

The work packages have been used as basis for developing the tools to meet the core objectives of the project, which are:

- Demonstrating the plausibility of the moving parts being able to be cheap and long lasting (maintenance-free for 20 years).
- Demonstrating that the visual impression the BICPV module creates is pleasant and in accordance with what architects and users would like to integrate in buildings.
- Demonstrating there will not be a heat problem in the BICPV module.
- Demonstrating a business case for the system and the market volume of the different segment addressed by this system.

The project is a feasibility study supported by ForskEL with a grant of 500.000 DKK. The project has met many obstacles on its way, which was not possible to foresee when it started. It is a rather small project which includes many scientific topics as well as administrative and market oriented. The nature of a R&D project is, that when you solve one problem several new ones arise entailed by the higher state of knowledge. The project partners are though happy with the results and how the project evolved.

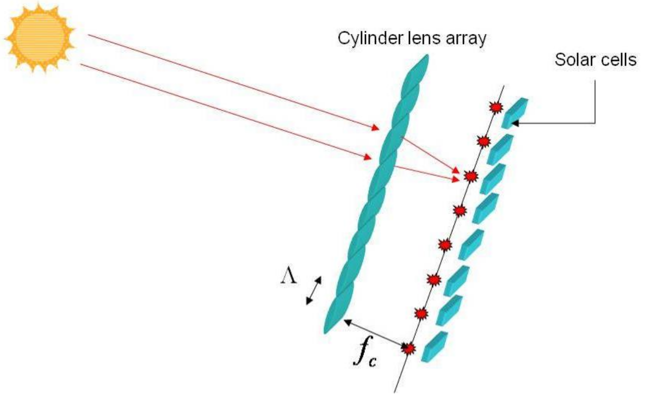
The risks of the project are embedded in the description above, that a small ambitious project has the risk of taking a few steps in many directions and not being able to connect the dots and overall get anywhere. Small resources stimulate creativity and on the market site the project has been used as case in the 10 ECTS point masters course Spring 2015 | 41633 Innovation and Product Development. A big thanks to the students: Jesper Byrdal Kjær, Lotta Ahonen, Denis Kirchhübel, Mathias Herlev, Bjarke Vad Andersen and Emil Gram Spork, for investing the business potential of the BICPV technology with focus on exploiting the technology for light environmental control for commercial greenhouses.

The project followed the milestones very well and since it was a one-year project there was really no time to depart from the project plan below.

År	2014												2015					
Work packages/Projektets arbejdspakker:	1	2	3	4	5	6	7	8	9	10	11	12	1	2	3	4	5	6
WP 0. Project Management																		
WP 1. System Research																		
WP 2. Development of optical system																		
WP 3. Development of PV system																		
WP 4. Thermal management																		
WP 5. Mechanical system design																		
WP 6. Building a demonstrator																		
WP 7. Market potential research																		
WP 8. Evaluation and reporting																		
Milestones/Milepæle																		
M1 Thorough litterature/patent/material search done									M1									
M2 BICPV Demonstrator produced																	M2	
M3 Demonstrator feasibility evalutated																		M3
M4 Final report finished																		M4
Commercial milestones/Kommerc. milepæle																		
CM1 Market potential/volume estimated																		CM1

1.5 Project results and dissemination of results

The original project idea was to develop a one-axis tracking system BICPV as shown below.



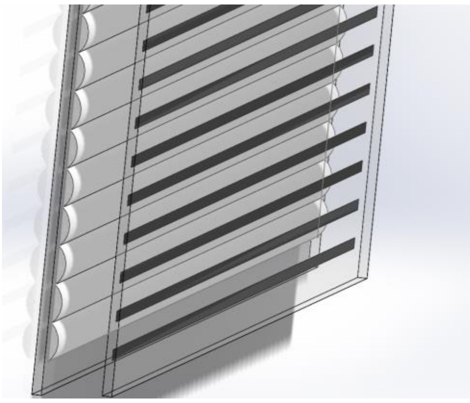
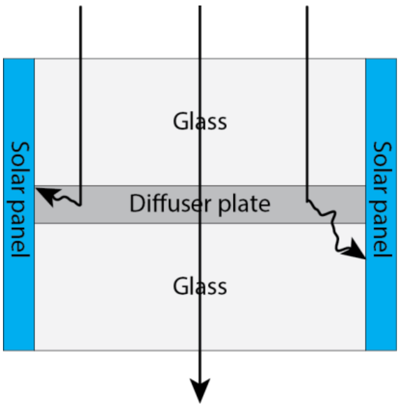
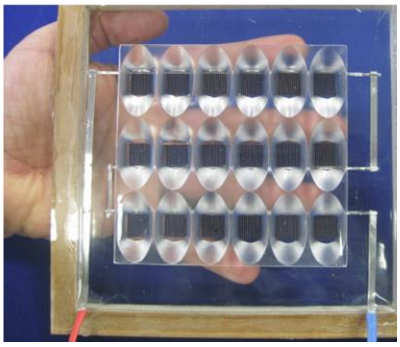


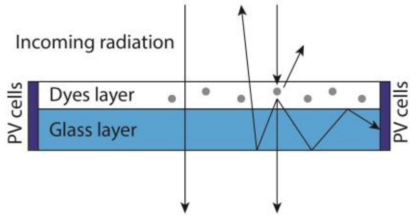
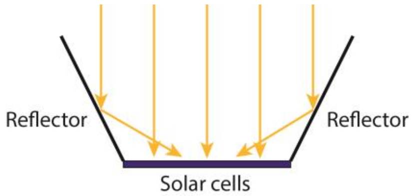
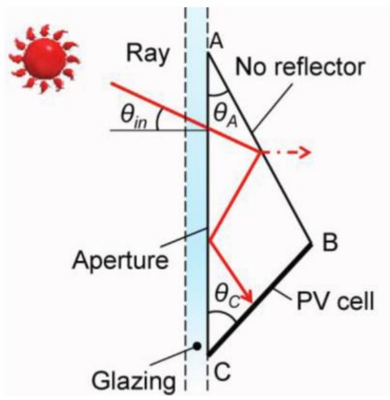
Figure 5 – The original BICPV project idea (left) developing a one-axis tracking system. The image to the right shows one of the first proposed solutions in the project.

The system is oriented towards south and the array of horizontally aligned cylinder lenses focuses the incident light onto an array of horizontal lines, at which the long stripes of solar cells are placed. As the sun elevation changes during the day, the focal lines will move away from the solar cells in case of no tracking. If the array of cylinder lenses is moved slightly vertically, the focal lines can be readjusted to coincide with the solar cells. In fact, the vertical movement necessary for readjustment is only a fraction of the distance between the lenslets in the lens array. Below the main activities of the projects and the results are described in detail.

1.5.1 System Research

There has been done research on the system on multiple levels. First of all, a literature study was made addressing alternative configurations to learn from in the present project.

PUBLICATION(S)	PRINCIPLE	CONCLUSIONS
[4] Lai, C. W., Chen, R. T., Lin, T. C., & Kang, C. C. (2014). Efficiency improvement of a diffusive solar cell window by optimizing the diffusion plate design with optical simulation, 463–465. [5] R. T. Chen, J. L. H. Chau, and G. L. Hwang, "Design and fabrication of diffusive solar cell window," Renew. Energy, vol. 40, no. 1, pp. 24–28, 2012.	**Diffusive solar cell window** 	Diffuse solar cell windows are simple, inexpensive and stationary see trough solar panel. Solar cells are placed in the frame of the windows and a diffuse plate is laminated between to glass panes that make up the window. Particle sizes can be optimized for diffusion and a >50% transmitting window I made with dimensions of 64 x 64 cm harvesting 0,46 mW/cm^2 where a typical solar panel will harvest something like 15 mW/cm^2. Only light with incident angle normal to the PV pane is simulated/tested.
[6] Sellami, N., & Mallick, T. K. (2013). Optical characterisation and optimisation of a static Window Integrated Concentrating Photovoltaic system. Solar Energy, 91, 273–282. [7] Sellami, N., & Mallick, T. K. (2012). Design of nonimaging static solar concentrator for window integrated photovoltaic, 106(2012), 106–109.	**Square elliptical Hyperboloid** 	Square Elliptical Hyperboloid (SHE) based Window Integrated Concentrating Photovoltaic (WICPV) system was shown based on (i) elliptical entry aperture; (ii) hyperbolic profile section and (iii) square exit aperture. The system is a fully stationary solar concentrator system using silicon solar cells for low concentration and has and optical efficiency of 68% at 4x concentration. Non-imaging concentrators combine the widest possible acceptance angels with high efficiency.

