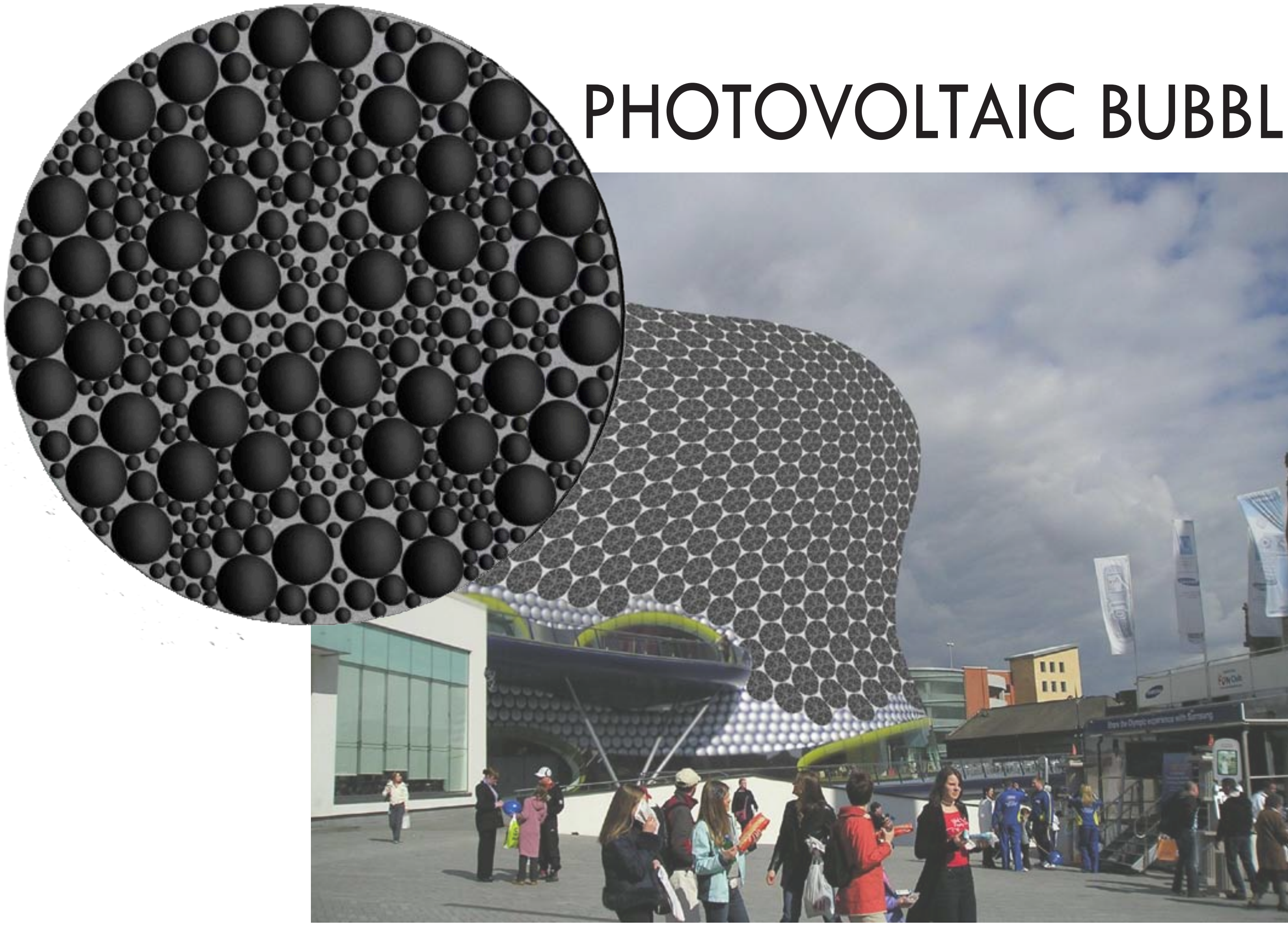
PHOTOVOLTAIC BUBBLE MODULE



BACHELOR THESIS

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13 January 2011

ENEA

UNIVERSITEIT TWENTE.

BACHELOR THESIS

“Photovoltaic bubble module”

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FOREWORD

You just started reading the report about my bachelor thesis at Twente University.

For this thesis, I went to Naples in Italy to design a so called “photovoltaic bubble module”. Near Naples ENEA in Portici is situated and there I have worked on my research to photovoltaics and my design of the Bubble module. ENEA is a research center to photovoltaics and therefore was the optimal working environment because of all their experience.

I have learned a lot about the subject and working and living abroad was a very instructive contribution to the total learning experience.

I would like to start with thanking my boyfriend, my parents and my friends in Naples and in the Netherlands for listening and motivating me when I needed it.
Then, I would like to thank my mentor at ENEA, Alessandra Scognamiglio, who was very helpful at every moment. Especially the building analysis phase I could not have done without her help.
I also want to thank Angele Reinders for her help from the Netherlands in every phase of the project.
For the analysis, I have done an interview among architects and I want to thank them for their collaboration.
Lastly, I want to thank AIESEC Napoli Federico II for their help during my first days in Naples and for giving me the possibility to meet a lot of new Italian and International friends.

SUMMARY

ENEA in Portici develops new products in the sector of technologies for energy saving and new energy sources in photovoltaics. Together with the University of Twente, the purpose is defined to develop a new PV module, which can be integrated in current architecture.

In chapter one, two, three and four, analyses of all information that is needed to design the new module are done. The working of PV is been studied in order to get to know some understanding of this technology. The ins and outs about power generation are studied, so that the power generation of the PV bubble module could be calculated, and to be able to make the electrical scheme. The financial aspects have been researched so that an estimation of the costs could be made. Of course the composition of a PV module and a PV system is listed and the positioning of PV modules is been researched so that the knowledge about this important aspects can be used in the new design. The electrical and mechanical requirements given by the International Electrotechnical Commission are listed and the requirements according the aesthetical performance given by the International Energy Agency are listed. Then, a small market research to the current innovative products has taken place in chapter four.

In chapter five new information is acquired by an interview about the wishes of architects, the selection of a material and an analysis of Blob buildings has been done. All this information, together with the analyses of chapter one, two, three, and four results in a list of requirements. The next step was to generate concepts in chapter six.

The one that meets the requirements the best, was chosen. This is the concept called “Round” and it consists of round modules and connection parts. The connection parts connect three modules to each other and take care of the wire-connection between the modules. The elaboration of this concept is done in chapter seven, where the renders electrical schemes, material selection and explanation about the working can be found.

The result is a concept for a PV bubble module, which can be applied on the envelope of Blob architecture. But, in order to be able to commercialize the product, more research should be done to the working of the spherical cells, the electrical connection of the cells and of the modules, the production methodology, the maintenance of the product and the specific mechanical aspects.

SAMENVATTING

ENEA in Portici houdt zich bezig met het ontwikkelen van nieuwe technologieën voor energiebesparing en nieuwe energiebronnen in de fotovoltaïsche sector. Samen met de Universiteit Twente is de doelstelling vastgesteld om een nieuwe PV-module te ontwikkelen, die geïntegreerd kan worden in de huidige architectuur.

In hoofdstuk een, twee, drie en vier, zijn analyses gedaan van alle informatie die nodig is om de nieuwe module te gaan ontwerpen. De werking van PV is onderzocht om inzicht te krijgen in deze technologie. De details over de energieopwekking zijn bestudeerd, om uiteindelijk de elektriciteitsproductie van de PV bubble module te kunnen berekenen en om het elektrisch schema te kunnen maken. De financiële aspecten zijn onderzocht, zodat een schatting van de kosten kan worden gemaakt. Verder is natuurlijk de opbouw van een PV-module en een PV-systeem uitgezocht en de beste manier van positionering van PV-modules is onderzocht, zodat deze kennis later gebruikt kan worden in het nieuwe ontwerp. De elektronische en mechanische eisen die door de International Electrotechnical Commission zijn opgesteld zijn weergegeven en de eisen betreft de esthetische aspecten die zijn opgesteld door de International Energy Agency zijn gegeven. Verder is er een klein marktonderzoek gedaan naar innovatieve producten.

In hoofdstuk vijf is nieuwe informatie verkregen over de wensen van architecten door middel van een interview. Verder is er een materiaalselectie en een analyse van de Blob-architectuur gedaan. Al deze informatie, samen met de analyses van hoofdstuk een, twee, drie en vier, resulteert in het programma van eisen. De volgende stap was om in hoofdstuk zes concepten te genereren.

Het ontwerp dat het best voldeed aan de eisen die eerder waren gesteld, werd gekozen om uit te werken. Dit is het concept genaamd “Round” en het bestaat uit ronde modules en verbindingsdelen. De verbindingsdelen zorgen ervoor dat drie modules aan elkaar worden verbonden en zorgen ervoor dat de bedrading aan elkaar wordt gekoppeld. De uitwerking van dit concept gebeurt in hoofdstuk zeven, waar de maattekeningen, elektrische schema’s, materiaalselectie en uitleg over de werking kan worden gevonden.

Het resultaat is een concept voor de PV bubble module die kan worden toegepast op Blob-architectuur. Wanneer men het product wil commercialiseren, moet er echter nog wel meer onderzoek worden gedaan naar de werking van de bolvormige cellen, de elektrische verbinding van de cellen en de modules, de productiemethode, het onderhoud van het product en de specifieke mechanische aspecten.

CONTENTS

INTRODUCTION

ENEA is the name for the Italian National Agency for New Technologies, Energy and Sustainable Economic Development. ENEA in Portici is doing research and is developing new products in the sector of technologies for energy saving and new energy sources in photovoltaics. An important activity of the department in Portici is the development of various photovoltaic (from now on abbreviated to "PV") modules that could be used for several purposes in buildings, because of their great potential in the electricity production market. But the aesthetical quality of most of the current PV modules is not very high. The University of Twente and ENEA have entered a collaboration a few years ago. Assignments are defined and students from the UT are getting the opportunity to help ENEA with their issue within the framework of their Bachelor thesis or internship. The objective of this assignment is defined in a paper called "Thin film PV bubble modules for architectural integration" (Scognamiglio, A. Delli Veneri, P. Mercaldo, L.V. and Reinders, A.H.M.E., 2009) and is to develop a new PV module, which can be integrated in the current (Blob) architecture and has high architectural quality. In short, Blob the word for buildings that are curved in more than one direction. The new module will be called PV Bubble module, because sphere cells that are already developed by ENEA will be used and because the modules are designed to be able to apply them on the envelope of Blob architecture.

In order to achieve the goal of developing a PV bubble module that is able to integrate with the current Blob architecture, a lot of steps needed to be taken. Roughly this can be divided in seven parts.

In the first four chapters a literature research has been done.
First, there is done research to the working of all different kind of PV cells and their properties.
Then, in chapter two, the construction, electrical aspects, aesthetic aspects and financial aspects of PV modules are being investigated.
The third chapter goes one level upwards to the PV system. In this chapter everything that has to do with total PV systems, is described. This starts with describing how PV modules are connected and how an inverter works. Then de different levels of integration are listed. Next, the best positioning of a PV module is calculated. Finally, the requirements according PV systems that are already defined by the International Electrotechnical Commission, the International Energy Agency and the Dutch and Italian government are described.
In chapter four the innovative products that are already on the market and their advantages and disadvantages are listed.

The fifth, sixth and seventh chapter will no longer be literature research. In these chapter new information will be generated in order to finally create a new PV module.
The requirement are defined in chapter five. Here you can find a survey held by the IEA. The conclusion is that a new survey should be held in order to get more information about the wishes of architects concerning the integration of PV in buildings. So this is also done.
After that, the material of which the module should be made is selected. The next step was to define the requirements for the PV bubble module by using all information that was already gathered in the last four chapters. Lastly, several Blob buildings are being analyzed, in order to get to know more about their features.
In chapter six, concepts are generated and one of them is chosen. This final concept is developed in chapter seven. The positioning of the spherical shaped PV cells in the module is determined, the electrical scheme has been drawn and the connection between the modules is set. Finally you can find the dimensional drawings and renders of the PV bubble module and the final design is tested whether or not it meets the requirements that were defined before.

1. PV CELLS

For the word photovoltaic the abbreviation “PV” is often used. Photovoltaic modules are also called photovoltaic panel or solar panel. It are all words for an interconnected assembly of photovoltaic cells. Because of the fact that only one PV module does not generate enough current, mostly more PV modules are connected in a photovoltaic system. This can be used to generate and supply electricity for private or commercial purposes.
In this chapter there will be started with the working of PV cells and especially thin film cells will be given extra attention.

1.1 THE WORKING OF SOLAR CELLS

The types of PV cells can roughly be separated in two categories: crystalline and thin film. Thin film PV has approximately 15% market share; the other 85% is crystalline PV (Photon International, 2009). The built up of crystalline and thin-film solar cells will be described below.

1.1.1 Monocrystalline and multicrystalline

As said, there are two major types of crystalline silicon solar cells: monocrystalline and multicrystalline, also called polycrystalline. Monocrystalline is made from a thin slice of a single crystal obtained from pure molten silicon. Multicrystalline cells sets as a large irregular multicrystal as it cools, and is then cut into thin square slices to make individual cells. These slices can be fitted in a module and fine contact fingers are used to conduct the electric current away.

Silicon in its pure state is an intrinsic semiconductor because at low temperatures its valence electrons are tightly constrained by bonds but when it gets in contact with energy such as heat or light, the bonds can be broken and the electrons are free to migrate through the lattice. Shining light on the crystal produces broken bonds and then the silicon becomes a conductor. The more bonds are broken, the greater its conductivity. An electron that has broken free wanders through the lattice and it leaves behind a broken bond, with a positive charge, known as a hole. When electrons jump into vacant spots, a hole moves through the crystal as a positive charge (See figure 1). If two contacts are attached and an external voltage is applied by using a battery, current will flow due to free electrons will move one way through the holes. This mechanism is shown on figure 2 and is named the semiconductor p-n junction. (Paul A. Lynn, 2010)

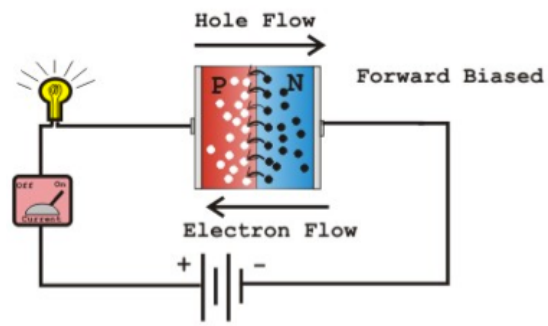


Figure 1: electron flow

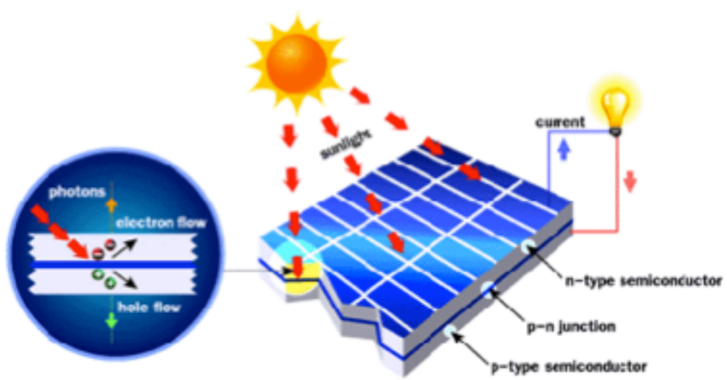


Figure 2: p-n junction

1.1.2 Thin-film PV cells

In figure 3 the build-up of an amorphous silicon PV cell is showed.

Making a thin-film cell starts by taking a superstrate or substrate, which is the name of the front- or backside of the module, which can be metal, glass or plastic. The next layer is a layer of amorphous silicon, copper indium diselenide (CIS) or cadmium telluride (CdTe), which is used as the semiconductor material. This semiconductor layer is deposited on the super- or substrate (S. Roberts & N. Guariento, 2009). The term “thin film” owes its name to this method of ‘depositing’ the film. The layers are applied in strips in order to achieve the inter-cell connections.

Thin-film modules do not have a metal grid for the top electrical contact. Instead, it uses a highly transparent conducting oxide, such as tin oxide. They conduct electricity very well. Unless the transparent conducting oxide serves the function of antireflection, an antireflection coating is needed on the top of the conducting oxide layer. (www.daviddarling.info)

To provide mechanical strength and the electrical connections, the solar cells are encapsulated in a layer of ethyl vinyl acetate (EVA). The top is covered by glass or plastic and to maximize light transmission, it is sometimes treated with an antireflection coating made of silicon nitride or titanium oxide and this makes the appearance dark blue. Sometimes for aesthetic reasons the antireflection coating is left off so the cells will stay natural dark grey, although a disadvantage is that reflection losses increase from 3% to 30%.

Underneath the PV cells a sheet of a synthetic polymer like Tedlar is situated, to protect the cell from fluids and chemicals.

Most PV modules are provided with aluminum frames to support structure and to simplify attachment to the roof. Only when reflections are undesired, modules without frames are preferred.

Thin-film technology is an aesthetically suitable cladding material. The modules cost less than crystalline silicon modules and standard thin-film modules are available in a variety of sizes. (S. Roberts & N. Guariento, 2009). Most of the commercial production of thin film solar is cadmium telluride, with an efficiency of 11%. (Photon International, 2009).

ENEA developed a curved solar cell by depositing thin film amorphous silicon layers on circular slightly curved borosilicate glass. These glass substrates are on the market in sizes ranging from 40mm to 250mm. Then the cells are deposited on transparent plastics and finally the cells can be electrically connected in PV modules.

A remark needs to be made. The technologies used need to have some improvement before it can be used. The thickness of the amorphous silicon layer and its electrical conductivity reveal a strong disuniformity in thickness. This can be caused by the varying spacing between substrate and power electrode. So before the cells will be usable, an improvement of the thickness uniformity is necessary in order to realize this kind of PV cells.

(Scognamiglio, A. Delli Veneri, P. a.o., 2009)

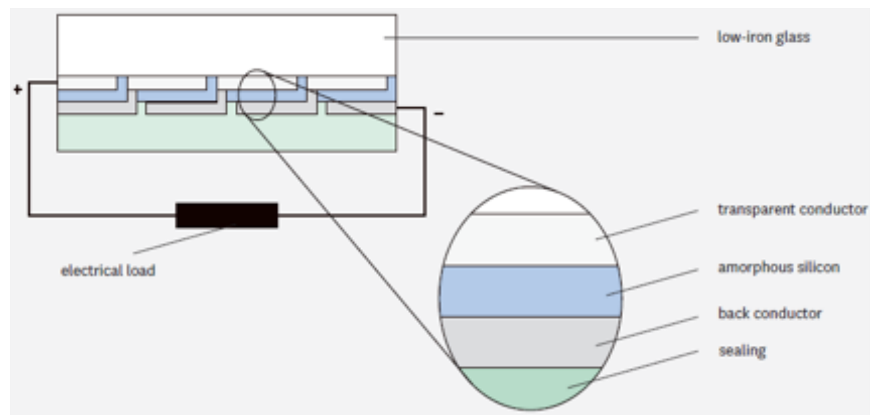


Figure 3: build-up amorphous silicon PV cell

2. PV MODULES

2.1 CONNECTING PV CELLS IN A MODULE

In the previous part of this chapter the working of PV cells was explained. In short, a PV module is made by connecting PV cells in a string and placing them in a frame.
When talking about PV modules, most people firstly think about the standard square, flat, dark colored PV module, which is showed in figure 4. This exterior features have its origin in aerospace and was directly adopted from there. Later, man started to pay attention to the aesthetics for the use on earth. Nowadays, more and more innovative PV products are introduced to the market. Some of them are shown in chapter four.
The dimensions of PV modules are various. They are available in the sizes of 0,25 square meter up to about five square meters. The thickness can vary from about one millimeter to about forty millimeters. Of course the weight varies and depends on the size and thickness of the module. The modules are dark colored, mostly black, grey or blue.
The cells in a thin-film PV module are connected by ribbon. This is a wire rolled from round copper that is burr-free. It is also been coated,

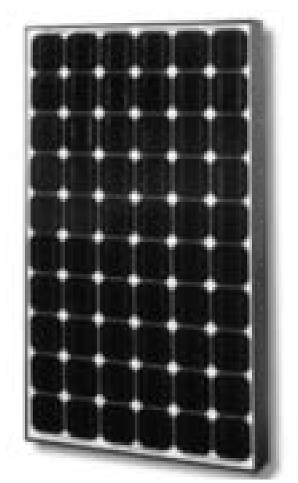


Figure 4: Lumos LS250 black frame

to ensure protection against corrosion or interaction with PV module encapsulants (www.enlog.us).

2.2 GENERATING CURRENT

A string of PV cells is called an array. It is important to make arrays of cells that are able to generate the same amount of current, which is determined by the irradiance and tilt, because the resulting current will be determined by the minimum. This rule also counts for arrays into a module.
Keeping the effect of connecting arrays with different current energy low, is a reason for designing modules that are not or only slightly curved. Because when modules are curved, they will catch sunlight from different directions that decreases the total generation of electricity.
Further, it is important to keep zones sufficiently large, because the zones are divided in the amount of current they generate and every different zone needs a separate inverter. In the next chapter, more information about inverters can be found. The second reason for keeping the module large, is that having a low number of connections between the individual modules means decreasing the chance of mismatches.

Formulas cells connected in series: U_{total} = number of cells * $U_{one\ cell}$. And $I_{total} = I_{one\ cell}$.
Formulas cells parallel connected: I_{total} = number of cells * $I_{one\ cell}$. And $U_{total} = U_{one\ cell}$.

Figure 5: formulas current and voltage

PV modules can be bought in different kind of voltages, for example 12, 16 or 20 V. The number of cells you need in a PV module depends on the kind of cells and how many there are connected in series. The current and voltage a cell produces, differs per sort of PV cell. For example, a crystalline PV cell produces 3W at 0.6V DC. So the current is (3/0.6) = 5A. To realize a higher power unit and a higher voltage, thirty or more PV cells are connected in series and parallel and together they form a PV module. In order to realize high voltage, cells are connected in series. The power will be made high enough by connecting these strings parallel. For the formulas of cells connected in series and parallel, you are referred to figure 5. In the example of using crystalline cells, a PV module of 6V, 4A can be made by putting (6V/0.6V=) 10 cells in series, and (4A/0,5A=) 8 cells parallel.

The voltage generated is direct current (DC) and can be used to charge a battery when putting it on its two output contacts. When using a PV inverter (figure 7), the DC current can be converted to alternating current (AC) and then it can be used on the grid. The (nominal) power output of photovoltaics is usually described in kilowatt peaks (kWp). (Paul A. Lynn, 2010)

This power rating is given by the manufacturer of the module or system. It is the power output of the module measured at 1000W/m2 solar irradiance, a module temperature of 25°C and a solar spectrum corresponding to an air mass of 1.5, all tested under Standard Test Conditions. (www.re.jrc.ec.europa.eu). If you want to calculate the voltage, the illumination, system losses, slope and azimuth, this is the horizontal angular distance from the northern point of the horizon, need to be taken into account.

2.3 AESTHETIC ASPECTS

Cells based on CIS and CdTe have a dark brown to black appearance because they are designed to reflect a minimum of light to produce maximum electricity. Other colors can be obtained by varying the thickness of the anti-reflection coating, and by treating the glass or plastic that supports the PV module with certain techniques, different textures can be obtained. But of course the reflection will increase and efficiency will decrease by 15–30% depending on the color. Cells which are custom made like this can be two or three times the price of normal cells. It is also possible to make flexible and curved thin film PV modules.

2.4 EFFICIENCY AND PRICE

The efficiency of thin-film cells is lower than for crystalline silicon technology and of course a lower efficiency means a larger area is required to achieve the same power. But on the other hand, crystalline silicon is more expensive. (S. Roberts & N. Guariento, 2009)

Over all it can be said that prices of PV panels drop every month. In October 2010, the average price for monocrystalline and polycrystalline silicon PV was €3,2 per watt. The lowest price found in October for thin film modules is €1,0 per watt. Amorphous silicon is in generally 0,5 times the price of mono and polycrystalline silicon, so this will be 1,6. The price of inverters measured in October €0,5 per watt. These prices are exclusive of sale taxes. When purchasing a whole PV system also the inverter and install costs need to be considered. In general it can be assumed that a PV system is 1,5 times the cost of the PV panels (www.solarbuzz.com). In table 1 an overview of different types of solar cells and the corresponding efficiency, area requirement and price per watt is shown.

Type	*Typical module efficiency*	*Area requirement*	*Price in October 2010*
monocrystalline silicon	12–15%	7–9 m^2/kWp	€3,2 per watt
multicrystalline silicon	11–14%	7–10 m^2/kWp	€3,2 per watt
thin-film CIS	9–11%	9–11 m^2/kWp	€1,0 per watt
thin-film CdTe	6–8%	12–17 m^2/kWp	€1,0 per watt
amorphous silicon	5–7%	14–20 m^2/kWp	≈ €0,5 per watt

Table 1

The reason why thin film solar modules have not replaced older types yet is because they are not as efficient as you can see in table 1. On the other side, their thinner structure needs less material, and this allows much cheaper modules to be produced. Thin film modules are as high as other technologies in terms of price per watt (www.solarpowerfast.com). Biggest reason why thin film cells will be used in this project is their flexibility and therefore their possibility to apply in a wide variety of applications (ezinearticles.com). Since we are talking about spherical (bubble) shaped solar cells, the flexibility is a requisite.

3. PV SYSTEMS

3.1 CONNECTING PV MODULES

Only one PV module does not generate enough current to make profit of solar energy. Therefore more PV modules need to be connected in a photovoltaic system. This can be used to generate and supply electricity for private or commercial purposes. A PV installation includes an array of PV modules, an inverter, interconnected wiring and batteries or a connection to the grid.

The formulas for calculating the current and voltage of the PV system are the same as the formulas used to calculate these electrical features in PV modules. PV modules can also be placed in series and parallel at the same time. When, for example, two 12V/4A panels are placed in series and two parallel, the voltage will be two times 12, which is 24V and the current will be two times 4A, which is 8A (figure 6).

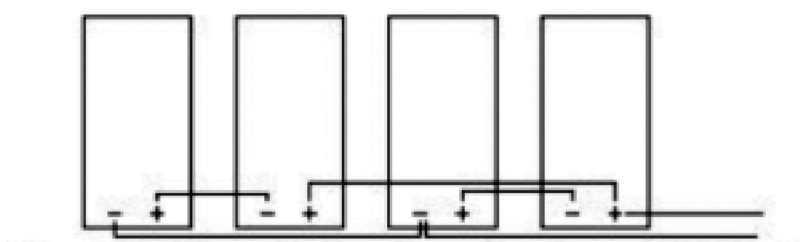


Figure 6: Two 12V/4A panels in series and two in parallel. This doubles the current and voltage to 24V and 8A.

3.2 INVERTER

To convert the current that is produced by a number of panels to a higher voltage an inverter is needed, which converts DC to AC.
Mostly, several modules share the same inverter because they are more efficient and cost effective at higher voltage.
Inverters are available in several colors and sizes. Mostly they are square and the size and price depends on the power that has to be converted (see figure 7). This can vary between 1 kW, with a size of 200*400*400 mm and 20 kW, with a size of 700*500*250 mm.
It is important to connect modules with the same current, caused by irradiance and tilt of the module to one series string. This is because the resulting current will be determined by the minimum, so this being from the modules receiving least irradiance. When zoning a PV array, zones should be kept sufficiently large so that zones of an equal area will generate a high voltage. The other advantage is that there is only one size of inverter in use, which helps with maintenance and replacement.

Figure 7: magnum inverter MS 2012

3.3 LEVELS OF INTEGRATION

Three levels of products to integrate photovoltaics can be distinguished: not integrated, partially integrated and totally integrated PV modules. These levels are being explained and an example will be showed.

3.3.1 Not integrated PV modules

On the first level you can find PV modules designed to be used on any building (figure 8). A particular mounting system is needed. Not integrated PV modules are also called added-on photovoltaics. This means that PV modules are constructed on a building using a metal structure and the only function is to generate energy.

Figure 8: Lumos LS250 black frame

3.3.2 Partially integrated PV modules

Partially integrated PV modules are designed to be used on a particular part of the building (figure 9). The mounting system is designed for the particular module. But the modules are not substituting the surfaces where the PV is added on. Examples are: shading devices, PV modules on green houses, terraces or roofs, facades, balustrades or modules on urban furniture elements and acoustic barriers. For this project PV modules are designed to be used on roofs and facades, but the modules are not substituting them. For this reason the module to be made can be placed in this category.

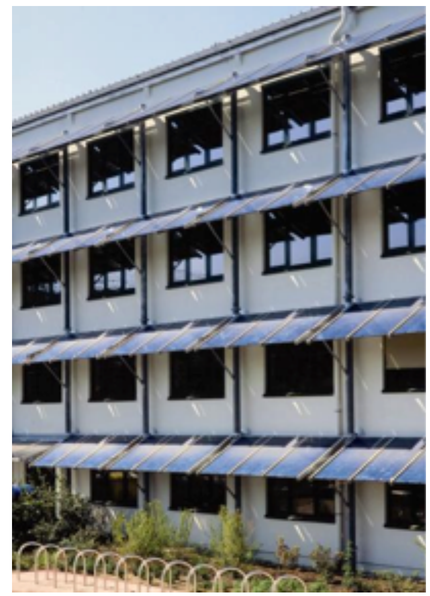


Figure 9: PV louvres at an office building in Neustrelitz

3.3.3 Totally integrated PV modules

This is also called building-integrated photovoltaics (BIPV). These are PV modules that substitute the traditional building components (figure 10). In other words, the PV modules are not only used for producing electricity, it also takes on the role of a building element. This PV system is designed to be directly integrated in the building. The mounting system is also totally integrated. BIPV has a low market penetration. In Germany in 2004 only 1% of the energy generated by PV came from BIPV. (S. Roberts & N. Guariento, 2009)

Figure 10: PV cladding on a building

3.4 POSITIONING OF PV MODULE

External aspects that need to be taken into account are insolation and spectral distribution of sunlight. Insolation is shared very unequally, because of the spherical shape of the earth and because of clouds. It is possible to calculate the average insolation at a particular location. Then the next important thing is to consider the sun's spectral distribution, because different types of solar cells respond differently to the various wavelengths in sunlight. Indirect solar radiation also needs to be taken into account, one is the diffuse component because of light scattered by clouds and dust particles in the atmosphere. (Paul A. Lynn, 2010)

The Satellite Application Facility on Climate Monitoring (CM SAF) has an online application in which it is possible to calculate the performance of grid connected PV in a certain point in Europe with a certain kind of PV cells. Using this website, a comparison will be made between different PV cells: crystalline silicon and thin film CIS and different places in Europe: Portici and Enschede.

Filled in on re.jrc.ec.europa.eu (See fig. 11):

- Radiation database: Climate-SAF PVGIS, because this is the newest database version, and it includes a choice of solar radiation databases for some regions.
- Portici, Italy and after that Enschede, the Netherlands is pointed on the map
- PV Technologies are crystalline silicon and after that CIS, because it is the thin-film module type with the highest efficiency.
- Installed peak PV power: 1,0 kWp.
- Estimate system losses: 14%
- Mounting position is building integrated
- Take the optimal slope, which is 35°.
- Take optimal azimuth, which is 0°

Output is a table (table 2) and a graph that shows the average monthly electricity production from the given system in kWh and the average daily sum of global irradiation per square meter received by the modules of the given system in kWh/m².

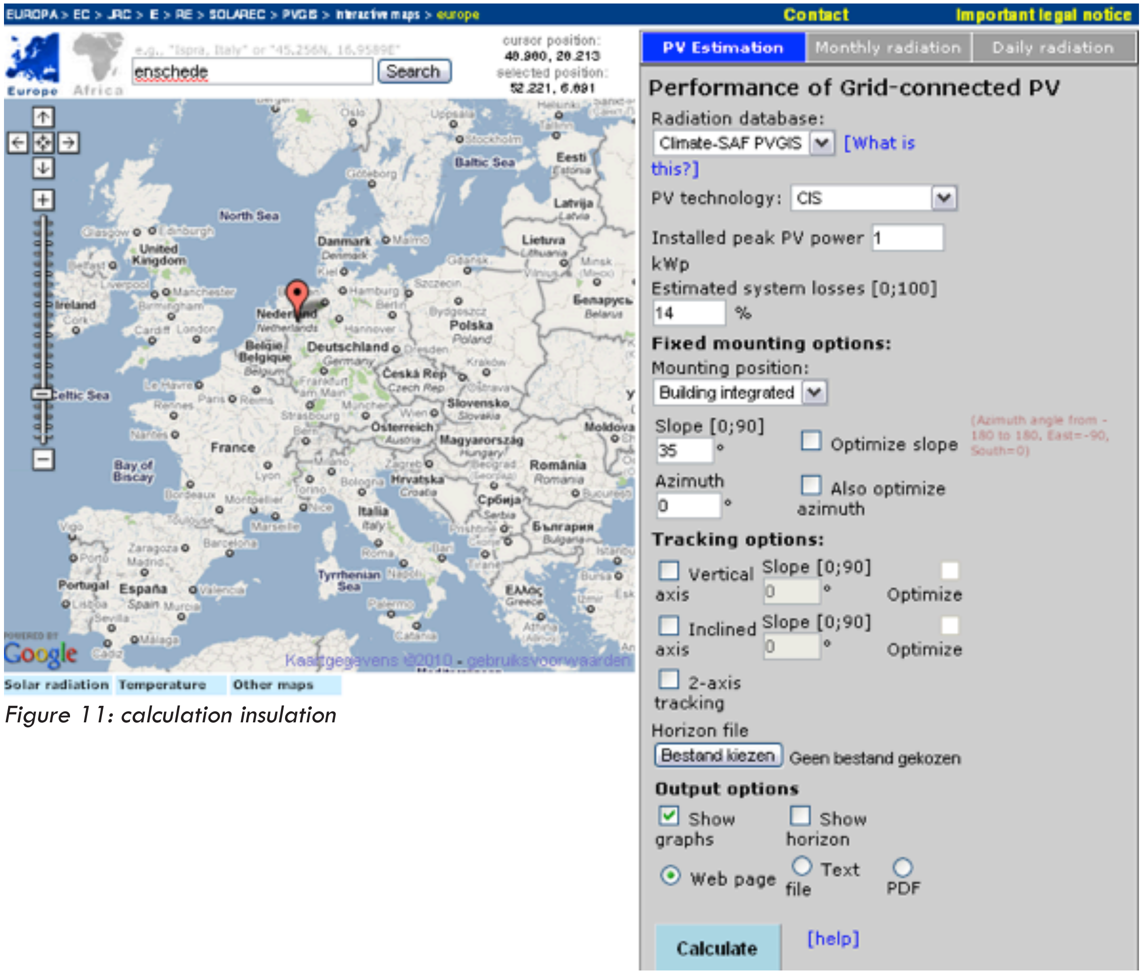


Figure 11: calculation insulation

	Portici – Italy		*Enschede – the Netherlands*	
	Crystalline silicon	Thin film CIS	Crystalline silicon	Thin film CIS
Average monthly production	116 kWh	120 kWh	72,9 kWh	74,7 kWh
Total production for one year	1390 kWh	1440 kWh	874 kWh	896 kWh

Table 2: production in Portici and Italy

The average monthly production and consequently the total production for a year is only a little bit higher for crystalline silicon than for CIS, due to the estimated losses. The loss due to temperature, using local ambient temperature, is 12.4% for crystalline silicon and 10.3% for CIS. Because this difference between crystalline silicon and CIS cannot be seen in a graph, below a graph (figure 12) of the monthly production in kWh through the year in Portici and Enschede is shown.

In sum, building integrated CIS 1,0 kWp modules with an optimal slope and azimuth and a 14% system loss in Portici has the highest average yearly electricity production, which is 1440 kWp a year. In the Netherlands, that is 896 kWp, which 62% of the production in Portici.