[8] Laus, L. C. Andreani, and D. Comoretto, "A Multi-optical Collector of Sunlight Employing Luminescent Materials and Photonic Nanostructures," Adv. Opt. Mater., pp. 147–155, 2015. [9] L. H. Slooff, R. Kinderman, A. R. Burgers, A. Büchtemann, R. Danz, T. B. Meyer, A. J. Chatten, D. Farell, K. W. J. Barnham, and J. A. M. van Roosmalen, "The luminescent concentrator illuminated"2006.	**Fluorescent Concentrators**  	The idea of using Fluorescent concentrators is to concentrate both direct and diffuse radiation without tracking system by a matrix of dye molecules absorbing and reemitting radiation at longer wavelengths. Most of the emitted light is internally totally reflected and therefore trapped and guided to the edges of the concentrator where a solar cell converts it into electricity.
[10] D. Chemisana, M. V. Collados, M. Quintanilla, and J. Atencia, "Holographic lenses for building integrated concentrating photovoltaics," *Appl. Energy*, vol. 110, no. 2013, pp. 227–235, 2013.	**Holographic concentrators** 	A volume transmission phase holographic element was designed and constructed to perform as a building integrated photovoltaic concentrator. The holographic lens diffracts light in the spectral bandwidth to which the cell presents the highest sensitivity with a concentration factor of 3.6X. In this way, the cell is protected from overheating because the infrared for which the solar cell is not sensitive is not concentrated. In addition, based on the asymmetric angular selectivity of the volume hologram and based on the linear concentration, only single-axis tracking is needed. The use of the holographic element increases the efficiency of the PV cell by 3% and the fill factor by 8%.
[11] N. Martín and J. M. Ruiz, "Optical performance analysis of V-trough PV concentrators," Prog. Photovoltaics Res. Appl., vol. 16, no. 4, pp. 339–348, Jun. 2008 [12] H. Bahaidarah, B. Tanweer, P. Gandhidasan, and S. Rehman, "A Combined Optical, Thermal and Electrical Performance Study of a V-Trough PV System—Experimental and Analytical Investigations," Energies, vol. 8, no. 4, pp. 2803–2827, 2015. [13] N. Fraidenraich, "Design procedure of V-trough cavities for photovoltaic systems," Prog. Photovoltaics, vol. 6, no. September 1997, pp. 43–54, 1998. [14] C. Q. Yan, "Output Characteristics Study of V-trough PV Concentration System," Appl. Mech. Mater., vol. 71–78, no. 2, pp. 2077–2080, 2011.	**V-Through concentrator**  	V-Through cavities are simple to manufacture and can be used with conventional 1-sun solar cells. A one-axis tracked 2.5X system shows a 100% larger annual yield than a fixed PV flat panel in a site in Brazil. A fixed C=2.5X system shows a 21.6% increase in output power from plat panel based on polysilicon cells to a V-trough concentrator system. No V-Trough system was found for integration into buildings as a multifunctional element for controlling light into the building.
[15] N. Yamada, K. Kanno, K. Hayashi, and T. Tokimitsu, "Performance of see-through prism CPV module for window integrated photovoltaics.," Opt. Express, vol. 19 Suppl 4, no. May, pp. A649–A656, 2011.	**Prism system**  	See-through photovoltaics module that uses a low-concentration prism concentrator is examined. The incident angle dependency of the prism concentrator makes it possible to concentrate direct solar radiation onto solar cells and transmit diffuse solar radiation. Fewer solar cells can then be used without sacrificing the conversion efficiency or lighting performance. The module generates approximately 1.15 more electricity than a conventional module while operating with 63% less solar cell area.

All of the above is addressing 2 topics

- the topic of concentrating light onto solar cells by cheap lenses saving expensive semiconductor material
- Using the concentrator system for solar lighting control in the building.

The BICPV system developed in this project has most similarities with the holographic concentrator system and the prism system described above.

The authors investigated the market for commercial systems addressing the same issues. One system is the PVGU (PV Glass Unit) window made by Pythagoras Solar which is shown in Figure 6.

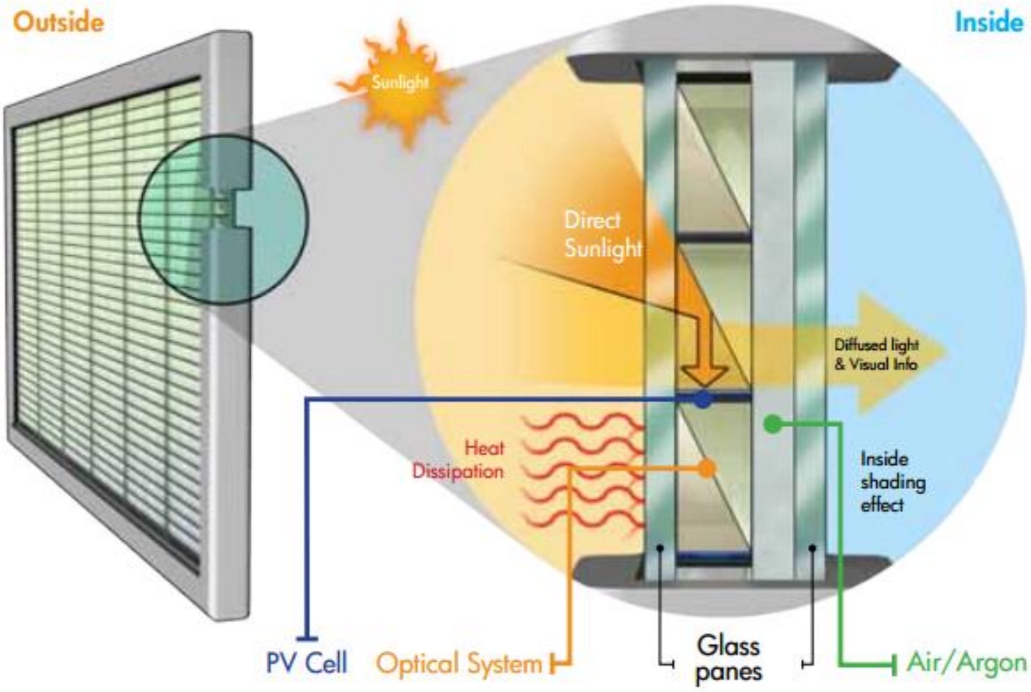


Figure 6 – PVGU window made by Pythagoras Solar

The PVGU window is a passive system where the direct solar irradiation is focus by a prism onto a solar cell being placed horizontally in the window system. The diffuse light passes through to the interior of the building. The window can be gas filled and therefore be compatible with thermal windows for thermal control of the building. Pythagoras Solar closed in 2013 of reasons not known by the authors.

Another passive transparent PV concentrator system is proposed by Stellaris which is shown below.

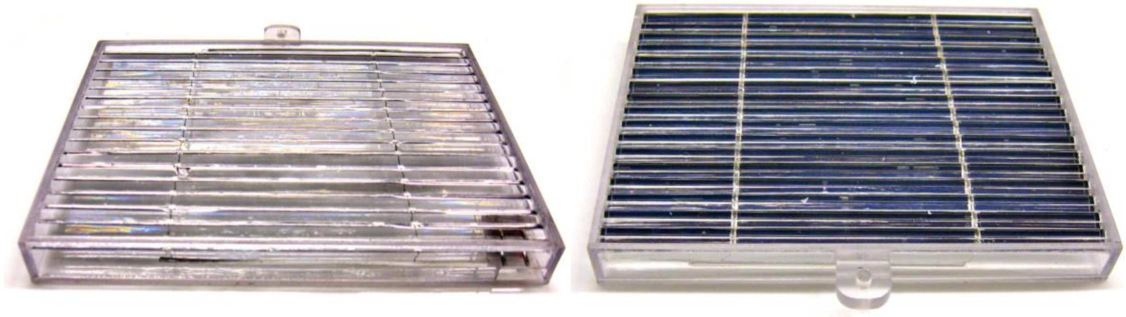


Figure 7 – Stellaris solar charger module

The working principle of the Stellar PV system is shown in Figure 8.