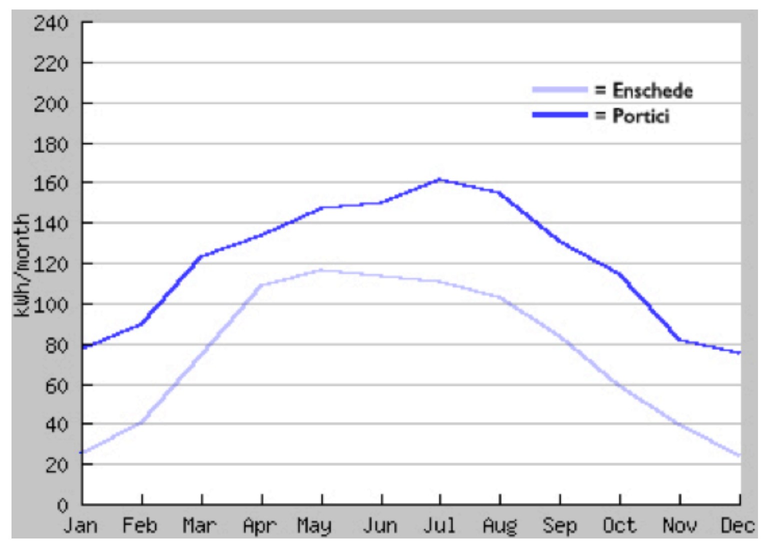


Figure 12: production per month in Enschede and Portici

3.5 REFUNDING

When connecting the PV system to the grid, it is possible to export electricity when building demand is low. In case of high demand and using all PV output, electricity of the grid can be added. Switching between building use and export happens automatically. (S. Roberts & N. Guariento, 2009)

In a lot of countries overproduction of solar energy can be supplied to the grid in exchange for compensation. In the Netherlands it is officially stated in the Energy Law. From 2010 the rule is that the supply of solar energy is refunded up to a 5000 kWh production per year for the price of current of the moment. When supplying more than 5000 kWh/year, the compensation differs per energy supplier. But solar systems are not profitable in the Netherlands; it is a matter of breaking even. In the next table (table 3) the regulations for the three biggest energy suppliers in the Netherlands are shown.

It can be concluded that the average proceeds amounts 0,23€/kWh*5000 = €1150. If more energy than 5000 kWh is generated, the profits are very low.

	Total refund is...	Thereafter
Essent www.essent.nl	The price to be paid for current: approximately 0,234€/kWh	Equal to average supply tariff. For this part no energy taxes and BTW is received, so 0,085 €/kWh will be paid
Nuon www.nuon.nl	Nuon supplies five different sets of panels that generate less than 5000 kWh. Refund of €539,33 for a 2397 kWh production = 0,225€/kWh	
Eneco www.eneco.nl	Is price to be paid for current: approximately 0,23 €/kWh	0,07681 €/kWh. No energy taxes and BTW is received

Table 3: refunding solar energy

3.6 IEC REQUIREMENTS FOR PV MODULES

The International Electrotechnical Commission (IEC) is an international organization for standardization of all national electrotechnical committees. In IEC 61730-1 the fundamental construction requirements for photovoltaic modules are described in great detail. Below an overview of relevant standards for my project are shown.

Construction
A module that comes from the factory shall be completely assembled or it shall be provided in subassemblies. An assembly part needs not to be affixed to the module at the factory.
Ground continuity should not be interrupted by installation of the module.
If loosening, turning or moving of parts could result in a risk of injury to persons, parts should be prevented from that. While preventing a part of turning or loosening, friction between surfaces is not acceptable.

Mechanical securement
A connection shall provide electrical contact without strain on connections and terminals. Connections will also be mechanically secure which means they are held by encapsulation systems.
An uninsulated live part will be prevented from turning or shifting in position, by securing it to its supporting surface.

Connections
A module shall lead to accommodate current-carrying conductors of the load circuit.
Field connections shall be located that they will not be exposed to direct sunlight or it will be rated for exposure to direct sunlight and its degrading effects.
A connector for the output circuit shall have the right voltage and current. The connector shall be assumed to be suitable for assembly only. A material that is water and UV resistant shall enclose a connector that will be exposure to the outdoor environment. A module with accessible conductive parts that form a frame or mounting system or with a conductive surface area greater than 10 cm^2 shall have provision for grounding.

Material
Any material or combination of materials should be provided against deterioration or corrosion.
All polymeric materials shall have a thermal index of at least 90°C. In addition, the minimum Relative Thermal Index shall be at least 20°C above the maximum measured operating temperature.
Polymeric materials that will be used as the outer enclosure for a module shall have a maximum flame spread index of 100. The polymer shall be evaluated for ultraviolet radiation resistance.
Superstrates or substrates made of polymeric materials without appropriate IEC insulation pre-qualification, shall comply with the requirements of the partial discharge test. This implies a maximum system voltage test in which the solid insulation has passed the test if the mean value is greater than the given maximum system voltage.

3.7 IEA REQUIREMENTS FOR PV MODULES

The International Energy Agency (IEA) was concerned with photovoltaics integrated in buildings within Task 7 “Photovoltaic Power Systems in the Built Environment”, Task 10 “Urban-Scale Photovoltaic Applications” and task 41 “Solar energy and Architecture”. The criteria for designing with high architectural quality when applying BIPV architects are defined in Task 7 of the photovoltaic Power Systems Program of the IEA. Although a module has to be designed which is suitable to add on the building and not to integrate in the building, these are also good guidelines for this project.

1. Naturally integrated: the PV system completes the building.
2. Architecturally pleasing: the PV system adds eye-catching features to the design.
3. Good composition: color and texture of the building should be in harmony with the other materials. Often, also a specific design of the PV system can be aimed at (e.g. frameless vs. framed modules).
4. Grid, harmony and composition: The sizing of the PV system matches the sizing and grid of the building.
5. Contextually: the total image of a building should be in harmony with the PV system.
6. Well-engineered: this concerns the question if design details are well conceived.
7. Innovative new design: architects should think innovative and creative to enhance the PV market and add value to buildings.

(Schoen, T, Prasad, D e.o., Task 7 of the IEA PV power systems program – Achievements and outlook, 2001)

3.8 BUILDING REGULATIONS

3.8.1 The Netherlands

The Ministry of Housing, Spatial Planning and the Environment (In Dutch: Ministerie van Volkshuisvesting, Ruimtelijke Ordening en Milieu) formulates regulations concerning space, living, environment and government buildings. If the six requirements concerning solar modules below are met, a building permit is not necessary:

1. The solar module must be situated on the building.
2. The solar module is intended to provide in energy supply of the building itself. It is also permitted to place the module on or at the building in order to supply another building on the land.
3. The module has to be integrated with the electrical store installation. If that is not the case, the installation has to be placed in the building in question.
4. In case the module will be placed on a pitched roof, then it must not stick out the roof, must be placed directly on the roof and the angle of inclination of the module must be the same as the pitch of the roof.
5. In case the solar module will be placed on a flat roof, it must be placed at least as far from the roof as the height of the roof and the inclination of the module cannot be over 35°.
6. The module can’t be placed at a monument or building which is marked as protected by the state. (VROM, 2003)

The Ministry of Finance (In Dutch: Ministerie van Financiële zaken) supports the so called SDE (In Dutch: Stimulering Duurzame Energieproductie) which stimulates projects concerning durable energy which do not return enough money. SDE covers the shortage if man applies for a subsidy.
Subsidy apply is possible in the category installation of at least 1,0 kWp and at most 15 kWp and the category of 15 kWp until 100 kWp. (www.senternovem.nl)

3.8.2 Italy

In Italy there are no specific building regulations concerning PV in or at buildings at this moment. There are only requirements to be met if you want to be qualified for getting subsidy in the form of a feed-in tariff. This is a policy mechanism designed to encourage the use of renewable energy resources and to help accelerate the move toward grid parity. With grid parity the point at which alternative means of generating electricity is equal or cheaper in cost than grid power is meant.

Two different tariffs are established depending on the level of integration of PV. The higher the level of architectural integration, the higher the tariff will be.

The Ministerial Decree introduced the reward rate for architecturally integrated PV systems on the 19th of February 2007 in the so called "Guida agli interventi validi ai fini del riconoscimento dell integrazione architettonica del fotovoltaico" (In English: recognition of architectural integration PV-guide). In this you can find guidelines concerning the distinction between totally or partial integrated PV. In the case of partial integration, three typologies are taken into account and in the case of architecturally integration, ten typologies are taken into account.

The decree is valid until December 2010. Starting from January 2011, until the end of 2013, the Ministerial Decree will substitute the previous regulations. The main change is that there is no longer a distinction based on the level of integration, but only four categories of PV systems are admitted to be funded. One is "Building Integrated PV with innovative features". Since the guide has not yet been published, we still do not know the exact definitions of the categories.

In the guide totally integrated PV is described in the following subdivisions:

1. PV integrated in the building skin (cladding)
2. PV integrated in pensiline, pergola or tettoia:
   - Pensiline: structure ancillary covers placed parking or pedestrian walkways.
   - Pergole: the relevant units in nature residential, to allow the support of green vine on terraces courtyards or gardens, with a reduced area of coverage in the plant
   - PV tettoia: is a structure that covers outside buildings, consisting of pitched resting on the wall of the buildings themselves.

   These three kinds of modules must have a minimum ground clearance of two meters.
3. PV as transparent surfaces of buildings
4. PV used as acoustic barriers on side of the road
5. PV integrated in lighting elements and public facilities
6. PV sun-shading systems
7. PV integrated in balustrades and parapets
8. PV integrated in windows
9. PV integrated in awning/sunblind inside the house
10. PV used as covering or coating for buildings

(Gestore Servizi Elettrici, 2009)

4. PRODUCTS

In this chapter a small market research is done. Innovative products that are suitable for Blob-buildings are listed and explained. The pros and cons of every product are also given. These arguments are concluded by drawing the modules on several buildings (see Appendix I).

4.1 FLEXIBLE THIN FILM MODULE

Thin-film solar photovoltaic technology offers the benefits of low-cost in exchange for high efficiency. The lightweight and flexible technology can easily be put on for example the facades, roofs or rain screens of a building (figure 13). For this building the surface area should not be an issue, because for an optimal generation of energy a large area is required. (www.pv-tech.org)

Figure 13: a flexible thin film module

Pros and cons

The biggest advantage is that the module is flexible so it fits on curved surfaces. It is a disadvantage that the modules cannot be placed on small surfaces because in this case the energy generation will be too low.

4.2 SPHELAR

The most important Sphelar product is the module that is half spherical-shaped (figure 14). The solar cells are placed on the inside of the envelope of the sphere. That is why they can produce electricity from any incoming light, including light that is already bounced off other surfaces, giving an efficiency rating of around 20%, so it has a competitive position in comparison with high-end traditional solar cells. It provides in small and compact PV modules and can be used for low power applications and they can be connected either in parallel or in series. It is available in sizes from 38.1 x 24.1mm until 155 x 52mm. The maximum power varies between 45mW and 940mW.
Sphelar also has modules in an array of 12 cells, in a cylinder shape and a spherical micro solar cell mounted in a plastic case. (www.kyosemi.com)

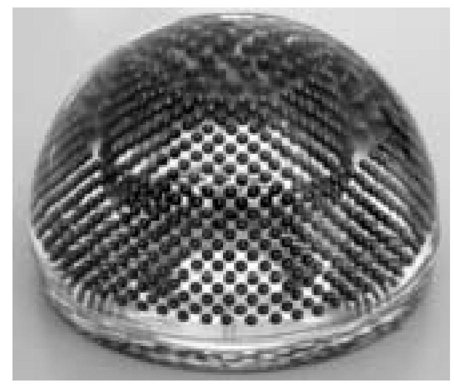


Figure 14: sphelar

Pros and cons

The biggest advantage is that the sphelar is small-sized. No matter how sharp the curves of the building envelope are, the underside of one of the sphelar will fit on every envelope.
The building envelope can almost be covered by the sphelars, because of the availability of bigger and small ones, but little pieces of the skin will be uncovered. A disadvantage can be that because of their height, they will be placed in each others' shadow, on some hours of the day. Because of their typical shape it is insuperable to influence the character of the building.

4.3 ETFE

This technology is based on extremely flexible, amorphous thin-film PV cells embedded in ETFE laminates. It has a total thickness of 1µm (fiure 15). They can be cut to length and be aligned to meet every specific requirements of any project, up to three meters because of the laminating equipment. This process of lamination ensures that the photovoltaic cells are effectively protected against loads and stresses, as well as against UV, moisture and weathering.
The surface is resistant to soiling. PV Flexibles can be used for roofs and facades without an additional supporting structure. It is also used in the outer layer of pneumatically supported cushions. The PV cells are not only generating current, they also provide shade.

Figure 15: ETFE

Pros and cons
ETFE is an appropriate product to replace roofs and facades because it is possible to resist UV, moisture and weathering. A disadvantage is that it is only available up to three meters so a supporting system is needed in case you wish to cover a bigger surface. Because of the pneumatic cushions, curved shapes can be achieved, but with this technology a double curved, S-shape cannot be reached without a supporting system in between.

4.4 SOLYNDRA

Solyndra (figure 16) is the name for the long cylindrical shaped panel. Each panel is made up of individual modules, which are all placed horizontally. One module contents 150 individual solar cells. The panels are able to capture sunlight from a 360-degrees angle, so besides direct sunlight also diffuse and reflected sunlight will be added to the energy production. For this a white roof surface is necessary. The system is light weighted and no mounting system is needed.
(www.solyndra.com)

Figure 16: solyndra

Pros and cons
An advantage is that the shape allows placing the panels on building surfaces which are curved one-sided, but two-sided curved surfaces cannot be covered with Solyndra. Another big advantage of this system is the higher efficiency rate because the cells are facing 360-degrees. Because of the striking shape it is insuperable to influence the character of the building.

5. DEFINING THE REQUIREMENTS

In this chapter the requirements are defined. This will be done by using the information that was already gathered about PV cells, modules and systems and gathering new information about the wishes of architects, materials and Blob buildings. This chapter starts with a summary of a survey held in the past. Then a new survey is shown. Next, a material selection will be done, Blob buildings will be analyzed and this chapter will end with a list of requirements.

5.1 IEA SURVEY

The International Energy Agency (IEA) Task 41 has dealt with this issue of wishes of architects for new PV modules. Members of this taskforce held a survey concerning the integration of solar energy systems and architecture in order to identify barriers that architects are facing concerning integrating PV technologies in their design.
The international IEA Task 41 group defined eighteen barriers and seven strategies of solar system utilization and the respondents were asked to vote for the issues they consider as most important.
The survey was about photovoltaic systems and solar thermal systems but for this assignment only information about photovoltaic systems is useful. The differences in outcome between countries is not important in this case, so the average outcome will be used.

The survey was sent out to architects in thirteen countries (most of them in Europe, the rest in Canada and South Korea). Through the survey the barriers and possible strategies of integrating solar energy in architecture and the needs of the architects considering solar energy in architecture are investigated. Below the main conclusions of the 255 responses are listed.

Barriers

- Economic issues were found to be the most important barrier (21%), especially the high product price. Clients are mainly interesed in the paid back time and therefore interested in the investment costs. But, solar components can replace other building components by their integration into the building envelope, consequently they fulfil multiple functions and relative costs become lower.
- The lack of knowledge of architects is considered as second most important barrier (19%). There is resistance because solar systems are not considered to be building components, but technical devices. Clients and developers should have a basic knowledge of solar energy systems to understand the benefits of their investment.
- Third most important barrier is the lack of oriented literature on the technologies and useful and understandable data for architects about solar energy (18%). A solution to take away this barrier is to make architecturally oriented information about solar energy available, in the form of for example handbooks or websites.

Strategies

- Regarding the strategies, Economical strategies are considered to be the best (42%). Participants of the survey think governmental incentives can be an important support. Two systems used are subsidies for the initial investments and feed-in-tariff systems. The second one means that overproduction of electricity is bought by the electricity distributor.
- Second most important strategy is process (23%). Not enough simplified computer solar tools are available for architects. There are many tools for solar design. Free or subsidized technical support from professional associations for the early design stage would encourage the use of solar products in architecture.

General

- There were 255 responses. Relatively, this is a big number of respondents for a survey like this one. The survey was sent to a lot more architects over the world and only a small percentage was returned. This can be an indication that could confirm the assumption that architects are not really interested in the issue. The lack

of interest by clients and developers has his origin in the fact that solar modules are considered to be technical devices rather than building components, mostly due to the lack of knowledge about technology and available products. Therefore architects and even more clients often resist using them in their design.
It should be remarked that the barrier "products" is considered as being the last most important barrier (11%). A variety of products have been developed for building integration but still aesthetical issues are not the focus of product development. There is a need for complementary building components like for example dummy elements. (Farkas, K, Munari Probst, M.C., Horvat, M., 2001)

5.2 PERSONAL SURVEY

In order to create a concept for the bubble PV modules that are likely to be used in the future, the wishes of architects should be taken into account. As mentioned before, the International Energy Agency has dealt with the issue of general barriers that architects are facing concerning integrating PV technologies in their design. Outcome of the survey was that economic issues were the largest barriers.
In this phase it is necessary to go more into detail to be able to develop a product that enables architects to integrate PV in architecture more easily. Consequently, a survey is sent out in which architects were asked to fill in questions about barriers, wishes and solutions concerning PV products to be used in architecture and in architecture with curved envelopes.

The survey can be found in Appendix II and is held among five architects. The data is various because the nationalities, backgrounds and experience of the architects differ from person to person. The architects interviewed execute their profession in Italy, the Netherlands, Norway and Japan.
One of them has not worked with PV modules, three architects worked with PV modules in one or two projects and one very experienced architects worked on a hundred PV projects. A summary of the usable outcomes is listed below.

Barriers
The architects were asked to consider the importance of five possible barriers for integrating PV modules in architecture by using a 1-5 scale.
The largest barrier appears to be the shape of PV modules with an average grade of 3,8.
The general lack of products is rated to be the second largest barrier (grade: 3,0) and the third largest barriers are color and material of the modules and price of the modules with both an average grade of 2,8. Harmony with the environment is considered to be the least important barrier (grade: 2,2).
A note needs to be placed. According to the opinion of Mr. Martocchia, PV elements need to be treated as a technical installation and not as if they are architectural elements. Therefore he graded all barriers as 1. There is one other problem mentioned: not being updated. To the opinion of Mr. Røstvik another barrier is the lack of knowledge about the properties of and possibilities with PV modules. The reason that is mentioned mostly for not using PV is the price for building integrated design. Clients avoid additional investments and affordable modules integrated in a facade are usually are aesthetically unattractive.

Customizability
According to the opinion of the architects the most important customization of PV modules should be the shape. Color, positioning of cells and integration of LED's follow on second place. Other possibilities mentioned are transparent PV modules and attractive roof tiles in a traditional shape.

Curved envelopes
Most of the respondents consider small PV modules and flexible thin film modules as a solution to integrate it in curved architecture. Another option mentioned is curved PV modules. Mr. Røstvik on the

other hand, noted that for small PV modules the chance of electric and material connection failure increases due to the number of connections you will need when using a lot of small PV modules. Regarding to thin film modules he mentioned that the efficiency per m^2 is too low to even cover only a small part of the energy consumption of a building.
Largest barriers for standard module in curved architecture are price and lack of products.

Conclusions regarding the PV module to be made
Some interesting conclusions can be made, which can be translated in the following requirements for the PV module to be made:
- The shape of the module must fit on the shape of the curved architecture.
- The price of the PV modules to be integrated must not be too high.
- It is important that the kind of material and color of the module can easily be integrated with the building.
- The shape of all the modules together on a building needs to be customizable.
- Customizable properties like color, positioning of cells and integration of LED's are optional.
- The number of electrical and material connections needs to be kept low in order to increase the change of connection failure.

5.3 MATERIAL SELECTION

5.3.1 Fire safety
When constructing a building, regulations for fire safety should be considered. In the Dutch law it is said in short that materials may not be easy flammable and may not spread fire easily. Practically this means that in case of fire the material should not take fire quickly and when it is in fire, it should not spread through the material quickly. A material that slows down the fire is preferred in a lot of cases (overheid.nl). To determine how safe a part of the building needs to be, firstly the category in which the material of the construction parts is used needs to be determined. Categories are for example the function of the room, the kind of building, the size of the room and the locations (totally inside or partly outside). Secondly, NEN (Stichting Nederlands Normalisatie-Instituut) divided the materials contribution to fire in four classes, from low (class 1) to strong (class 4) contribution to fire spread. This also depends on the flammability of the material. (www.nordictimber.nl). It can be found that parts that are usually integrated in walls, such as a door, window or window frame is placed in class 4, which means that these parts of the house are allowed to contribute strongly to the spread of fire. When one of the sides of the construction parts is positioned in the direction of a street, the corresponding class is 1, which means that contribution to fire spread should be low. But this does not hold for the top a roof (wetten.overheid.nl). If the material is easy flammable or spreads fire easily, it could be treated with a fire-resistant coating. This is a thin film material that can be used to cover the material, in order to make it resistible to fire.
The conclusion is that a roof and wall and so PV modules that are placed on them, are allowed to contribute strongly to the fire spread. So the material where the module is made of may have the property of being highly flammable. But to make the module safer, it is possible to treat the material with a fire-resistant coating.

5.3.2 Material selection in CES

To select a proper material for the outside of the thin-film PV module Cambridge Engineering Selector (CES) is used. The IEC requirements are translated in the next requirements to be filled in in CES (table 4):

- All materials are participating in this selection process.
- All polymeric materials shall have a thermal index of at least 90°C. In CES the maximum service temperature can be defined, so this will be done on 90°C.
- Polymeric materials that will be used as the outer enclosure for a module shall have a maximum flame spread index of 100. Flame spread index is in short a comparative measure of the ability of the material to resist flaming combustion over its surface (www.answers.com). But this aspect cannot be found in CES. Therefore flammability will be taken into account, which is represented in CES. Flammability is ranked on a four-point scale, because most polymers are inherently flammable, although to differing degrees.
- Because price and embodied energy are the only quantitative properties, these two will be put on the x- and y-axis.

The result of these requirements are shown in the graph you can see on the right.

When using this approach there are only three materials left which meet all the requirements (see figure 17). Unfortunately those materials are quite expensive. The costs of Fluoro elastomer (FKM) is about 29 €/kg. For Fluor elastomer (FEPM) this is 42 €/kg and Perfluoro elastomer costs about 831 €/kg. To compare: the average price of glass is about 5 €/kg.

So a different approach is tried. It is found that the biggest problem is the ability to resist UV radiation and the flammablility. It is possible to add additive materials or a coating to optimize this material property.

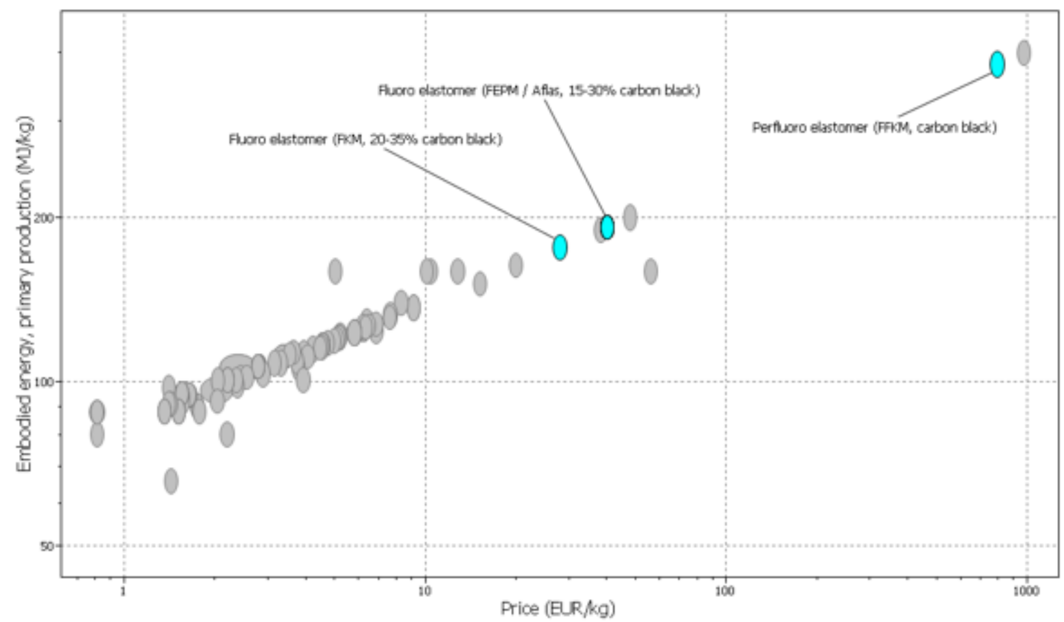


Figure 17: materials in CES

Requirement IEC	**Corresponding property CES**	**Apply in CES**
Thermal index ≥ 90°C	Maximum service temperature	Set maximum service temperature on 90°C
Provided against deterioration	Organic solvents	Exclude everything except: Excellent
Corrosion	Durability water (fresh)	Exclude everything except: excellent
Flame spread index ≥100	Flammability	Exclude everything except: non-flammable
Ultraviolet radiation resistant	UV Radiation (sunlight)	Exclude everything except: Excellent
Other requirements	**Corresponding property CES**	
Costs	Price	X-axis
Embodied energy	Embodied energy, primary production	Y-axis

Table 4: IEC requirements in CES

The second strategy is to look for materials in products that are used outside, because from these products, we know they should be at least resistant against organic solvents and water. A list of suitable materials is selected (table 5) and the corresponding properties for products like outdoor furnishing, containers and bumpers.

As said in the chapter before this one, the PV modules are allowed to contribute strongly to the fire spread. So the material where the module is made of may have the property of being highly flammable. The maximum service temperature was set on 90°C. UV resistance is no hard requirement because an UV resistant coating can be used.

These facts put forward "PP (homopolymer, clarified/ nucleated)" as the best material, because it meets the requirements and has one of the lowest embodied energy and the lowest price. To compare: the average embodied energy from glass is about 27 MJ/kg and for aluminum it is 200 MJ/kg. PP is not resistant to UV radiance so there has to be treated with an UV resistant material.

PP can be molded and this is the perfect production method for the parts that are needed in the module. One of the tradenames of this material is Polybatch and this is available in several kinds of colors. (see figure 18).

Material	*A selection of typical uses*	*Maximum service temperature (°C)*	*Organic solvents*	*Durability water*	*Flammability*	*UV Radiation*	*Price (€/kg)*	*Embodied energy (MJ/kg)*
ASA (extrusion, injection and blow molding)	Outdoor signs, exterior panels, garden furniture	67	--	++	HF	+	1.43	95.5
PP (copolymer, clarified, nucleated)	Containers, automotive exterior, bumpers, agricultural applications	86.8	++	++	HF	-	1.28	99.4
PP (copolymer, impact, 30% glass fiber)	Bumpers, general machine parts, furniture, pipes, garden equipment	124	++	++	HF	-	2.48	103
PP (homopolymer, clarified/ nucleated)	Bumpers, Containers, furniture, pipes, outdoor furnishings, buckets	99.1	++	++	HF	-	1.24	98.7
PP (copolymer, 40% calcium carbonate)	Pipes, bumpers, garden equipment, automotive interior trim, battery cases	85.2	++	++	HF	-	1.51	90
PP (copolymer, high flow)	Containers, outdoor furnishing, foil, pipes	83.8	++	++	HF	-	1.28	97.2
PP (copolymer, 20% talc, flame retarded, 5VA)	Swimming pools, garden equipment, containers, bumpers, bottle crates	94.8	++	++	SE	-	2.05	98.3

Table 5: suitable materials

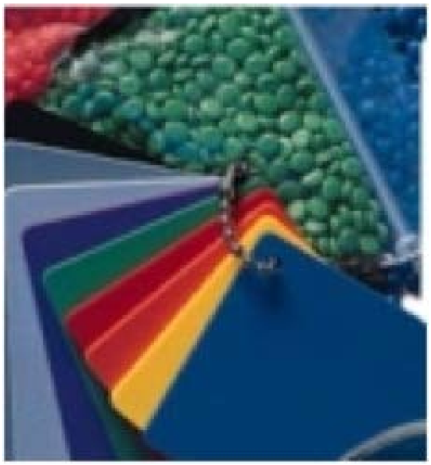


Figure 17: Polybatch

5.4 ANALYSIS OF BLOB BUILDINGS

Before starting the Blob analysis, it is required to first define the term "Blob". In literature, people are having different views on the term. Below the explanation that is found most of the times is been summarized.

BLOB is an abbreviation for the words Binary Large OBject. This is a collection of binary data in a data management system. Computer-aided-design software is needed to define the shape.
In the architectural context Blob is a movement in which buildings have organic shapes. In Blob buildings there are various curves, different slopes and sharp angles. The walls and roof are double-curved and mostly the walls follow the floors in a smooth way.

In this sub-chapter an analysis is made of seven very different Blob buildings. The dimensions of the total building, of the seperate parts of the building, curvations, the radii, the use of materials and the presence of bubbles are considered. Because of the variety in shape and dimensions, these buildings can be seen as a representation of all Blob architecture.

On the following seven pages the next buildings have been analyzed:


1 Guggenheim Museum

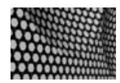

2 Selfridges building


3 Rabin Center


4 Water Pavilion


5 Kunsthaus


6 Fluid vehicle bus station


7 International Convention Center

1 GUGGENHEIM MUSEUM

Abando, Bilbao, Spain

Frank Gehry, 1997

pdphoto.org

The Guggenheim Museum Bilbao is a museum of modern and contemporary art. Large-scale art is placed in the biggest room of the museum, which is 30 by 130 meters. On this picture you can see about 160 meters length of the building.

DIMENSIONS TOTAL BUILDING
- Total length: 220m by 130m
- Height: 50m
- Smallest radius of surfaces where PV modules can be placed on: 5m, biggest radius: 100m

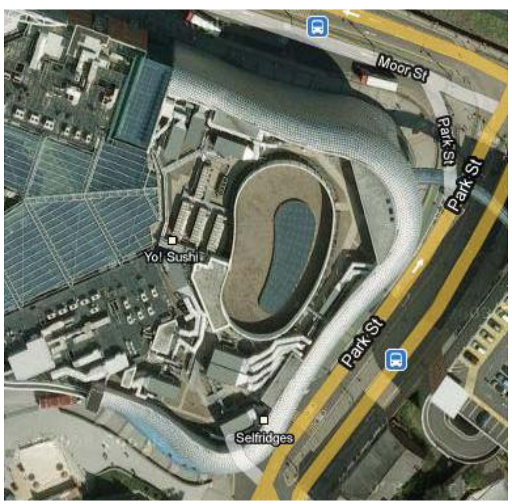
DIMENSIONS SEPERATE PARTS
- Average dimensions of the seperate parts of the buiding: 20x40m.
- Average dimensions of the maximum simple geometric parts: 0,5x0,5m.

CONSIDERATIONS
- Parts are curved one-sided. Seperate parts are placed in all different directions, so surfaces are facing all quarters of the compass.
- Bubbles can be found on architectural scale.
- Facades and roofs does not merge into one another.
- Use of material is heterogenous (steel frame, sinuous stone, glass and titanium cladding).

2 SELFRIDGES BUILDING

Birmingham, England

Future Systems Architects, 2003



contemporist.com

The Birmingham store consists of three walls. It is blue and is clad with around 15000 spun aluminium discs, each 0,6m in diameter. The fluid form strikes a contrast with conventional buildings nearby, but it is a bit alike gothic architecture. The selfridges building is curved three-dimensionally. Its design makes no distinction between 'walls' or 'roof', and there are no abrupt angles to break the organic, flowing lines.

DIMENSIONS TOTAL BUILDING
Dimensions: 100x110m.
Length bridge: 37m.
Smallest radius: 8m. Biggest radius: 40m.

DIMENSIONS SEPERATE PARTS

- Average dimensions of the maximum simple geometric parts: 0,6x0,6m, which are the dimensions of the discs.

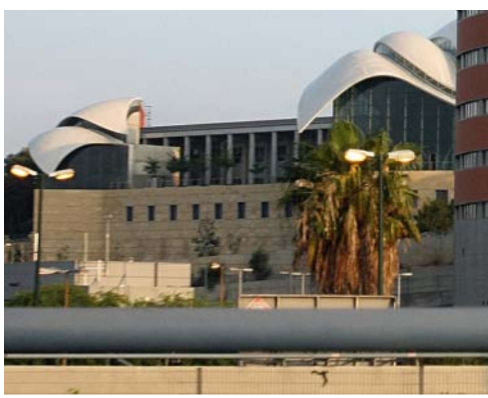
CONSIDERATIONS

- Parts are curved three-dimensionally.
- Seperate parts are facing all quarters of the compass.
- Bubbles can be found both on architectural scale and as a structural element on the envelope, because of all the aluminium discs placed on the building.
- The building is not closed. It has one facade and no roof.
- Use of material is heterogenous.

3 RABIN CENTER

Tel Aviv, Israël

Moshe Safdie, 2009



1.bp.blogspot.com

The building is made of giant surfboards of foam with stressed skins on both sides. The roof is subdivided into five different roof wings, two on one side and three on the other. In between a square building can be seen. Under the roof a wall of glass can be found.

DIMENSIONS

- The biggest roof wing is about 30x30m. The minimum length dimensions of one of the wings is about 30x15m.
- Maximum radius: 20m, minimum radius: 10m.

DIMENSIONS SEPERATE PARTS

- Average dimensions seperate parts: 15-20m.
- Average dimension of maximum single geometric parts: 0,5x0,5m.

CONSIDERATIONS

- Parts are curved three-dimensionally.
- The roofs are placed in all different directions, so surfaces are facing all quarters of the compass.
- Bubbles can be found only on architectural scale.
- There is a clear distingtion between facades and roof.
- Use of material is heterogenous, but the surface of the roof is made of one material.

4 WATER PAVILION

Oosterschelde, the Netherlands

Nox/ Lars Spuybroek, 1997

joostdevree.nl

The Water Pavilion is made up of a fresh water pavilion which is 60m long and a salt water pavilion which is 40m. In both of the buildings complex two-sided curves are used. The buildings surface exists of thin stainless steel.

DIMENSIONS TOTAL BUILDING
- The three-dimensional curved building made of stainless steel is 60 meters long.
- The height is 12 meters
- This building is made up of 20 vertical parts of each 2m.
- The maximum radius is 3m, minimum radius is 6m.

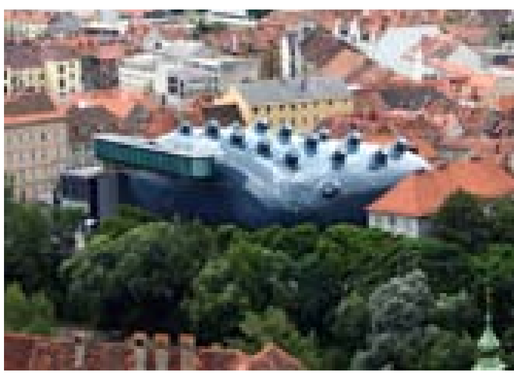
DIMENSIONS SEPERATE PARTS
- The average dimension of maximum single geometric parts is about 0,25x0,25m.

CONSIDERATIONS
- Parts are curved three-dimensionally.
- There are no windows in the building
- The roofs are placed in all different directions, so surfaces are facing all quarters of the compass.
- Bubbles can be found only on architectural scale.
- Floors, facades and roofs merge into one another.
- Use of material in the building surface is homogenous.

5 KUNSTHAUS

Graz, Austria

Peter Cook and Colin Fournier, 2003



marekbartelik.wordpress.com

The museum which is called “Friendly Alien” was built as part of the European Capital of Culture celebrations in 2003. Contemporary art of the last four decades are exhibitioned. The form and material of the gigantic buliding, stands out consciously against the surrounding baroque roof landscape.

DIMENSIONS TOTAL BUILDING

- The total surface of the building is approximately 7200m^2. Sloped and special shaped roof is 4050m^2.
- The dimensions spherical shaped parts is approximately 100x50m.
- The smallest radius of surfaces where PV modules can be placed on is 15 m. Maximum radius: 40 m.

DIMENSIONS SEPERATE PARTS

- The average dimension of maximum single geometric parts is about 1x1m for the big part, for the small parts on top of the building, this is 0,1x0,1m.

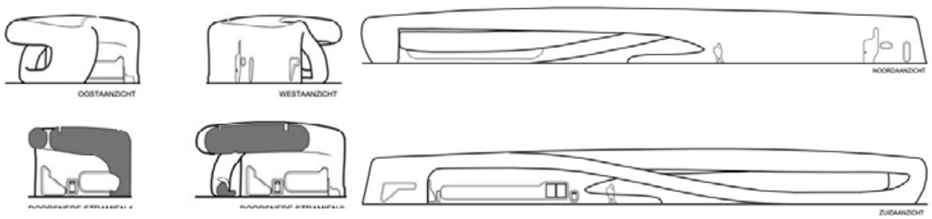
CONSIDERATIONS

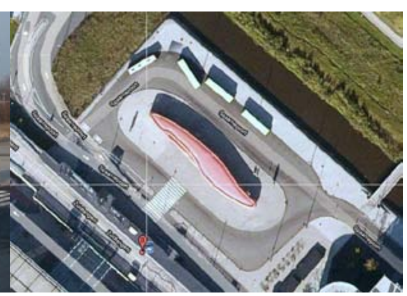
- Both the big part and the small parts where the building is made up of, are curved three-dimensionally.
- Bubbels can be found on architectural scale.
- During the evening/night “balls” of light can be seen on the envelope of the building so bubbles can also be found as a 2-dimensional pattern.
- Surfaces are facing all quarters of the compass.
- Floors, facades and roofs merge into one another.
- Use of material in the building surface is heterogenous.