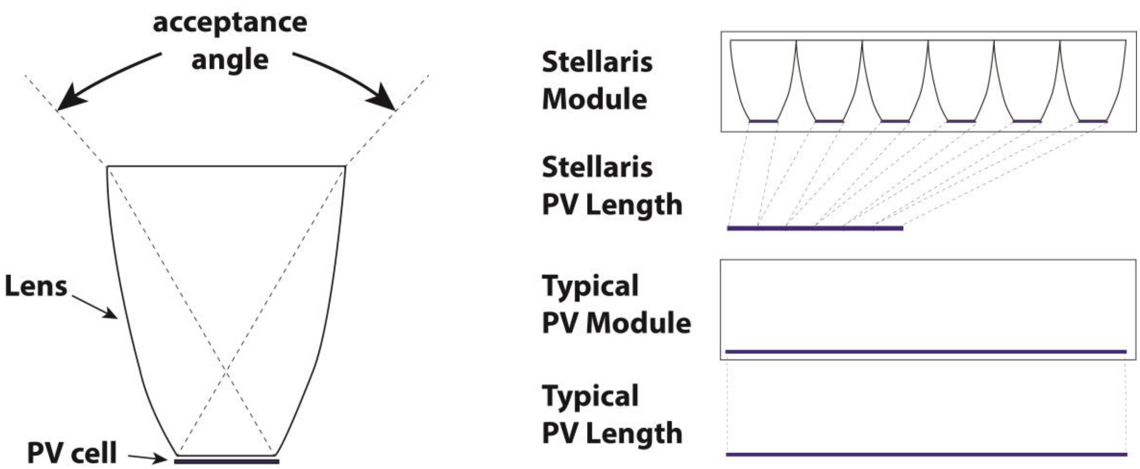


Figure 8 – Working principle of Stellaris PV Module. On the left a single lens concentrating light onto a PV stripe is shown and on the right these subunits are scaled into a module.

The concentration factor is claimed to be 3 in the system using only 1/3 of solar material to harvest the same amount of energy as a standard flat plate PV system. Stellaris claim to be able to use this platform inside a window too and make and achieve similar properties as the systems proposed in this project though the system is not on the market yet to the authors knowledge.

Yet another system is worth mentioning – is the French company, SunPartners, product for smart phones shown below.

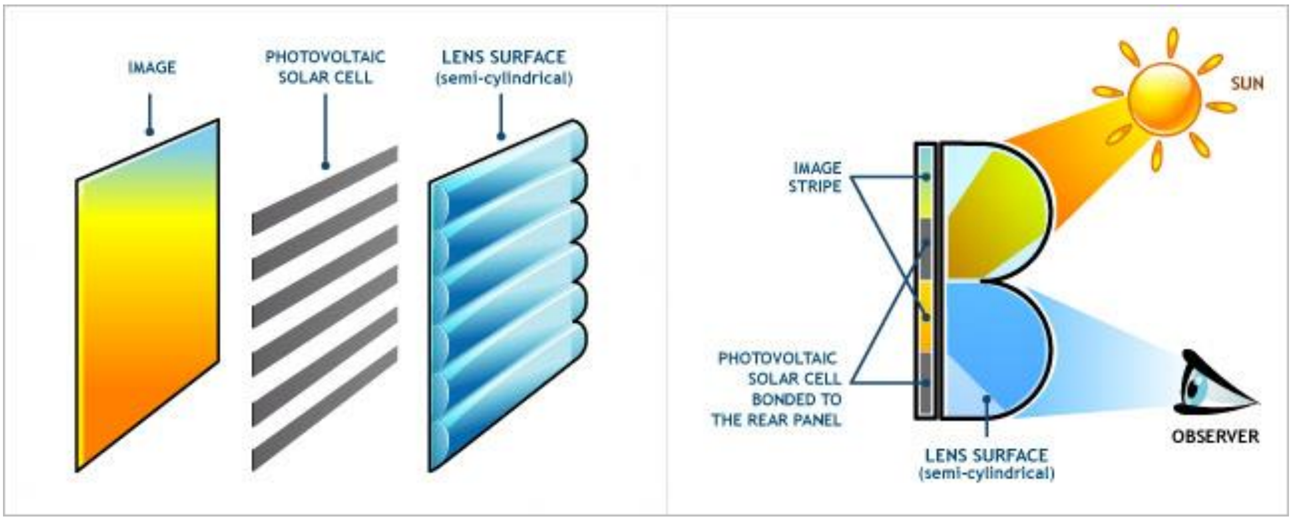


Figure 9 – SunPartners Wysips (What You See Is Photovoltaic Surface) technology

The basic idea of the Wysips technology is that the user looks viewing angle is always perpendicular to the screen and the user is therefore performing 2 axis tracking. Light coming from above is focused onto the solar cells while the light coming from the screen is visible to the user. The principle integrated into a smart phone display is shown below in Figure 10.

Figure 10 – Wysips PV system integrated into smart phone display.

SunPartner Group's screen collects solar power and delivers it to the phone. The module is a 300-micron-thick, solar cell module to fit under or on the touchscreen. SunPartner uses stripes of standard thin-film solar cells alternating with transparent film. Today amorphous silicon is used but any thin film technology could basically be used. It then adds a layer of tiny lenses that spread the image coming from the screen to make the opaque stripes disappear to the user and to concentrate rays coming in from the sun. The company claims to be able to integrate the PV lens platform in more or less any relevant transparent surface for harvesting energy while providing visual outlook and lighting transport and building integration into windows is mentioned though not on the market yet to the authors knowledge. The company seems to address smart glasses to power all kinds of smartness with the solar energy instead of buffered by integrated battery system instead of contributing to the buildings energy consumption by grid connecting the PV systems.

Based on the literature search and investigation of relevant optical PV systems on the market the project partners is strengthened in its believe of the relevance of this BICPV project. This exact market is addressed both by companies and through research and good solutions are developed. The obtained knowledge from the investigation is integrated into the work package of development of an optical system which is described in the coming section.

1.5.2 Development of the optical system

The optical concept is based on the strategy that the sun on the northern path of the hemisphere delivers most of its energy when it traveling over the sky from east to south and further to the west as shown on the image to the left below.

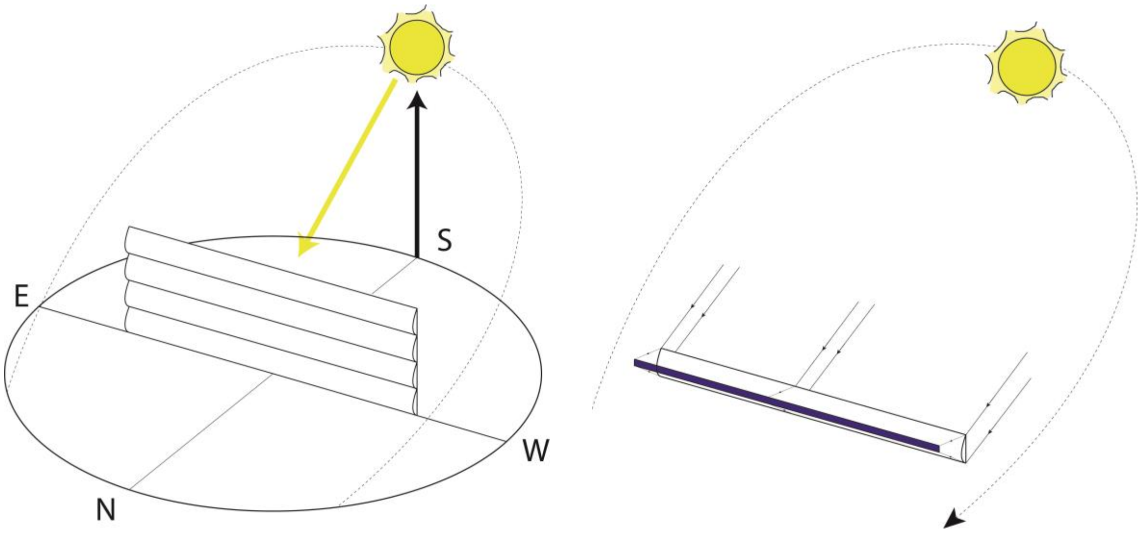


Figure 11 – Semicylindrical lenses oriented vertically towards south on the northern hemisphere.

During the day the sun will irradiate the panels from different sun heights being at the top point at noon. On Figure 11 to the right the focused light from one semi-cylindrical lens is shown to be of a stripe like nature. The focal plane is the plane where all the rays meet in a line. If the lenses are fixed and oriented towards south the focal plane moves vertically with the changing sun angles during the day. If solar cells should be placed in or close to the focal plane for energy harvesting the lenses or the solar cells need to move a bit vertically with as the sun travels over the sky during the day.