6 FLUID VEHICLE BUS STATION

Hoofddorp, the Netherlands

Maurice Nio, 2003





heingartner.com

This bus station is has a so called fluid shape and so is totally three-dimensional. It is completely made of polystyrene foam and polyester and when it was made, it was the world's largest structure in synthetic materials (50x10x5m)

DIMENSIONS TOTAL BUILDING

- The roof is very small, but long. The roof of the building is about 150 square meters.
- The building is made of seperate parts of about 0,5x0,5m.
- Smallest radius of surfaces where PV modules can be placed on is 2m. The maximum radius is: 100m.

DIMENSIONS SEPERATE PARTS

- The average dimensions of the maximum single geometric parts where the building is made up of are about 0,01x0,01m.

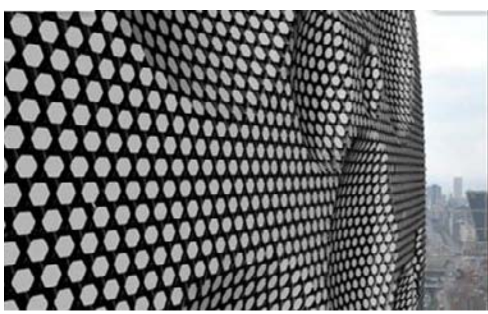
CONSIDERATIONS

- There are no windows in the building and the total building is made of the same material. So use of materials is homogeneous.
- It is curved three-dimensionally. Facades and roofs are merging into one another smoothly, there is no floor.
- Bubbels can be found only on architectural scale.
- Surfaces are facing all quarters of the compass.

7 INTERNATIONAL CONVENTION CENTER

Madrid, Spain

Mansilla + Tunon Architects in collaboration with Matilde Peralt



The building is scheduled to be completed in 2012. It is cylindrical shaped. It will house an rainwater catchment system. Approximately 21000 hexagonal solar modules will be placed on the surface. The building will contain an auditorium, event halls and exposition halls.

DIMENSIONS TOTAL BUILDING
- The dimensions are 110x40x125m.
- The building is made of seperate parts of about 0,5x0,5m.
- The maximum radius is 50m and the minimum radius 5m.

DIMENSIONS SEPERATE PARTS
- The building is clad with 21000 solar modules, so it can be said that the building can be split up in these single geometerical (hexagonal) parts of 0,75x0,75m.

CONSIDERATIONS
- There are no windows in the building. The building surface looks like it is made of the same material so the use of material appears to be homogeneous.
- It is curved three-dimensionally. The facades and roof merge into one another smoothly.
- Bubbels can be found both on architectural scale and as a structural element on the envelope in 3-d. This one can be found in two ways: the hexagonal solar panels, and the bubbles which go into the right side of the building.
- Surfaces are facing all different directions.

www.inhabitat.com

5.5 CONCLUSIONS BLOB ANALYSIS

Two important conclusions can be made of the research to Blob architecture. One is about the biggest single geometrical part where the buildings can be divided in and one is about the smallest radii that can be found in the buildings.

The minimum dimensions of the maximum single geometric parts where the building is made up of is 0,25*0,25 meter in the Water Pavilion. The average maximum dimensions of all Blob buildings together are 0,53*0,53 meter. There must be said that this are the dimensions of the surface of the building which are suitable for PV modules to be placed, so very small protrusions and separate parts of the building are not taken into account.
The smallest radius that can be found in the buildings was 2 meters in the fluid vehicle station. In this case again dimensions of very small protrusions and separate parts of the building are not taken into account. The average smallest radius of all buildings together is 7,3 meters.

Based on this information, it can be said that the maximum dimensions of a totally flat module applied on an average Blob building, should be approximately 0,5*0,5 meter.
If a larger module is preferred, consequently a slightly curved module should be used to fit closely onto the building envelope. If, for example a module of 2*2 meters is chosen, and the building has a radius of 6 meters, the module should be curved about 4% (see figure 19).

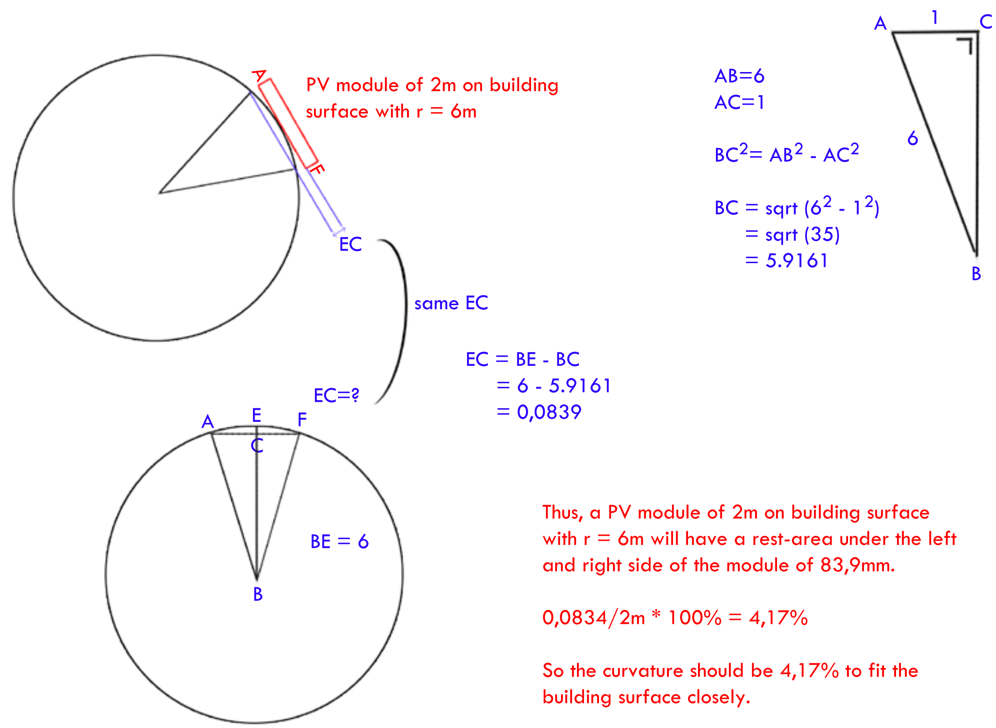


Figure 19: calculation rest area

In the calculation in figure 10 a minimum radius of 6 meters is chosen, because in this way most of the buildings are taken into account. In the Guggenheim museum there are only some parts with a radius of 5 meters. The Fluid vehicle bus station and the International Convention Center only have a smaller radius on the edges. So these buildings can be considered as if they belong to the group of buildings with a minimum radius of 6 meters. Only the water pavilion is not considered in the calculation because the minimum radius of 2 meters is too deviating.
In the calculation a module of 2*2 meters is chosen, because four of the buildings already have a front facade that is over 30*100 meters. This means that, if square PV modules would cover these front parts of the buildings, 750 of them are needed. To keep the number of electrical connections tolerably low, the minimum dimensions of the PV should be 2*2 meters.

5.6 LIST OF REQUIREMENTS

By using all the technical information that was already found in the analysis and the outcomes of both of the surveys, a list of requirements can be made.

Requirements

- *Dimensions*

The available and preferred range of dimensions of the spherical shaped PV cells is 40 – 250 millimeters. The desirable dimensions of the PV module can be concluded from the Blob-research. So the maximum dimensions of a module will be 2*2 meters. When this module is placed on a building with a radius of 6 meters, a rest space can be found under the module of about 85 millimeters. This will be the maximum rest space accepted in the design.

- *Adaptability*

The module should be suitable on building surfaces with a minimum radius of 6 meters.
In this context the word 'suitable' means that the modules have a reasonably close fit on the building and the mounting system allows to be fixed on every surface.

- *Energy generation*

The area requirement for amorphous silicon is about 16 m^2/kWp. So the required energy generation is 62,5 Wp/m^2, which is approximately 60 Wp/m^2. So for example, the concept 'flexible' which has an area of 6,26 m^2 will have a peak power of 6,26 * 60 * 90% =338 Wp. The 90% is added because due to the use of round cells there will be some rest space between them of about 10% of the total area.

- *Installation total system*

It should not take too much time to install the modules on the roof, connect the modules and the inverters. The requirement is that it should only take 1,5 times the time it takes to install a standard crystalline module system.

- *Coverage*

The modules should be fit close to each other, in order to cover as much surface of the envelope as possible. The requirement is that 70% of the surface which is intended for producing electricity is actually covered.

- *Aesthetics*

The PV module should be designed with high architectural quality. The next requirements concerning aesthetics are concluded from Task 7 of the photovoltaic Power Systems Program of the IEA.
- The system is naturally integrated; the PV system completes the building.
- The PV system adds eye-catching features to the design.
- Color and texture of the building should be in harmony with the other materials.
- The size of the PV system matches the size and grid of the building.
- The total image of a building should be in harmony with the PV system.

- *Price*

The price of the installation of a PV system of bubble modules should be only 1,5 times the average price of the installation of a crystalline silicon system.

- *Material*

- The PV module should be resistant of fresh water, deterioration and of course to UV radiation.
- According to the IEC requirements, the maximum service temperature should be 90°C.
- As said, parts like a door or a window are allowed to contribute

strongly to the spread of fire. PV modules are placed on roofs or facades and therefore the same treated the same as a roof, door or window. So in conclusion it can be said that in the Netherlands PV modules on roofs and on facades are allowed to be easily flammable and to contribute strongly to the spread of fire.

- *Sustainability*

- The material should be sustainable. This will be compared to the embodied energy of primary production of aluminum, which is about 200 MJ/kg. The embodied energy for the primary production of the outside material of the PV module may not be higher than this value.

Wishes

- *Customizable*

- The positioning of the PV cells is adaptable.
- The color of the module can be adapted to the demands.
- There are light, warmth and movement sensors integrated in the system, in order to make it adaptable to the surroundings.
- LED's are integrated and they will respond on the changes measured by the sensors.

6. CONCEPTS

6.1 GENERATING CONCEPTS

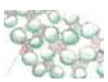
Now the requirements are defined, concepts can be generated. Seven concepts are made in total. They especially differ in shape, but with the size, material and positioning of the cells is also played. On the next seven pages, the concepts will be explained one by one. Per concept, the shape, the mechanical and electrical characteristics, the pattern of the cells and the connections will be explained. In sub-chapter 5.2 one of the concepts is been chosen to develop in more detail.

On the following pages the next concepts can be found:

 1 Hexagonal

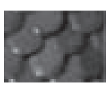
 2 Tile

 3 Small

 4 Round

 5 Flexible

 6 Imaginary circle

 7 Fish scale

Concept 1

Hexagonal

THE CONCEPT

This idea is inspirited by natural shapes. Hexagonals can be found in nature in for example honeycombs or as the crystal structure of a molecule. Unlike other geometrical shapes like pentagons and heptagons, hexagonals perfectly fit on flat surfaces. Pentagons do not, because when using them, there will be a lot of areas uncovered. When using squares or heptagons on a curved surface, the modules overlap or leave a lot of area uncovered. With only small left-over areas it is possible to cover slightly curved surfaces with hexagons.

SHAPE

The modules are shaped hexagonal. In this concept there will be a small rest space between every module. So in case they need to cover a curved surface, this small tolerance allows a small angle between the different modules. So it will be possible to achieve coverage of slightly curved surfaces.

ELECTRICAL CHARACTERISTICS

Type of cell: amorphous silicon

Estimated Nominal power module: 100 Wp

MECHANICAL CHARACTERISTICS

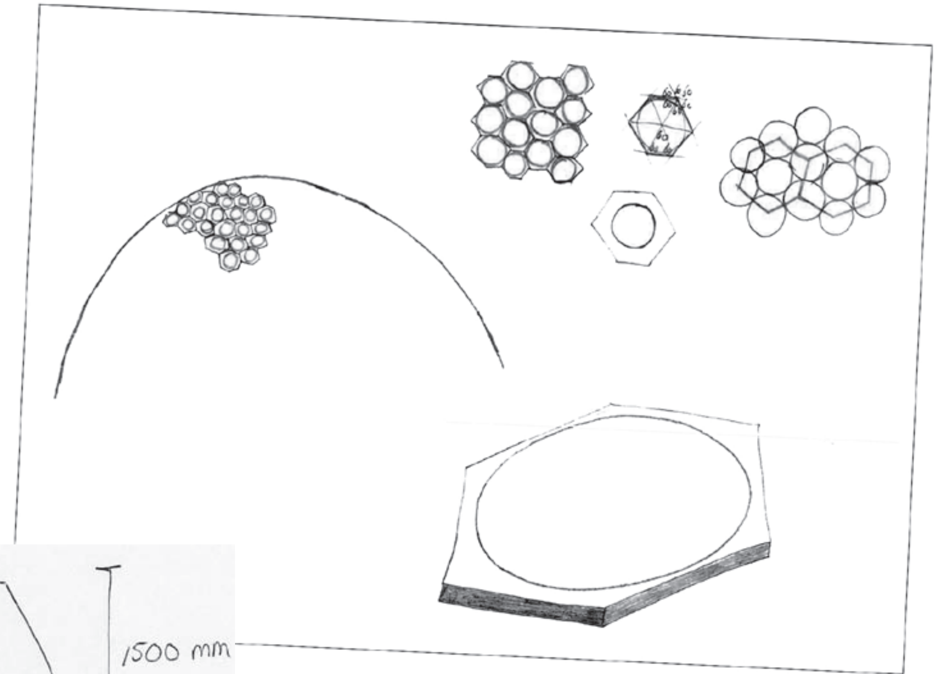
Dimensions (LxW): 1500 x 1500 mm

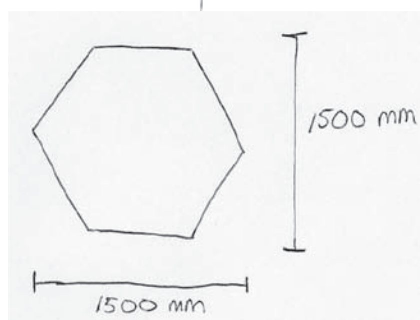
PATTERN CELLS

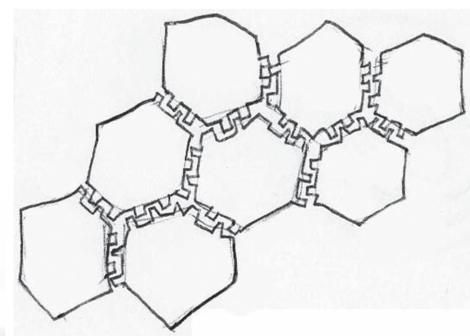
The cells of 40-250mm are placed on the whole module. A lot ot cells of 250mm are used. To cover the rest space between the cells, they will be surrounded by smaller cells of 40mm.

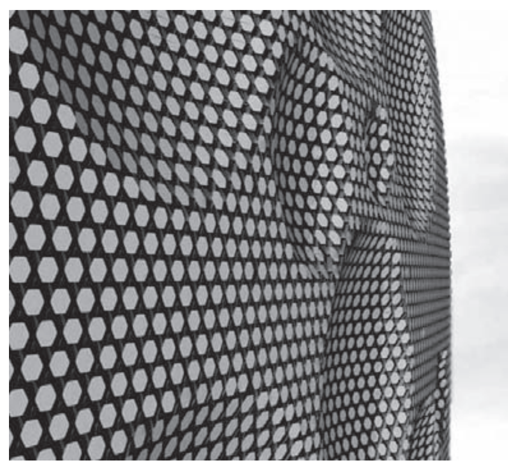
CONNECTIONS

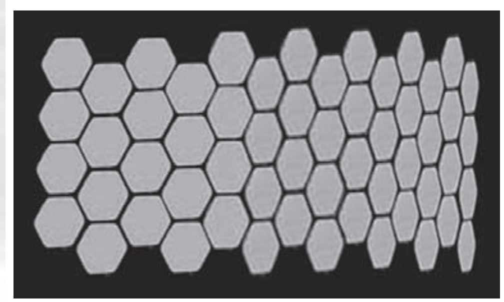
The modules will be electrical connected between the back of the module and the envelope of the building.











Concept 2
Tile

THE CONCEPT
The origin of this idea is to look for a simple geometrical shape which fits on curved surfaces but it should be a little bit more sophisticated than triangles. So this ‘tile’ shape was designed in order to be able to cover curved and flat surfaces with a module which is more appealing than just a triangle.

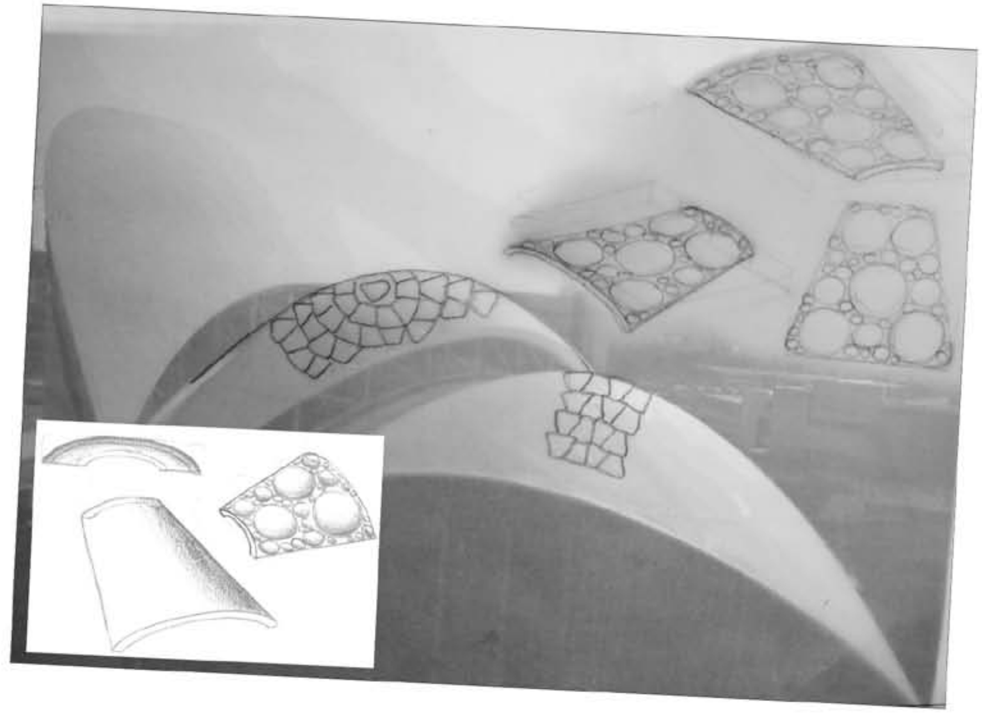
SHAPE
The module called ‘tile’ practically is a one-sided slightly curved trapezium where only two opposite sides are equal. This shape allows covering flat building envelopes and curved building envelopes only with a small percentage of unused space. Covering flat envelopes is possible by placing the modules alternately in opposite directions. Sharp curved envelopes can be covered when the modules are placed all with the small sides in the same direction.