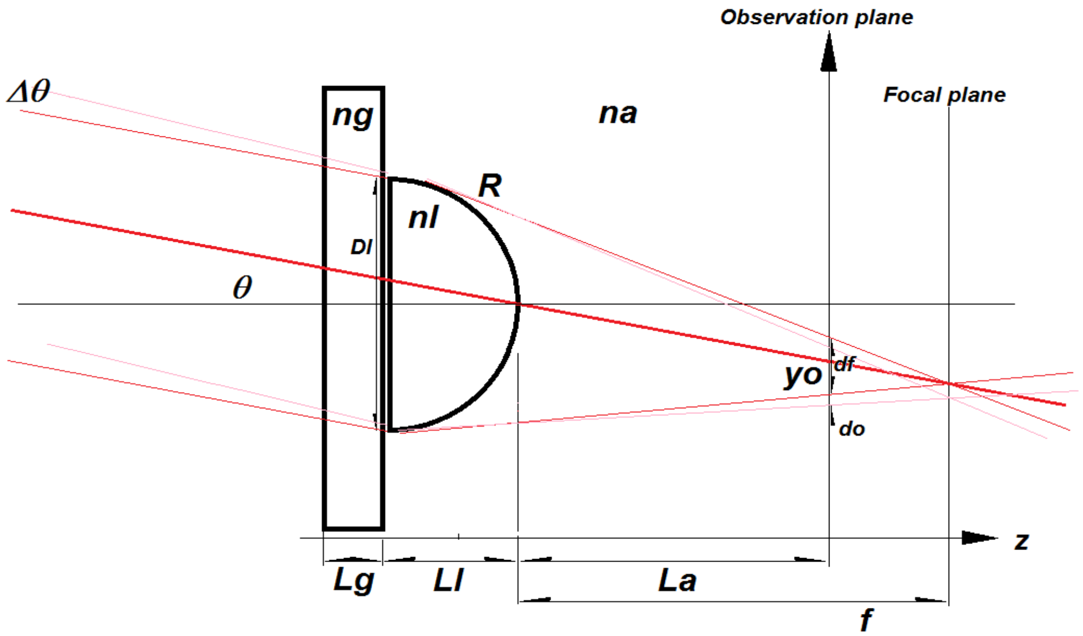


Figure 12 – The BICPV concept is realized mathematical in a model. The solar cells are placed in the observation plane a little in front of the focal plane to distribute the light over the solar cell surface.

To gain insight into the sizing of the components of such system and how it can be realized the best way, an optical model has been developed. Here, the lens diameter and the solar cell width relates to the optimal distance between the solar cell strips and the lenses. Furthermore, this optical model also describes the needed travel of the lenses (or PV cells) for keeping the concentrated light in the same plan during the day, and can calculate the width of the solar cell stripes as a function of acceptance angle. An overview of the model is shown in Figure 12. The model parameters are explained below in Table 1.

BICPV system	**Parameter**	**Start values**
The radius of the cylindrical lenses (m):	R	0.005
The refractive index of lenses:	nl	1.5
The diameter of the lenses (mØ):	Dl	0.01
The center thickness of the lens (m):	Ll	0.005
The paraxial focal length of the lens in air (m):	f	0.01
The thickness of the glass plate (m):	Lg	0.003
The refractive index of glass	ng	1.517
Distance to the observation plane (m):	La	0.013
The refractive index of air	na	1
Incoming light:		
Actual angle relative to horizontal (deg):	θ	66
Angular range (full width) for sun travels (deg.)	Bθ	10
Angular spread (half width) due to finite size of sun (deg.):	Δθ	0.5
Mean wave length (nm):	m	550
In the observation plane:		
Radius of spot due to defocus (m):	df	0.0015
Radius of spot due to finite size of source (m):	do	0.00011
Radius of spot due to diffraction (m):	dd	0.0000018
Total width (Ø) of the spot in the observation plane (m):	dspot	0.003
Actual position of spot relative to the optical axis (m):	yo	0.029
Total width covered by spot for angular range of sun (m):	wtot	0.0055

Table 1 – Parameters in optical model

Subsequently the equations have been implemented in the CAD model enabling the BICPV drawings to be visualized according to the model and it's parameters.

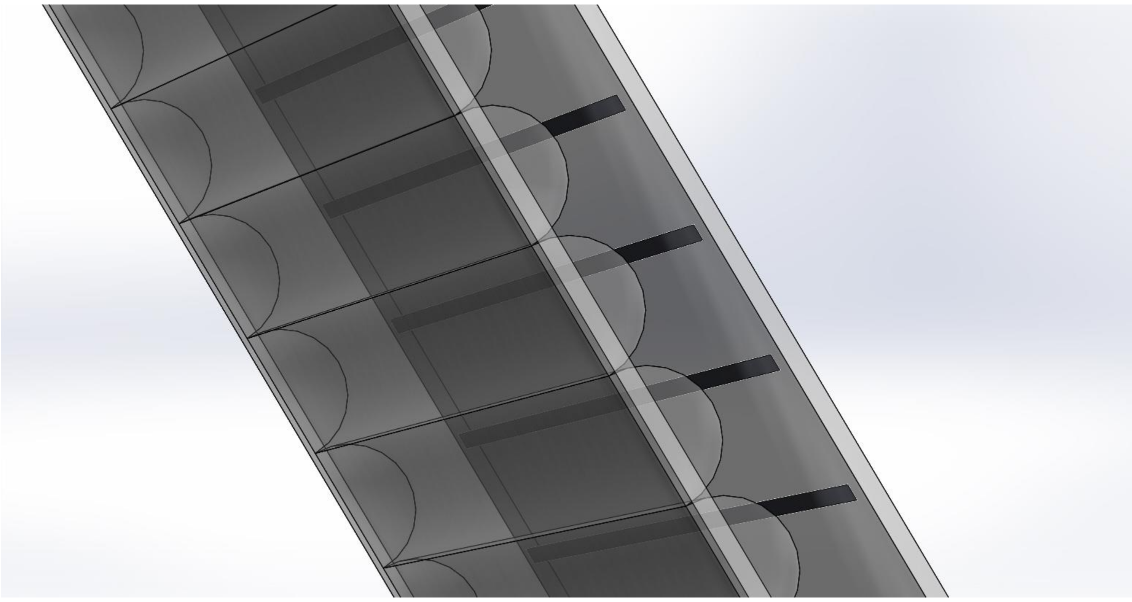


Figure 13 – SolidWorks sketch with some test parameters of the optical model.

The developed model tool is the cornerstone of the project and is used in the later sections to develop the full system. Using CAD software as a parametrical platform for realizing the optical equations directly into a visual mechanical presentation is a valuable approach, since it bridges well to the mechanical work packages.

1.5.3 Development of PV system

Since the systems scales with the lens diameter it was clear that it would be an advantage with long thins stripes of solar materials a few mm wide. Thin film solar cells are an obvious PV technology to look into since these already has been manufactured in lines on glass.

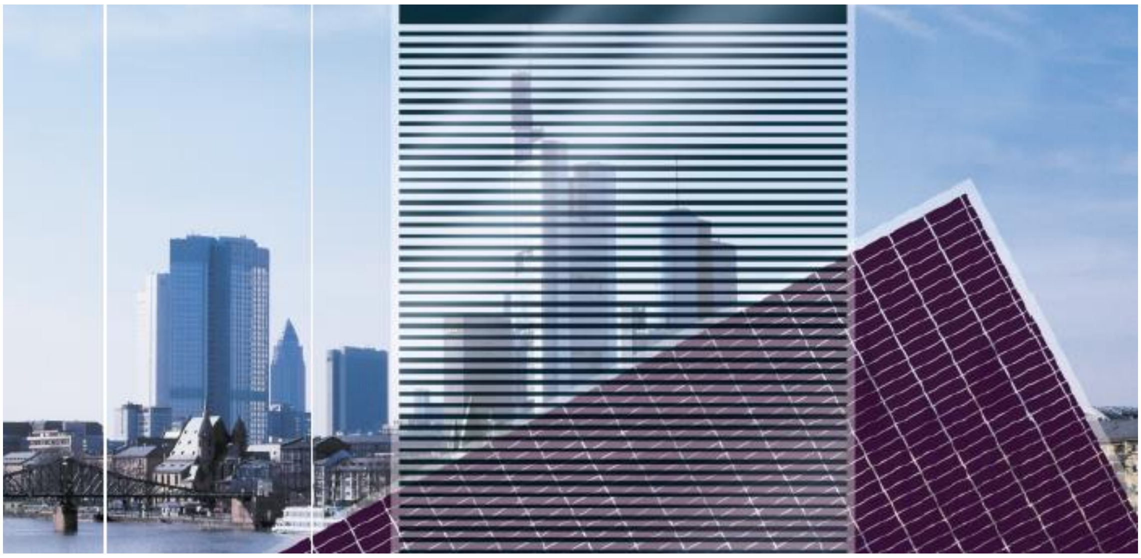


Figure 14 – Thin film solar cell integrated into a glass facade by SCHOTT Solar. The glass in the middle fits perfectly in the BICPV developed in this project.