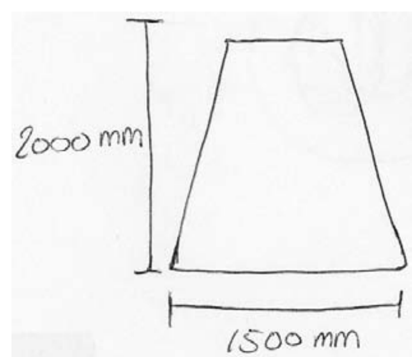
ELECTRICAL CHARACTERISTICS
Type of cell: amorphous silicon
Estimated Nominal power module: 180 Wp

MECHANICAL CHARACTERISTICS
Dimensions (LxW): 2000 x 1500 mm

PATTERN CELLS
The cells are placed all over the surface of the module. Cells of 40mm, 100mm and 250mm are placed in a random pattern with a lot of 250mm cells, which are surroun-ded by smaller cells.

CONNECTIONS
The modules will be electrical connected on the backside of the modules. This means that there will be some space at the modules surface where it is not possible to put cells.





Concept 3
Small

THE CONCEPT
Theoretically every module shape fits exactly on a curved roof, as long as you choose a size which is many times smaller than the roof itself. This allows looking for an exciting shape which is a little more complicated. Various types of shapes where made. Requisite was that all modules have the same shape and all together they fit exactly in a simple grid.

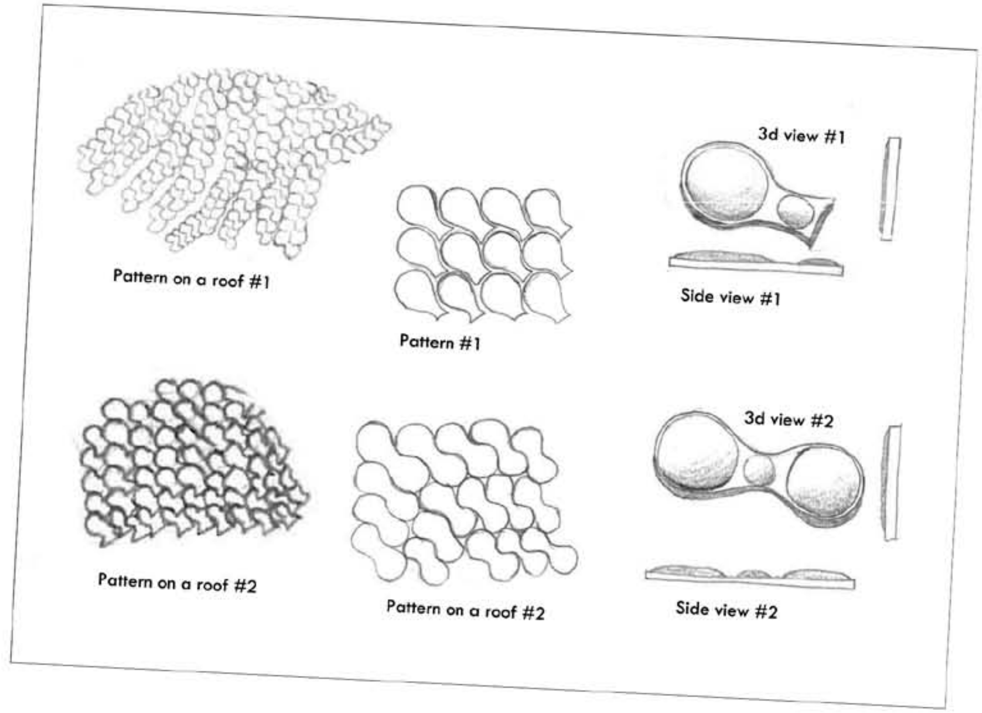
SHAPE
This concept exists of two variations. The first module has a shape which can be compared with the shape of an abstract sketched fish. The second one looks like two circles which are connected to one another smoothly.

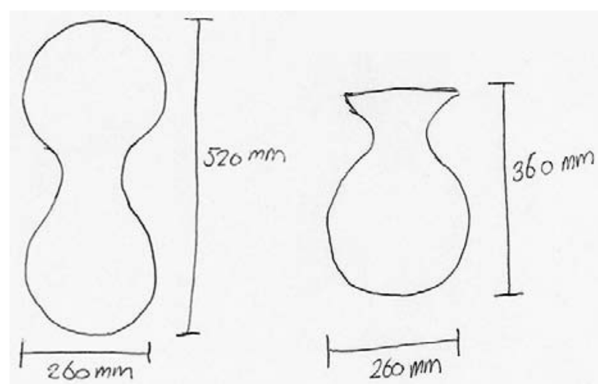
ELECTRICAL CHARACTERISTICS
Type of cell: amorphous silicon
Estimated Nominal power module: 5 Wp

MECHANICAL CHARACTERISTICS
Dimensions fish (LxW): 260 x 360 mm
Dimensions 'two circles' (LxW): 260x520 mm

PATTERN CELLS
In both the "fish" and the "two rounds" cells are placed all over the surface. On the "fish" one cell of 250mm is placed and on the "two rounds" two cells of 250 mm are placed. The rest-space is covered with cells of 100 and 40mm.

CONNECTIONS
The modules will be electrical connected on the backside of the modules. This means that there will be some unused space between the back of the module and the envelope of the building.





Concept 4
Round

THE CONCEPT
The idea in this concept was firstly to try to place a simple geometrical shape on a curved building. Secondly, it was the inspiration of the spherical bubble PV cell which led to the simple geometrical shape 'circle'. By putting circles in different patterns and analysing the rest-space, this concept turned out to be the most effective one.

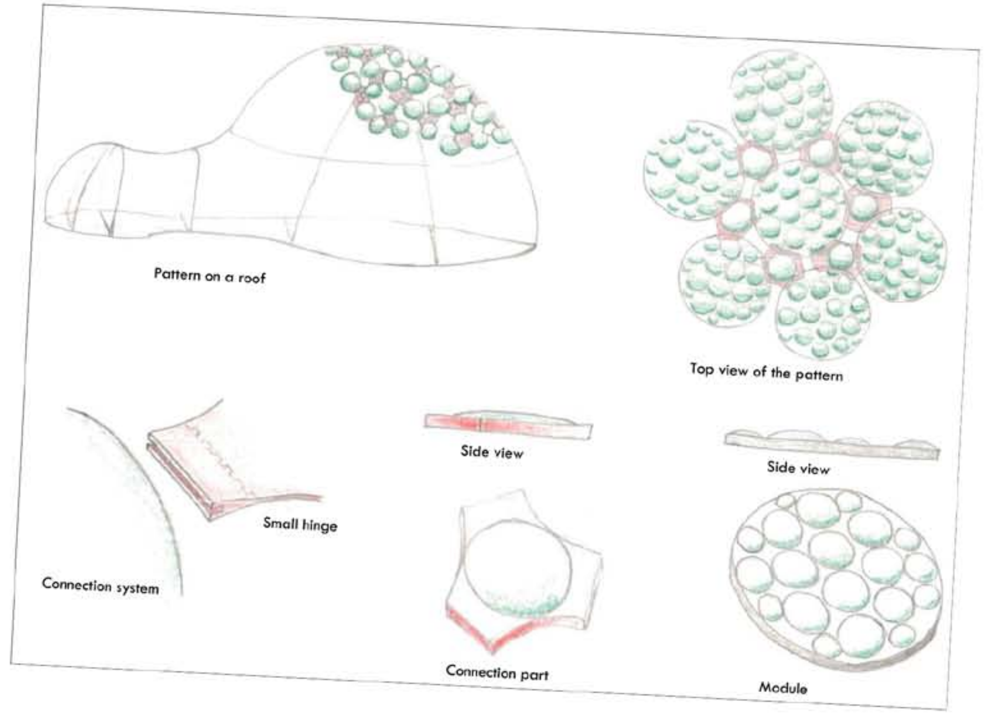
SHAPE
The module is circular shaped. Where three modules meet each other, in the middle a connection part is placed.

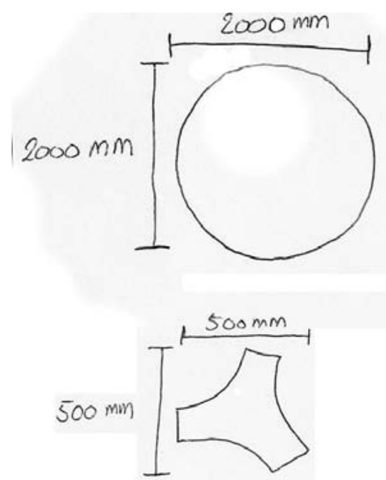
ELECTRICAL CHARACTERISTICS
Type of cell: amorphous silicon
Estimated Nominal power module: 200 Wp

MECHANICAL CHARACTERISTICS
Dimensions round module (LxW): 2000 x 2000 mm
Dimensions connection part (LxW): 500x500 mm

PATTERN CELLS
The module is the round part (see drawing on the right). On this, cells of 250mm, 100 mm and 50 mm can be found. In the center you can find the 250mm cells and near to the borders of the module more and more small modules can be found. On top of the connection part some PV cell are placed as well.

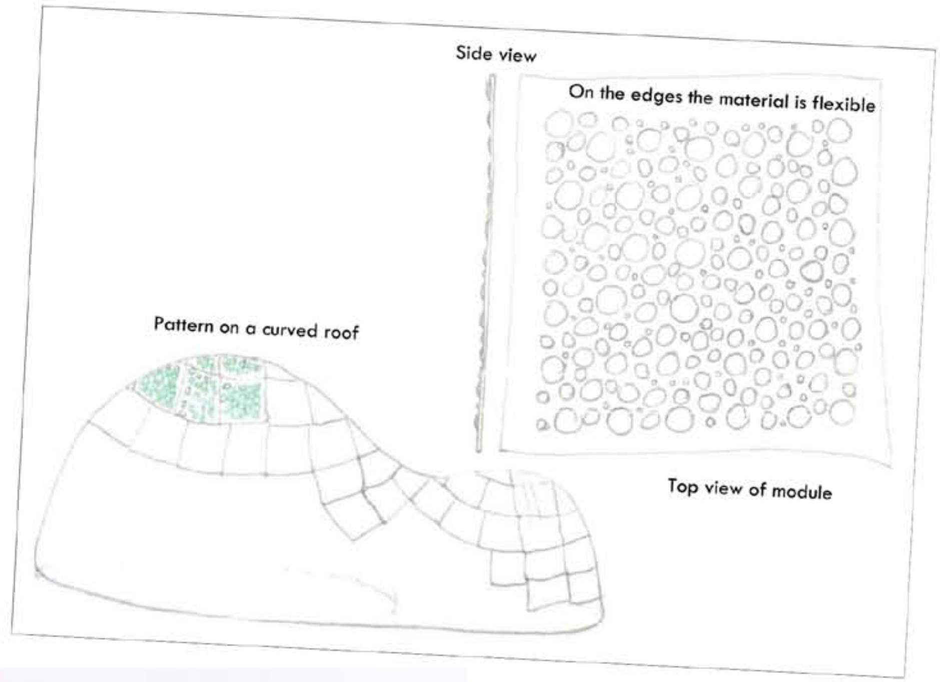
CONNECTIONS
The connection part realizes the electrical connection between three modules. The connection part is kind of triangle shaped and contains three hinges in order to allow small angles between the three modules.





Concept 5
Flexible

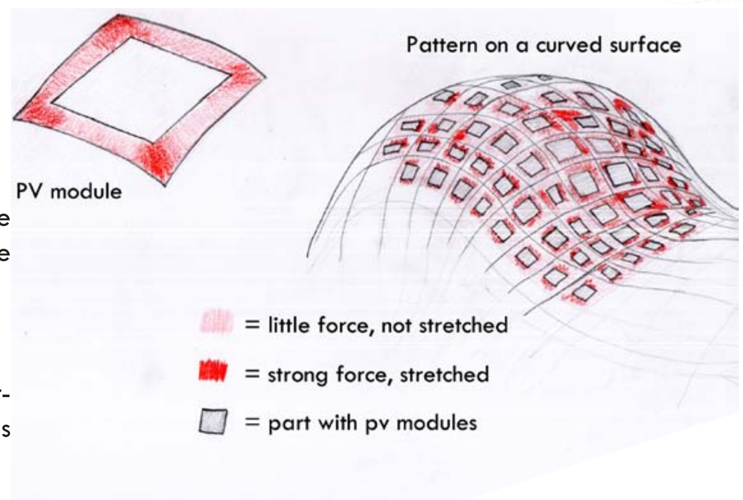
THE CONCEPT
In this concept there has been looking to the problem of a module fitting the building surface from a different angle. In this concept it is not the initial shape of the module which is adapted to the shape of the building surface but it is the material of the module which covers this problem.



SHAPE
This square module is made of a non-flexible material in the middle and a slightly flexible and elastical material on the borders. Due to the flexibility and elasticity of the borders of the module, it is possible to cover a curved building envelope.

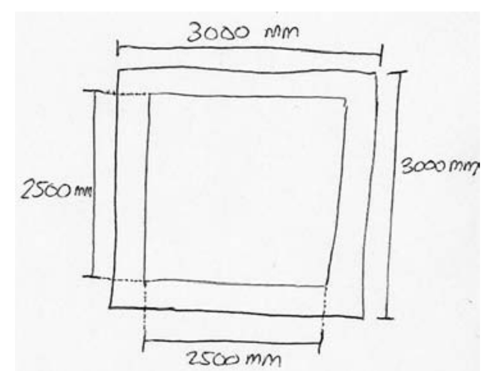
ELECTRICAL CHARACTERISTICS
Type of cell: amorphous silicon
Estimated Nominal power module: 400 Wp

MECHANICAL CHARACTERISTICS
Dimensions total module (LxW): 3000 x 3000 mm
Dimensions square with PV cells: 2500 x 2500 mm



PATTERN CELLS
The cells of 40-250mm are placed randomly in the middle part of the module. With this, I mean the white part of the module which is showed on the right side of this text.

CONNECTIONS
The electrical connection parts are integrated in the four corners of the module. The consequence of this will be that this part of the module cannot be covered with PV cells.



Concept 6
Imaginary circle

THE CONCEPT
Again the inspiration comes from the shape of the bubble cells. This concept is one of the different patterns that were generated. The shape of the rest-space makes you think you are looking to a pattern of circles.

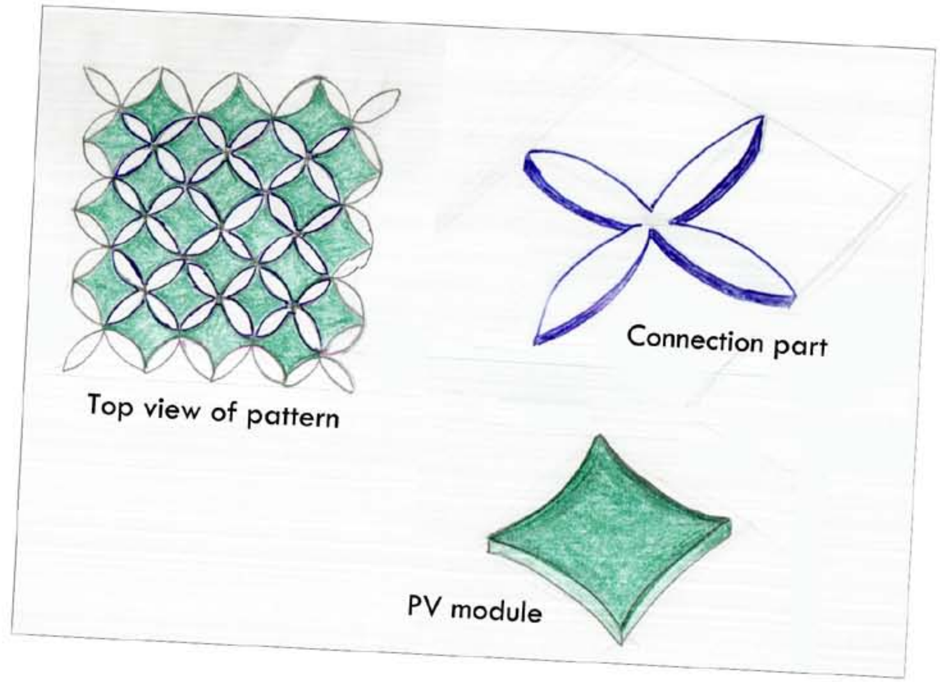
SHAPE
The shape of the modules is square, but every side is curved inwards.

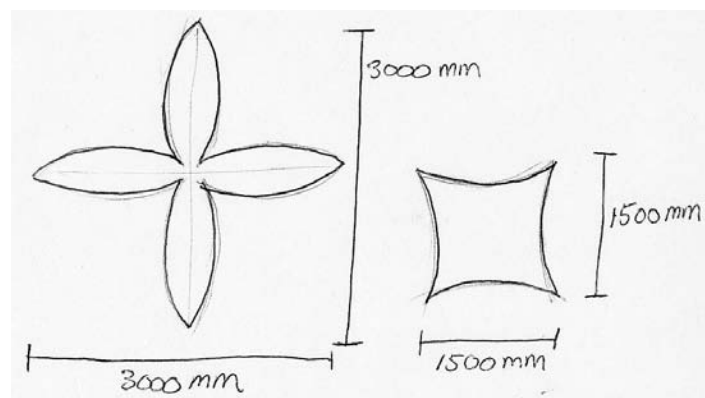
ELECTRICAL CHARACTERISTICS
Type of cell: amorphous silicon
Estimated Nominal power module: 60 Wp

MECHANICAL CHARACTERISTICS
Dimensions module (LxW): 1500 x 1500 mm
Connection part (LxW): 3000 x 3000 mm

PATTERN CELLS
Cells of 250mm are mostly placed on the borders of the PV module (this is the green part in the drawing). In the middle smaller cells with a minimum of 50mm are placed.

CONNECTIONS
In the area that is created by the inward curves, the connection part will be placed. This connection part is cross-shaped and the sides of the cross are curved outwards. On top of the connection part some PV cell are placed as well.





4.7.7 - Concept 7

Fish scale

THE CONCEPT
This concept also finds it origin in natural shapes. The round shapes are inspired by the shape of the bubble cells. The pattern of these modules together is the same as the skin of a fish. The separate module is a fish scale and when they are placed, two of them are overlapping one and this causes the particular pattern.