Figure 14 shows a glass with amorphous silicon solar cells deposited in lines on glass used in windows and produced by SCHOTT solar in its product series ASI® Glass. These can furthermore be intergraded into double glasses for thermal control combined with shading and power generation. SCHOTT though seems to have left the PV business in 2012. I though show that it is perfectly viable to make a see through glass with thin film based lines on and a much more suited technology for the BICPV product is CIGS. CIGS cell made by NREL [16] showed the following performance under concentrated sunlight:

Suns	Voc (mV)	Fill Factor (%)	Efficiency (%)
1.0	647	76.3	17.9
1.67	666	77.2	18.7
2.28	677	77.9	19.1
2.93	686	78.4	19.5
3.76	693	78.7	19.8
4.36	700	79.4	20.2
9.46	722	80.6	21.1
14.05	736	80.5	21.5

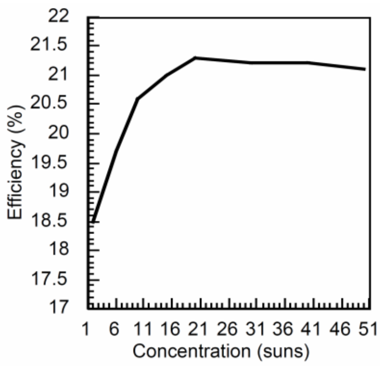


Figure 15 – Data from a CIGS solar cell made at NREL under concentrated sunlight. [16]

The cell has peak efficiency at 14.05 suns and seems to saturate at this level for unknown reasons. It is very promising that the cell reaches 20% at about C=4. The BICPV system proposed in this project is expected to have a concentration in the range of 3-7X. Several CIGS manufacturers have been asked if it is feasible to produce panels with thin CIGS lines and it is not a problem at all. In fact, there is an interest in this already for going to higher voltages for lowers loss in the grid integration process. The PV panel work package therefore ends with this proposed configuration as the rear glass in the BICPV sandwich structure illustrated for example in Figure 13.

1.5.4 Thermal management

Thermal modelling has been carried out, where a worst case scenario for Denmark is calculated, using parameters for worst cases, vertical insolation of 640 W/m^2, which correspond to the highest clear sky insolation, and with an optical amplification of 7. Such conditions will rarely happen for a long time – even on a sunny day the movement of the earth compared to the sun, will reduced the insolation due to the angular projection. As seen from the figures below, the Solar cell is estimated to reach a steady state temperature of around 100°C. A temperature of 100°C is acceptable, however it would be preferred if the temperature could be lowered. What can also be seen that the warm temperature is mostly confine to the solar cell stripe, and the temperature could potentially be lowered by choosing a more heat conducting substrate for the solar cells or doing other tricks.

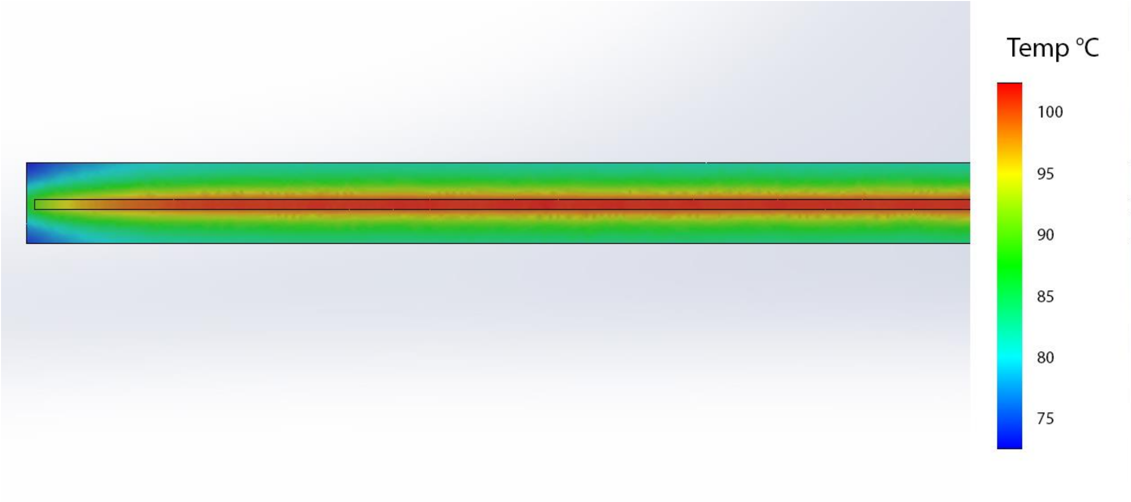


Figure 16 - Coarse thermal simulations using glass as substrate seen from front.

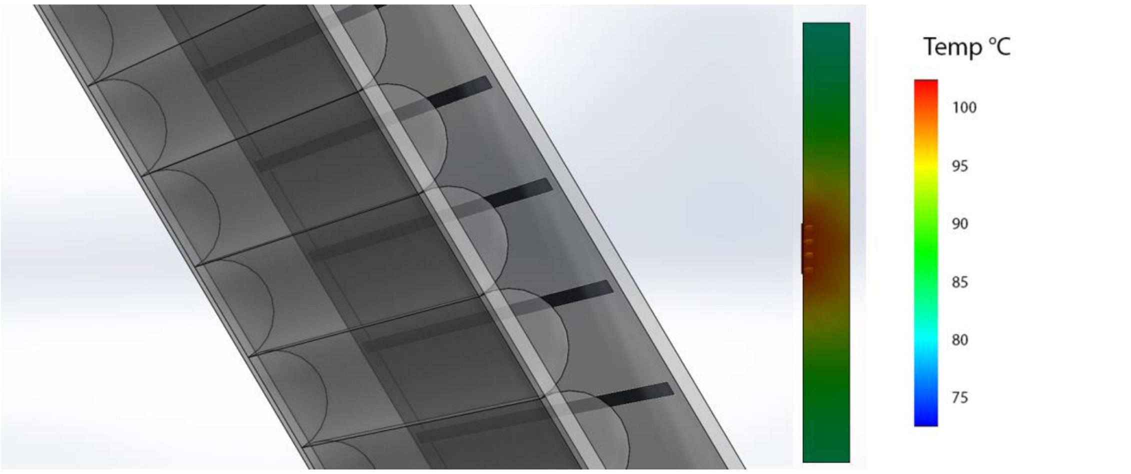


Figure 17 – Coarse thermal simulations using glass as substrate seen in cross section.

A simulation based on alumina as substrate with a 20 times larger conductivity than glass is shown below.

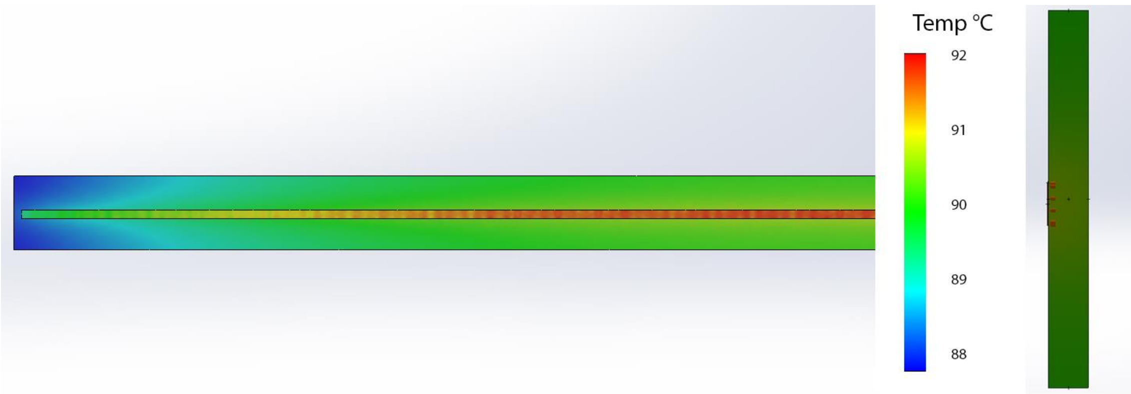


Figure 18 - Thermal simulation using the same parameters as before, but with alumina as substrate which have a heat conductivity that is 20 times larger than for glass. The

temperature is almost 10°C lower and the heat distributes much better. The cross section of the substrate (right) has an almost uniform temperature.

The simulations above, even though they are course, shows that the solar cell reaches a high but feasible temperature, for the worst case scenario, and some well-known engineering actions can be taken to lower the temperature.

1.5.5 Mechanical system design

The concept of the BICPV system involves 1-axis tracking vertically which is a rather complicated task to comply with a window element in a building. It has to work close to maintenance free for at least around 20 years. Developing a 1-axis tracker system for the BICPV from scratch will be a looser strategy since the risk of failure is too high. The project group has therefore looked at alternative systems already on the market, which can be fitted to work with the proposed concept. An attractive concept already involving a though rather primitive tracking systems is the venetian blinds integrated in a double glazing unit. Several companies produce such systems which has an integrated electrical motor system for lowering and raising the blinds and even tilting the blinds. The slat raising, lowering and tilting functions are achieved using a rotational magnetic transmission through the glass, guaranteeing the unit's hermetic seal. The mechanical systems are maintenance free and can be controlled programmed by remote control and can even be programmed to fit into building climate control systems. If the BICPV can be fitted to this platform it will be perfect for solving the mechanical system requirements.

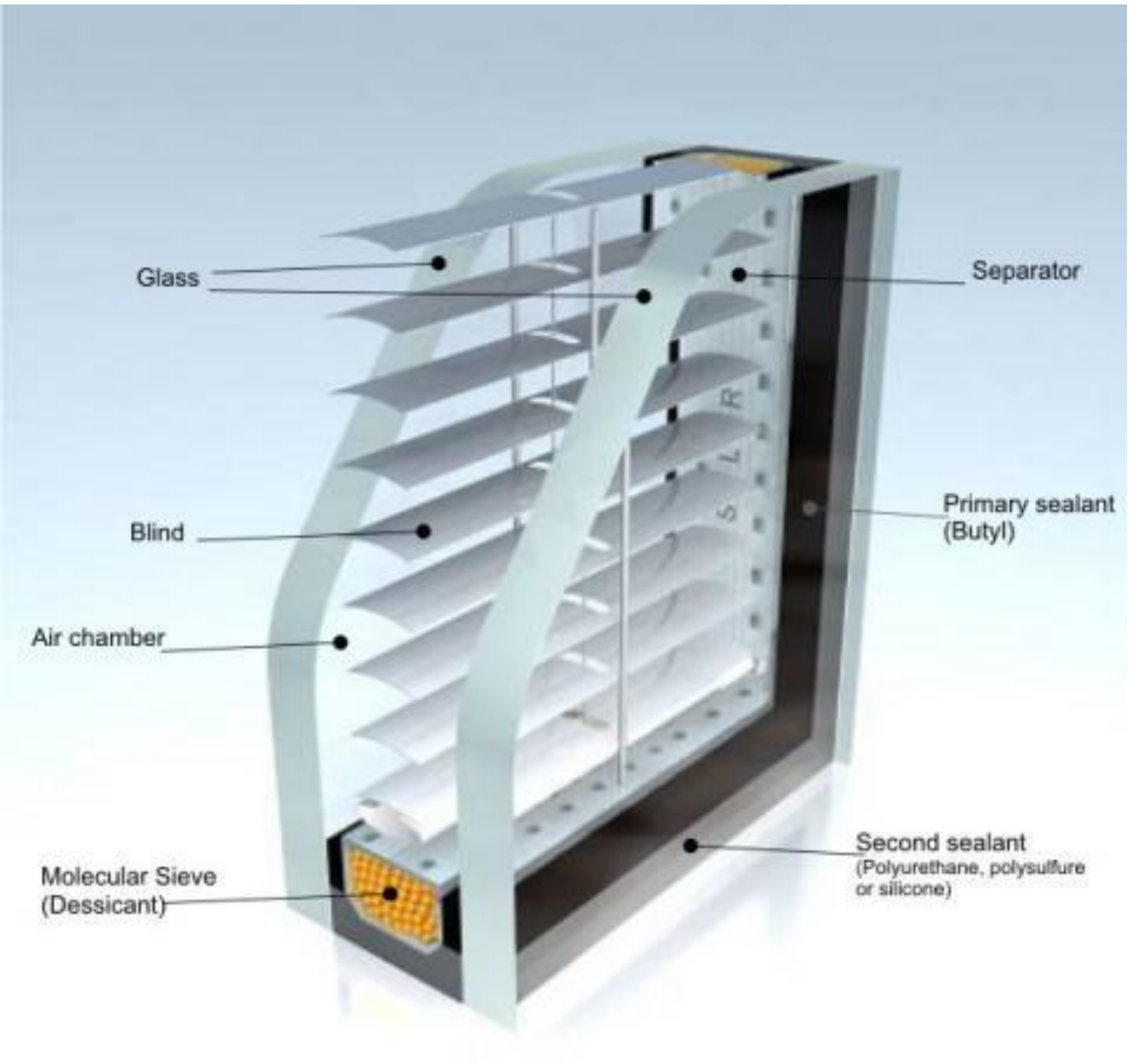


Figure 19 – Concept with venetian blinds integrated into double glazing units.

The concept is shown in Figure 19. For the BICPV systems to work with this it have to be modified so that the blinds become the lenses. The concept is shown below.

Figure 20 – Side view of the proposed BICPV concept

If the lens system is made of semicylindrical lenses the can easily replace the venetian blinds as shown in Figure 20. To keep the focal line in the same position, the lenses has to move up and down with the sun during the day. The BICPV principle has similarities to SunPartners Wysips concept and Stellaris optical principle though none of the other uses tracking. There are also similarities to especially the prism systems and the holographic concentrator found in the literature study in section 1.5.1. The proposed BICPV system in this work can definitely learn from these products and concepts since it might turn out more convenient to have the lenses made flat and be of the holographic, Fresnel or other types. The proposed systems is seen as a platform, where proof-of-principle is now shown but several obstacles can arise in the step towards the market, and it is a strength that e.g. changing the optical principle can give the same performance but change parameters in the systems relevant for production etc. Instead of moving the lenses up and down an optical system based entirely on tilting might be more feasible which requires another optical principle with e.g. one structure on the lens side facing the sun for focussing and another on the back side for guiding the light to the cells with rotation.

1.5.6 Building a Demonstrator

A physical demonstrator was built in a student project based on data from the mathematical model.