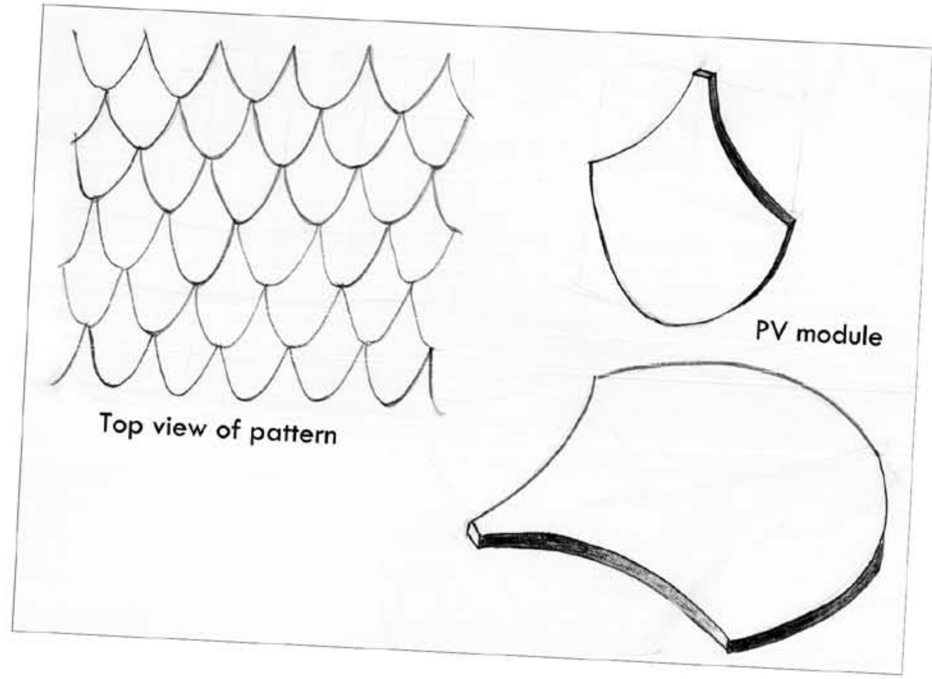
SHAPE
The modules have the shape of the scale of a fish and they are slightly curved. They will be overlapping each other a little.

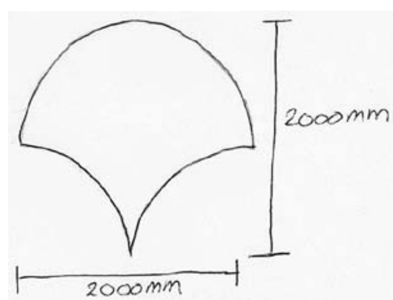
ELECTRICAL CHARACTERISTICS
Type of cell: amorphous silicon
Estimated Nominal power module: 120 Wp

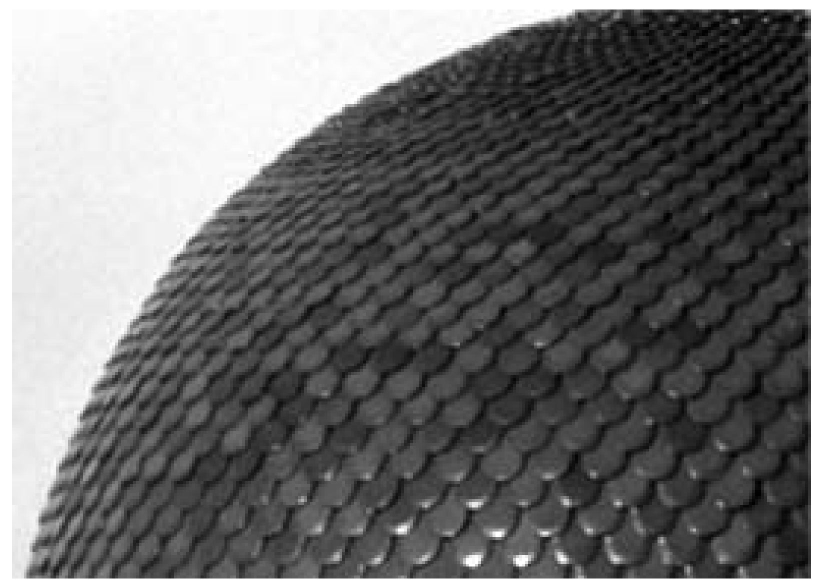
MECHANICAL CHARACTERISTICS
Dimensions (LxW): 2000 x 2000 mm

PATTERN CELLS
Large cells of 250mm are placed in all over the module. Cells with a diameter of 50mm will be used to fill as much non-covered space as possible.

CONNECTIONS
The electrical connection parts are integrated in the module. Because the fish scales are slightly curved, some rest-space is left under the PV module and in this area the electrical connection will be placed.







6.2 SELECTION OF ONE CONCEPT

The next step is to examine whether the concepts are meeting the requirements or not. This will be done in an organized table (table 6) with the requirements: adaptability, installation, coverage, aesthetics, price and customizability. Coverage and aesthetics are already explained in the previous chapter. The rest of the requirements need some explanation.

Dimensions and energy generation are two related properties. Although the dimensions and the energy generation are set in the concepts, these two properties are easy to adjust in the further development of the concept if this is required. So the possibility to fit on a curved building surface without having a lot of rest space is examined for a relatively big module of 3*3 meters. This depends on the shape of the module and the tolerance for angles of the mounting system. Basically, the possibility to adapt the PV module to the building, or shorter: the adaptability, is examined.

Examining if there is space left to integrate the electrical connections and if it is easy to mount the concept on the building surface checks the requirement 'installation'.

For the requirement 'price' the quantity of materials is examined. In this, the total amount of material needed per concept to cover the same building surface, but also the number of different kinds of materials is taken into account. The more material, the lower the grade.

Customizability is examined by asking if the concept allows to be customized in the area of positioning of cells, adapt colors and integration of sensors and LED's.

Requirements will be rated with 0, 1, 2 or 3. Zero means that the concept does not meet the requirement, one means that it only meets the requirement a little bit, two means that the requirement is met for the biggest part, and three means that the requirement is totally been met.

The concept called 'round' appears to have the highest score, so this will be the one chosen to be developed in more detail.

	1. Hexagonal	2. Tile	3. Small	4. Round	5. Flexible	6. Imaginary circle	7. Fish scale
Adaptability	2	3	1	3	3	1	2
Installation	1	2	0	3	2	3	1
Coverage	3	1	3	2	1	0	3
Aesthetics	3	2	3	3	3	2	3
Price	3	3	1	2	1	2	2
Customizability	3	3	2	3	3	2	3
TOTAL:	*15*	*14*	*10*	*16*	*13*	*10*	*14*

Table 6: rating the concepts

7. DEVELOPMENT OF THE MODULE

Now the final concept is chosen, roughly two aspects need to be elaborated. Firstly, the mechanical aspects need to be set. This includes determining the size of the module and the connection of the PV module to the connection parts. The results will be modeled in Solidworks. Secondly, the electrical lay out in the PV module needs to be determined and therefore the positioning of the PV cells need to be determined first.

7.1 SIZE OF THE MODULE

To discover if only one size of modules is enough to cover a buil-ding surface, one of the buildings that was already analyzed will be chosen as a representing building to try the modules on.
This building will be the International Convention Center (CICCM) in Madrid. This one is picked, because of two reasons. In the first place because this building has slightly curved parts and sharp curved parts on the edges, which are facing all possible directions. These two properties need to be present in a representing building. The second reason for choosing the CICCM is its largeness. The buildings in the Blob analysis can roughly be divided in two categories: small buildings with a building surface of about 800–4.000 square meters (the roof of the Rabin Center, Water Pavilion and Fluid Vehicle Station) and large buildings with a building surface of about 14.000–60.000 square meters (Guggenheim Museum, Selfridges building, Kunsthaus and International Convention Center). The size of the PV modules depends on the size of the buildings you are designing for. In this stadium there is chosen to design for the category of large buildings, because of the effectiveness of the used technology, which is amorphous thin film. For thin film amorphous a sufficient large area is needed to generate one kWp (14–20 square meters). This means that you will need to be able to make large strings of solar cells, which is only possible in large modules. So for this reason, a large PV module area and therefore a large building surface is needed to still have profit in terms of generated energy and so saving energy costs.

Below a render of one module on the CICCM (figure 20) is shown. You can also see a zoom in of the module on the International Convention Center. It can be concluded that there is no need to make two different sizes of modules, because there will be no big rest area under the modules due to the sharp curves in the building. Therefore the decision is made to develop only one module with a diameter of two meters.

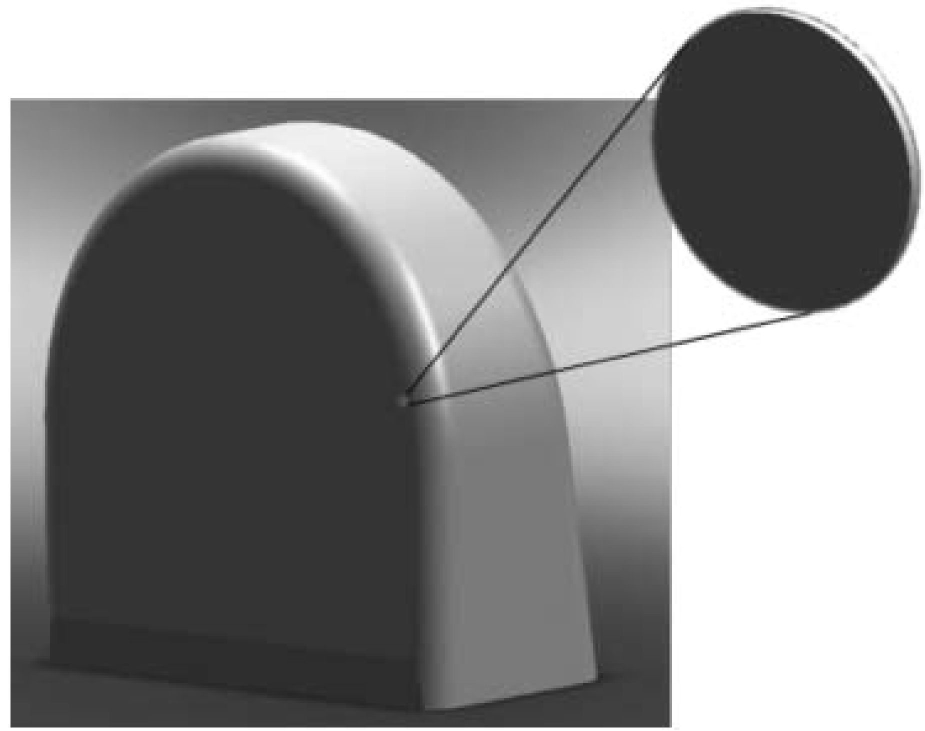


Figure 20: module on CICCM

7.2 CONNECTION BETWEEN MODULES

To investigate how the modules and connection parts behave compare to each other, a small and flat model is made of paper and connected with tape (figure 21). This model is placed on a curved object to investigate the needs for rotation. It can be concluded that the connection part needs to be able to rotate on its X and Z-axis with respect to the modules (figure 22).

Figure 21: representation PV system

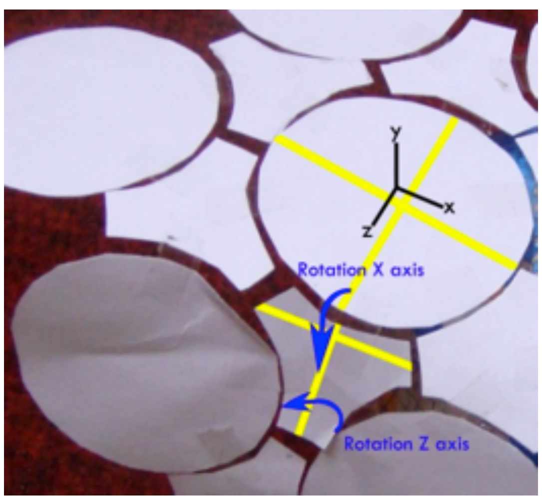


Figure 22: rotation PV modules

The next step was to search for a solution for the rotation problem. A small research to mechanical parts that allows objects to rotate in two directions has taken place. The so-called tripod; the stand of a photo camera, seems to be the perfect example for this design problem (figure 23).

Figure 23: tripods

This has been adjusted to this particular situation and thereafter it has been modeled in Solidworks as a part of the connection part (figure 24). A picture of the connection part, connected to two modules, can be found in (figure 25).

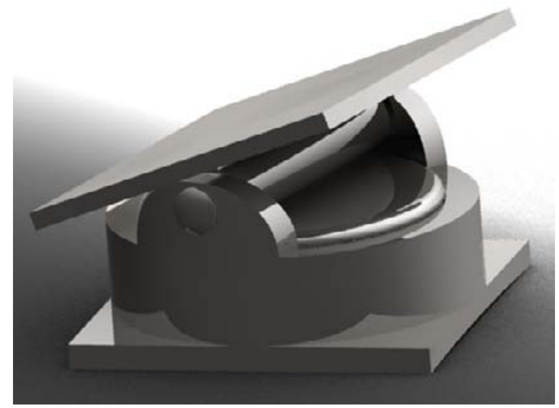


Figure 24: render of connection part

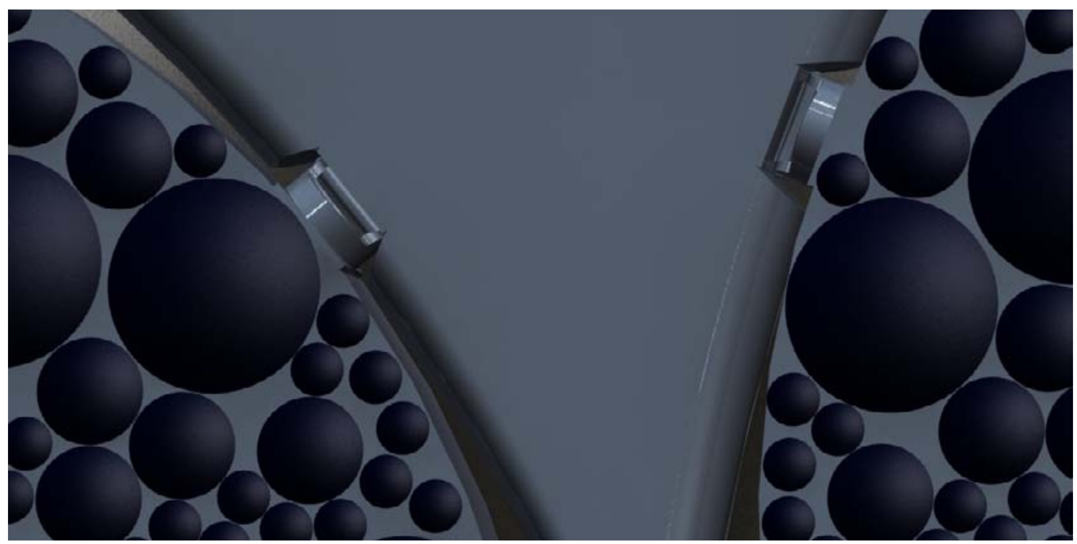


Figure 25: two modules connected

7.3 POSITIONING OF THE CELLS

A total building surface coverage of 70% is aimed at. The connection parts will take up 7% of the total surface. This means that the total loss of PV area due to rest space between cells may be 23%, so the PV cells should cover 77% of the total surface of the module to achieve the goal. In this chapter firstly it is tried to position the PV cells in a geometrical pattern and secondly it is tried to make a more naturalistic pattern.

7.3.1 Geometrical pattern

In the next layouts the background of the PV modules always has a diameter of two meters.

The first pattern that was tried, can be found in figure 26. In this pattern it is attempted to fill as much area as possible. Out of this drawing can be concluded that the total surface covered with PV modules is 2,63 square meters. This is 83,7% of the total surface. A big disadvantage of this layout is that due the use of too many different sizes of cells, the wiring will be very complicated.

Another geometric pattern was tried in figure 27, in which the attempt was to make a geometric but still appealing layout with only one size of cells. The radius of the cells is 100 millimeters. Out of this drawing can be concluded that the total surface covered with PV modules is 1,73 square meters[1]. This is a very low coverage of only 55%.

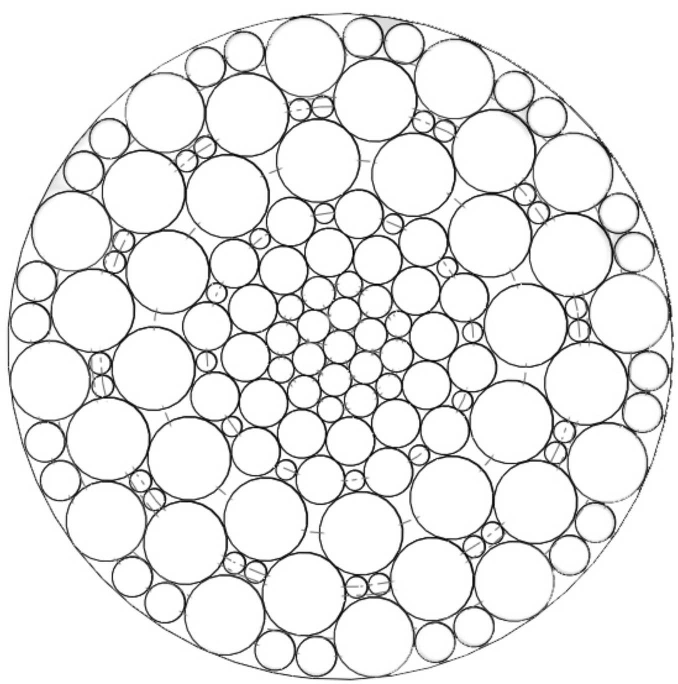


Figure 26: pattern in which as much area is filled as possible

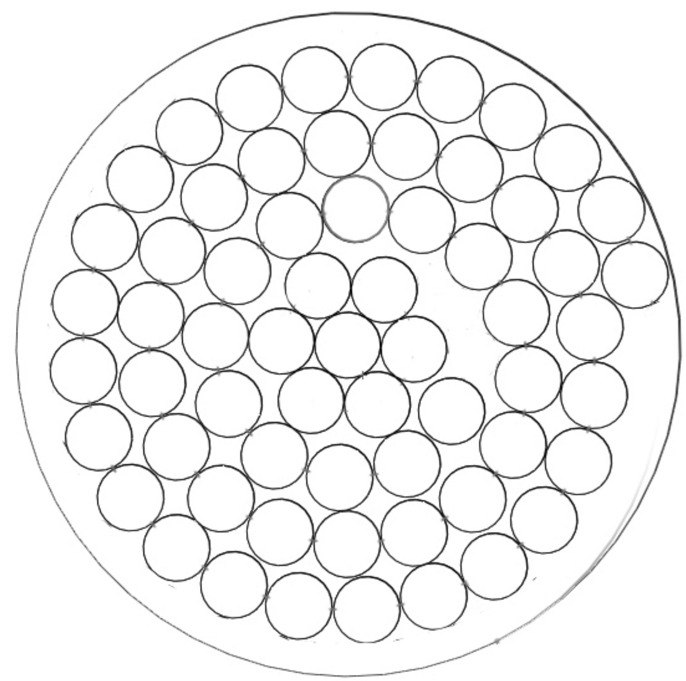


Figure 27: geometric pattern - a spiral

[1] There are 55 PV cells with a radius of 100mm. The formula for the surface of *n* circles is $n*(\pi r^2)$, so the total surface of the cells is 1,73 square meters.