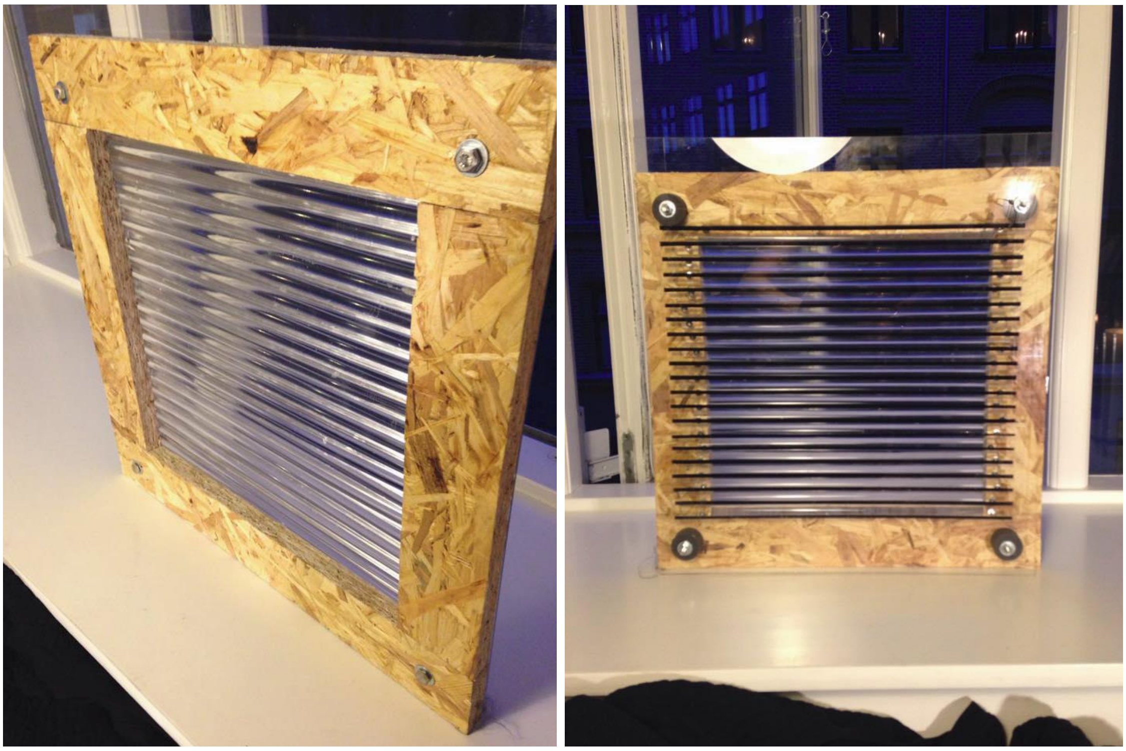


Figure 21 – Demonstrator of the Lens / PV line principle. Left: Front side towards the sun with the lens exposed. Right: View from the back-side of the system. The black lines illustrate the solar cell lines.

The demonstrator is of course passive but shows that the light focused onto the stripe when the light from the sun is at the right angle. The principle is shown by one lens in Figure 22 below.

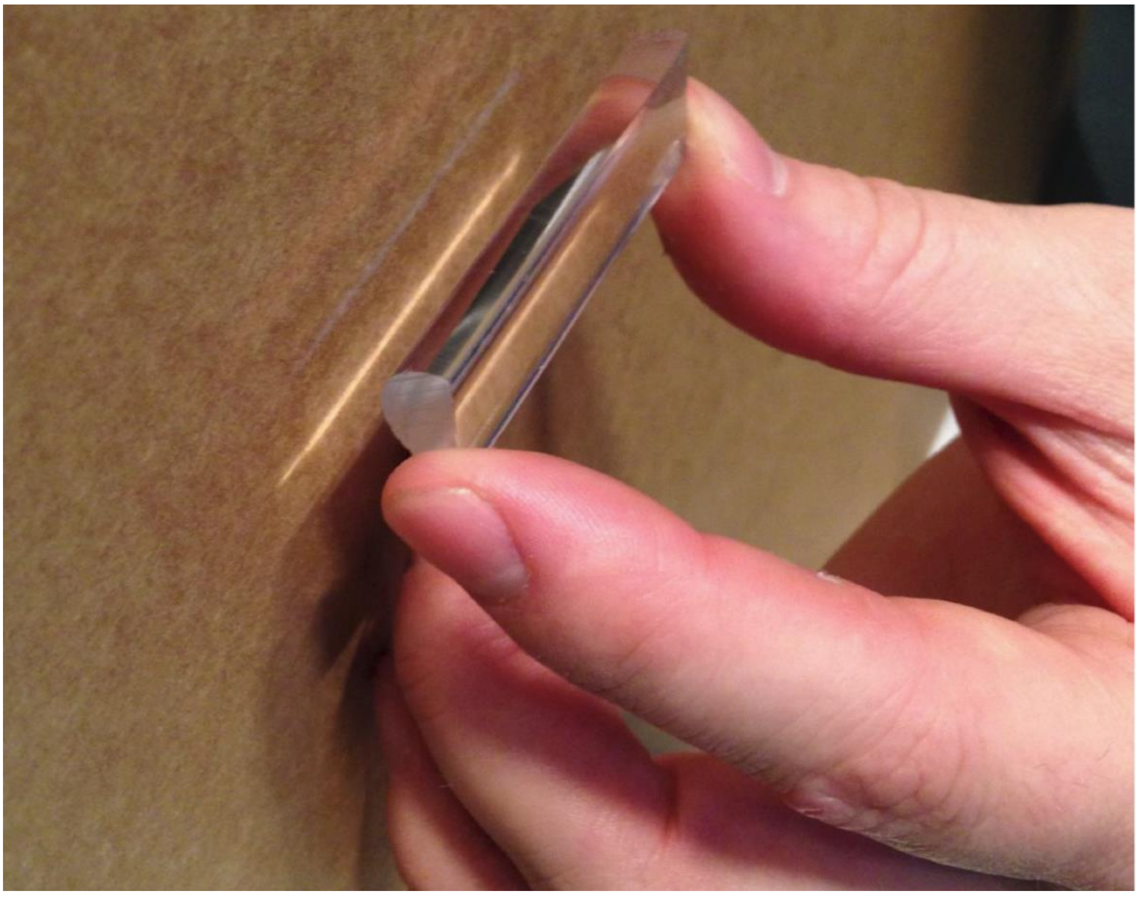


Figure 22 – Focused light by the semicylindrical lens.

A virtual demonstrator has also been made in SolidWorks and is shown below.

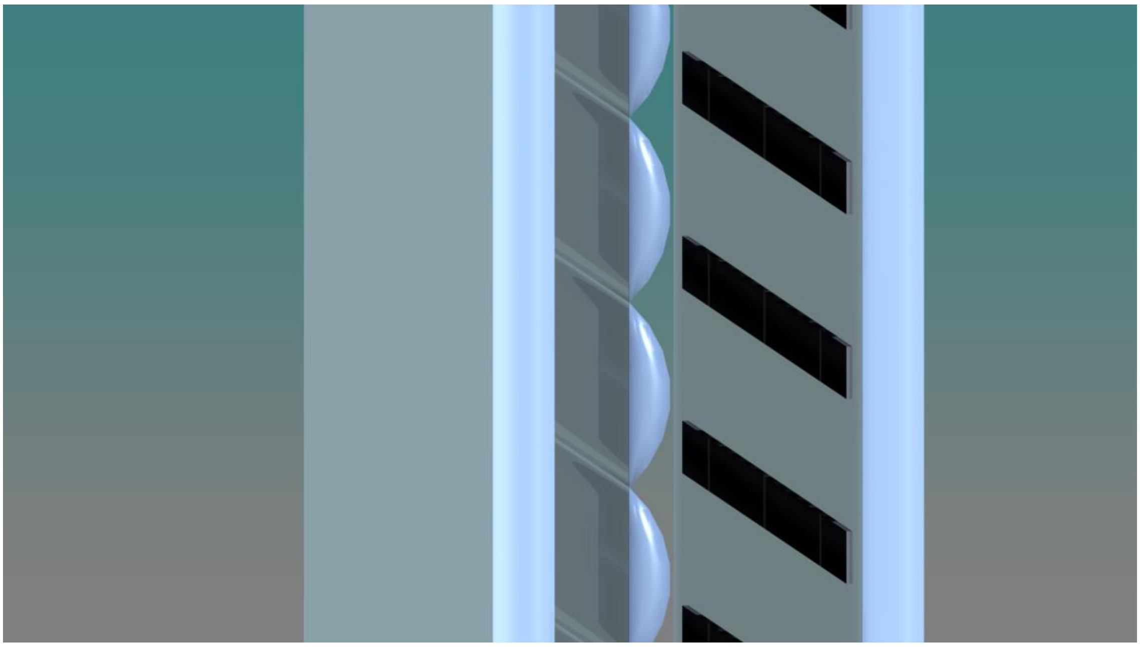


Figure 23 – BICPV virtual demonstrator – close up.

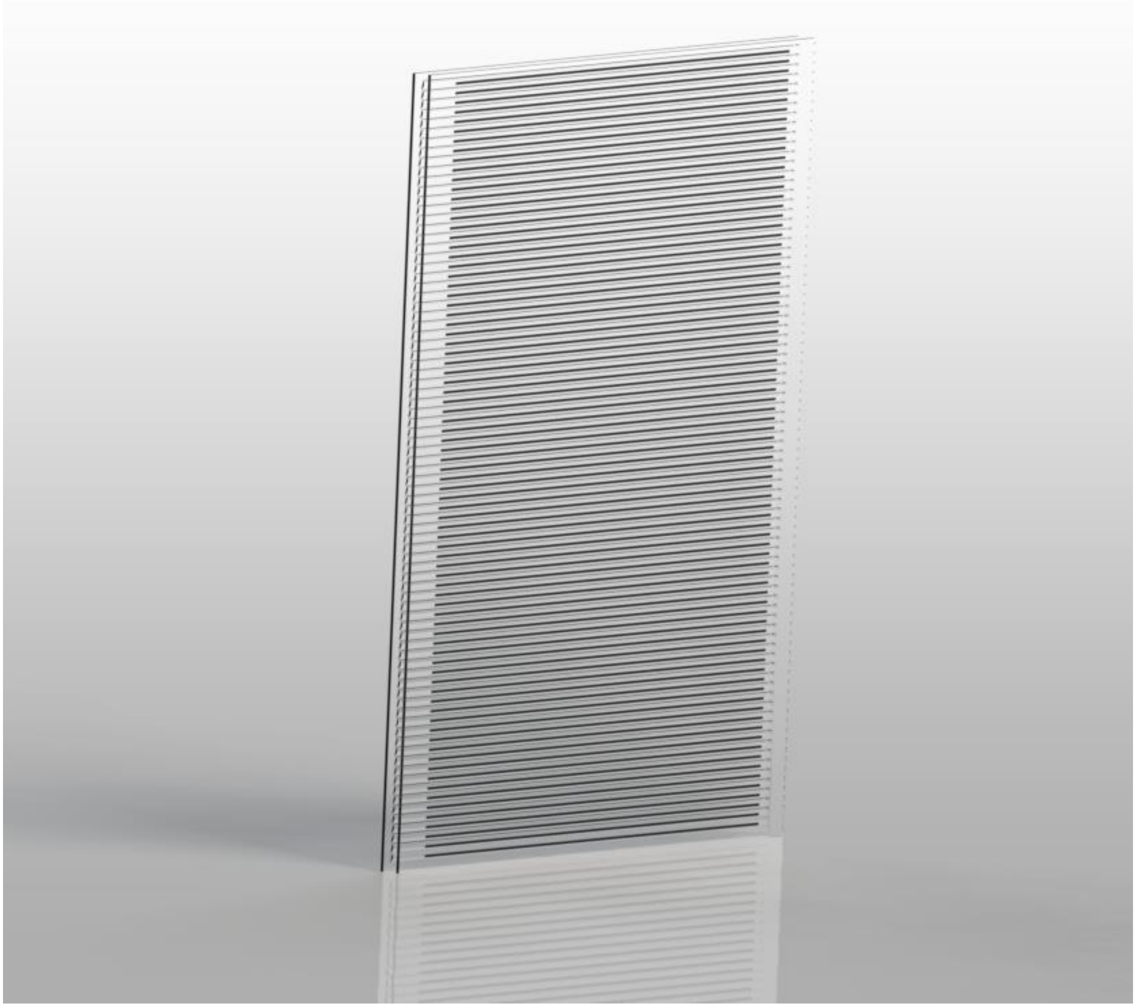


Figure 24 – BICPV virtual demonstrator – full pane.

Selected parameters used in the model is shown below in

BICPV system	Parameter	Value
The radius of the cylindrical lenses (mm):	R	8
The refractive index of lenses (PMMA):	nl	1.5
Lens height (mm)		12
The center thickness of the lens (mm):	Ll	2.7
Distance to the observation plane (lens middle to PV) (mm):	La	13.29
Distance from lens plane to PV (mm)		16
PV pitch (mm)		12
PV line width (		3.4
Concentration Factor (X)	C	3.5
Max displacement (mm) @ sun height = 56°		19.7

Table 2 – BICPV parameters and values

The values of the parameters are fitted so it fits well in size of traditional windows. The longest distance the lenses have to travel up and down is 19.7 mm where the sun height is at 56° which is the highest point on the Danish sky. This is compatible with the venetian blind system proposed for using as a platform for the system. The concentration factor of the selected parameters is 3.5. Solar irradiation data for Copenhagen over the year is shown in Table 3.

Month	H(90)	D/G	Direct	Diffuse
	Wh/m^2/day		Wh/m^2/day	Wh/m^2/day
Jan	1040	0.7	312	728
Feb	1650	0.66	561	1089
Mar	3430	0.51	1681	1749
Apr	3950	0.39	2410	1541
May	3430	0.4	2058	1372
Jun	3210	0.41	1894	1316
Jul	3330	0.42	1931	1399
Aug	3320	0.45	1826	1494
Sep	3340	0.5	1670	1670
Oct	2610	0.56	1148	1462
Nov	1240	0.66	422	818
Dec	812	0.73	219	593
Year average	2620	0.45	1344	1276

Table 3 – Solar irradiation data for Copenhagen on a vertical surface oriented towards south. (Source: PVGIS-CMSAF)

H(90): Irradiation on plane at angle: 90° oriented towards south (Wh/m^2/day)
D/G: Ratio of diffuse to global irradiation
Direct: Direct irradiation on a plane at angle 90° oriented towards south (Wh/m^2/day)
Diffuse: Diffuse irradiation on a plane at angle 90° oriented towards south (Wh/m^2/day)

Compared to a flat panel PV if the NREL thin film solar cell (Figure 15) was used in lines the production would have been:

Flat panel: 17.9% efficient CIGS – 170 kWh/m^2/year
BICPV: 19.7% efficient CIGS – 100 kWh/m^2/year

The energy production with the current BICPV composition is estimated to produce about 60% of the energy of a flat panel. The solar cell area is though reduces to only 28% of compared to a flat panel. The cell area in the BICPV therefore generates twice the amount of energy pr. area over a year than for a flat panel of the same size. From Table 3 it can furthermore be seen that the BICPV window functions very well for daylight control since only the diffuse light penetrates into the building which is a higher factor in the winter than in the summer. Therefore the light is more or less stabilized over there year since the direct part of the solar irradiation is huge during the summer and all is blocked by the solar cells.

1.5.7 Market potential research

The project has focused on the technical feasibility study and the market research has been done by interviewing companies about their interest in a product like the proposed BIPCV system. Scanglas (owned by Saint-Gobain) showed interest in the product and the product idea was pitched to several architects and glass companies. The solutions seems to be well suited for lighting control by energy harvesting in the architecture for light transportations into the building where visual information less relevant than day light since the visual impression is distorted by the lenses. In the growth house business the concept has been very well received for lighting control for plant growth.

1.6 Utilization of project results

The project is a feasibility study primarily oriented towards showing the technical feasibility of the proposed BICPV concepts of focus in this project. The proposed concept seems very feasible – especially due to its piggybacking on the technology of motorized venetian blinds integrated into double glazing systems. The concept is patent pending and if it is granted the market will be addressed through Scanglas in Denmark teaming up with producers of the venetian blind systems in double glazing and securing sales in higher end markets where customized solutions before economy of scale can bring the concept in a more standardized volume market. The patens process will be followed by a go-to-market strategy.

It is imparted in then national solar cell strategy that Denmark should be on the forefront when it comes to BIPV. The BICPV concept proposed in this project fit very well with the strategy. 40% of the worlds energy is used in the building mass and the integration of solar cells in the climate control of the building contribution to it's own energy consumption is obvious. The multifunctionality of the BICPV working as daylight/climate control, building envelope and electrical energy producer from the blocked surplus sunlight makes it a potential attractive building component.

No PhD has been included but on the educational side the project has been used as case in the 10 ECTS point masters course Spring 2015 | 41633 Innovation and Product Development. A big thanks to the students: Jesper Byrdal Kjær, Lotta Ahonen, Denis Kirchhübel, Mathias Herlev, Bjarke Vad Andersen and Emil Gram Spork, for investing the business potential of the BICPV technology with focus on exploiting the technology for light environmental control for commercial greenhouses.

1.7 Project conclusion and perspective

A BICPV concept has been investigated for use as daylight/climate control, building envelope and electrical energy producer from the blocked surplus sunlight by utilizing the direct sunlight blocked by solar cells and transporting the diffuse light into the building for use as daylight. A BICPV system is proposed in this work substituting venetian blinds in a double glass window with semicylindrical lenses and by raising and lowering the lenses with the sun traveling over the sky light the direct light can be focused on lines of solar cell materials on the inside glass towards the building with a thin film solar cell on the inside of a e.g. gas filled double glass window. A composition giving a concentration factor of C=3.5X is shown by optical modelling to use 28% of a flat panel solar cell area to produce 60% the energy thereby production twice the amount of energy pr. Solar cell area under Danish condition vertically oriented south. The concept is patent pending and a go-to-market strategy will be executed by the partners if granted. The concept is seen as a platform with many development and adaption possibilities, since the lenses can have other properties than the proposed for other purposes or optimization of the system for cost, size, advanced daylight control or other relevant parameters.

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