The next step was to fill the rest space (figure 28). Cells of 75, 65 and 45 millimeters are used. Now the coverage is higher, it is 2,06 square meters[2]. This is 65,5% of the total surface of the module. Unfortunately the layout is less appealing.

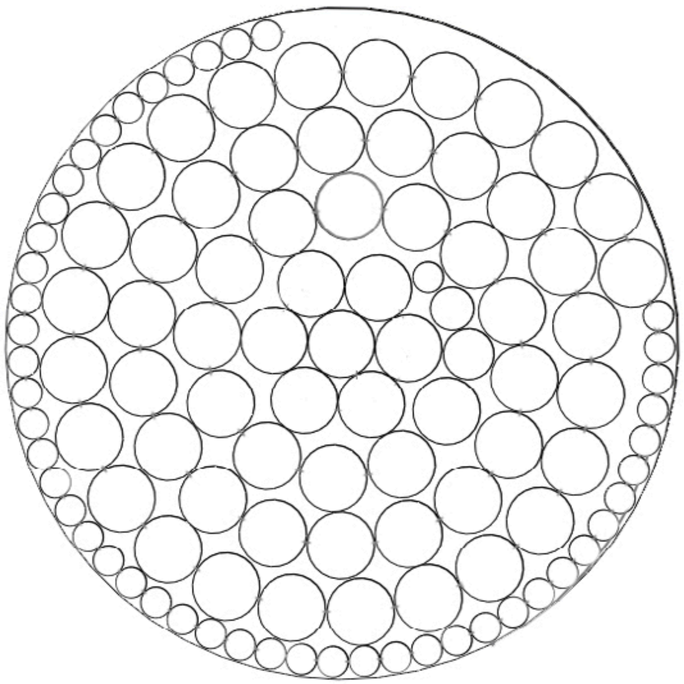


Figure 28: spiral and filled rest space

In sum, the following knowledge is gained. It was already said that the resulting current will be determined by the minimum. Therefore it is important to make an array of cells of the same sizes. When looking at the first try out, it can be concluded that this are too much different sizes, because wiring will be very complicated. The maximum amount of different sizes of PV cells will be set on three, so that wiring will not be too complicated. Secondly, it can be said that it will be hard to find a geometrical pattern that meets the requirement of coverage of 77% and is still appealing. Therefore random patterns are made.

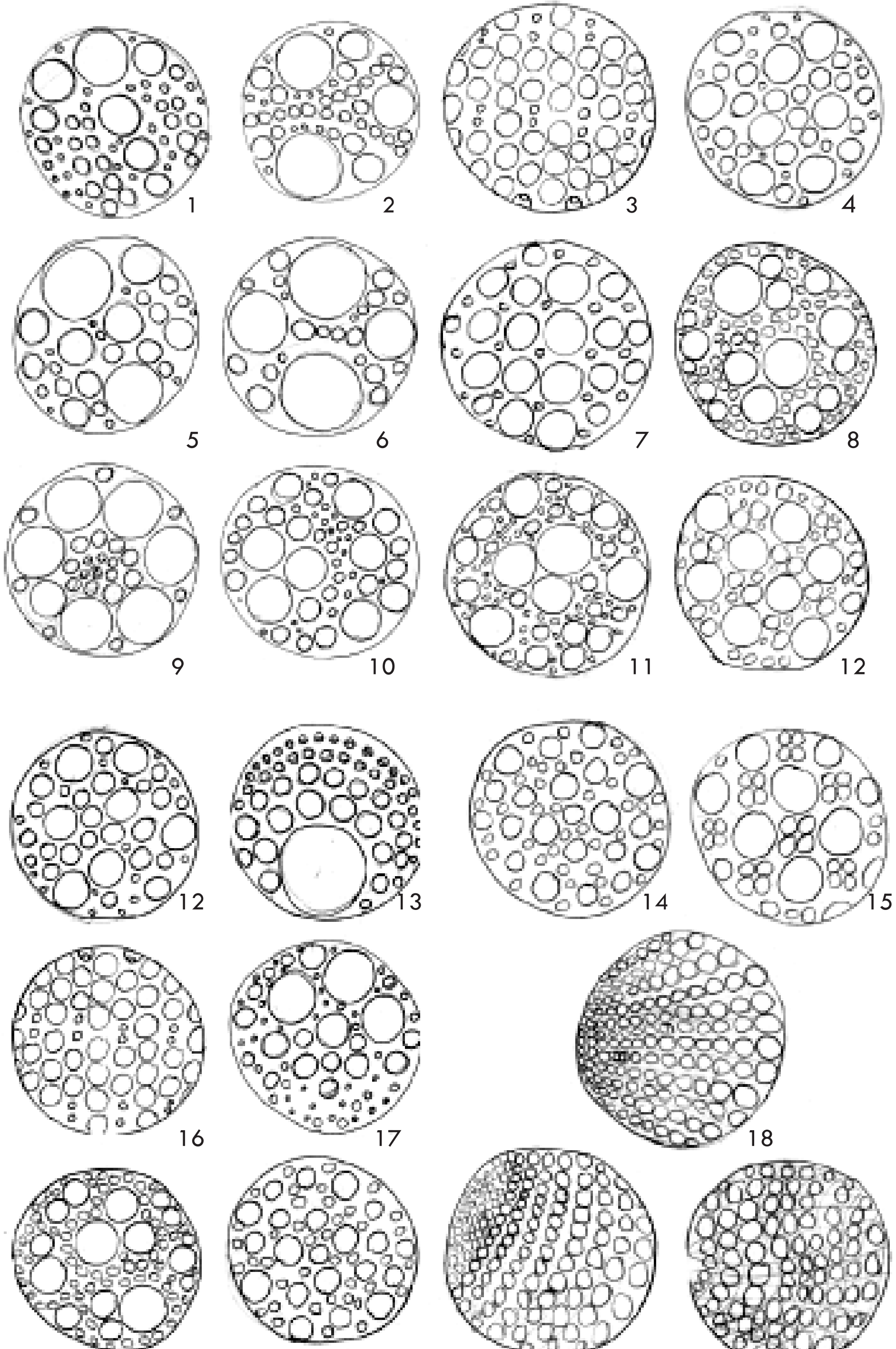
[2] There are 55 PV cells with a radius of 100mm, 48 cells with a radius of 45 mm, one cell with a radius of 75mm and one cell with a radius of 65 mm. Therefore the total surface of the cells is 2,06 square meters.

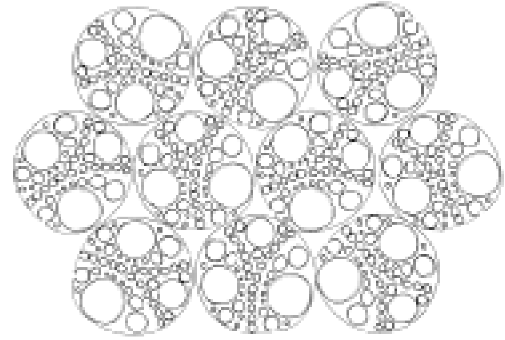
7.3.2 Natural pattern

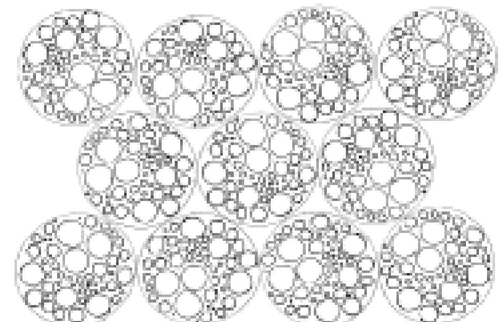
Random patterns of three and sometimes four different sizes of cells are tried out, on a module with a diameter of one meter. Inspiration is found in several pictures of patterns with circles (figure 29). The cells have been drawn on a module and there is tried to connect the cells of the same size, by drawing colored line through these cells.

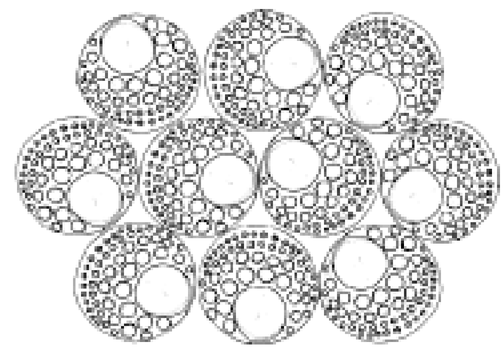
Figure 29: inspiration

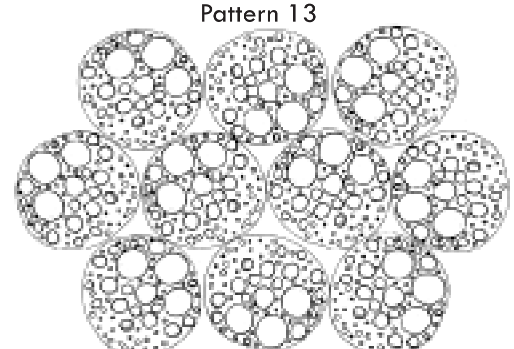
On left side of the next page the natural patterns of PV cells on a panel are shown. The four modules that are looking the best were chosen. From those modules, four patterns where made with the same modules, which you can find on the right of the page.




Pattern 2


Pattern 10


Pattern 13


Pattern 17

Pattern 10 is chosen to develop in more detail, because it looks appealing in a pattern, it is roughly made out of three different sizes of cells and the wiring will not be too difficult, because the cells of the same size are reasonable near to each other. The decision is made to use diameters for the cells that are a multiple of each other, because in this way it is the most easy to calculate the total current. So the sizes of the cells will be 200, 100 and 50 millimeters.

The next step was to draw a sketch of this module in Photoshop and analyze if the goal of a coverage of 77% can be met. This means a total cell surface of 77% of 3,14 square meters = 2,42 square meters. In the drawing 35 cells of 200 millimeters, 121 cells of 100 millimeters and 332 cells of 50 millimeters are used, which makes a total surface area of 2,70 square meters. The conclusion is that the goal of a coverage of 77% can be met when using this pattern. Because of the possibility to use the 50 millimeters cells to cover rest area, the assumption is made that the small module of 1 meters will also meet the coverage goal of 77%.

The module has been modeled in Solidworks (figure 30). On the module 42 cells of 200 millimeters, 70 cells of 100 millimeters and 300 cells of 50 millimeters are placed. This represents a total surface of 2,46 square meters, which is 78% of the total surface of 3,14 square meters.

7.4 ELECTRICAL LAY-OUT

Now the pattern and the number of cells are known, the current can be calculated. It was already said that the energy generation of amorphous silicon is about 60 Wp/m^2. The Voltage is 0,5V, so the current is 60W/m^2 divided by 0,5V is 120A/m^2.
So the cell with a diameter of 200 millimeter will have a current of $\pi(0,1)^2 * 120 = 3,77$ A. For the 100 millimeter cell this will be $\pi(0,05)^2 * 120 = 0,94$ A and for the 50 millimeter cell this will be $\pi(0,025)^2 * 120 = 0,24$ A.

After this, the parallel and series connections between the cells were defined. The results of this are shown in the fourth, sixth and seventh column. Logically, the current and voltage are determined by using this knowledge. These values can are listed in the last two columns of the table below (Table 7).

	Single		*Number of cells*			*Total*	
Cell	*I (A)*	*U (V)*	*Number*	*Parallel*	*Series*	*I (A)*	*U (V)*
d=200mm	3,77	0,5	42	1	42	3,77	21,0
d=100mm	0,94	0,5	70	2	35	1,88	17,5
d=50mm	0,24	0,5	300	6	50	1,44	25,0

Table 7: calculation of the current and voltage per module

As you can see, the voltage is not the same and this means that you need to use three inverters per module to prevent current losses. Technically and financially this is no option. This means that there are two choices: accept a loss or optimize the number of cells. For example, it would be an option to try to fit 40 200-millimeter cells, 80 100-millimeter cells and 280 50-millimeter cells in the module. This would result in the possibility to use only one inverter of 20 V, because 40, 80 and 280 are all numbers that can be divided by 20.

The wiring of the cells, carried out as described in the table, can be found in below in (figure 30). There are three separate electrical schemes, one scheme for each cell-size. The cells will be connected on the back side with ribbon.

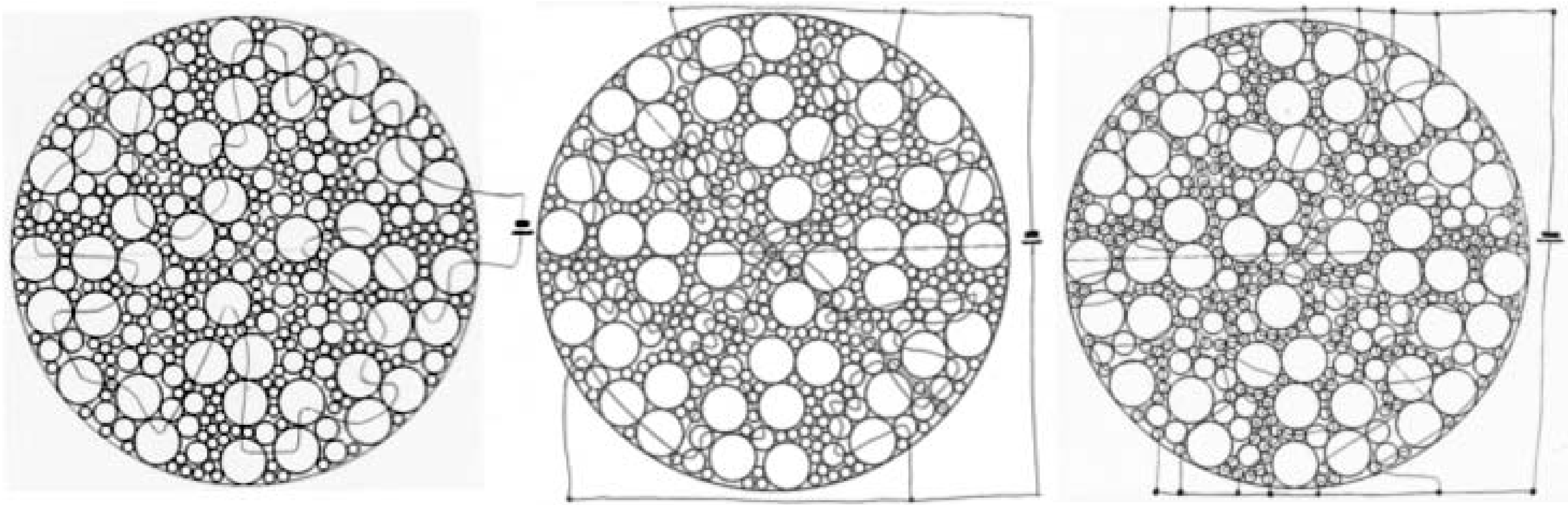


Figure 30: electrical lay-out of 400 (left), 200 (middle) and 100 (right) millimeter cells

7.5 RENDERS

The renders of the module are presented in this sub-chapter. Also the materials are mentioned on the next page. The dimensional drawings can be found in Appendix III.

The cells are made of curved borosilicate glass. On this glass, thin film amorphous silicon layers will be deposited.
The cells will be positioned in a “mall” with holes. Under this layer, the wiring that connects the cells is positioned.

The appearance of the module can be customized. The material where the module is made of, PP, is available in many colors. On the right renders of four different colors of modules are showed.

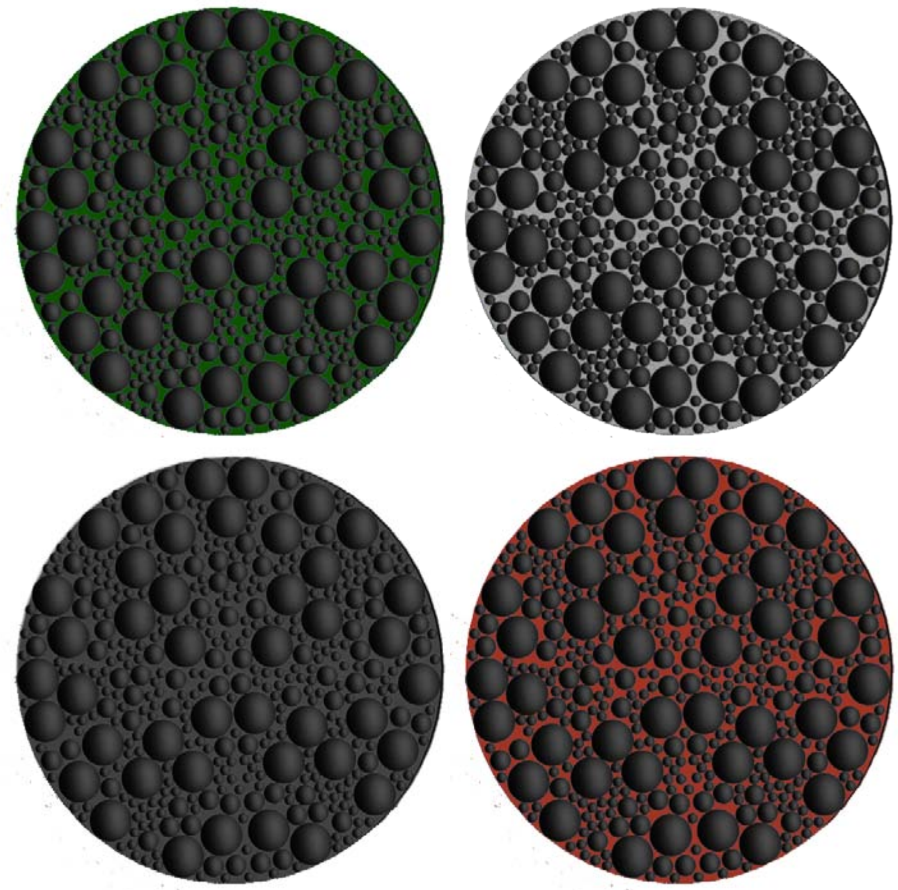


Figure 31: PV modules in green, white, black and red.

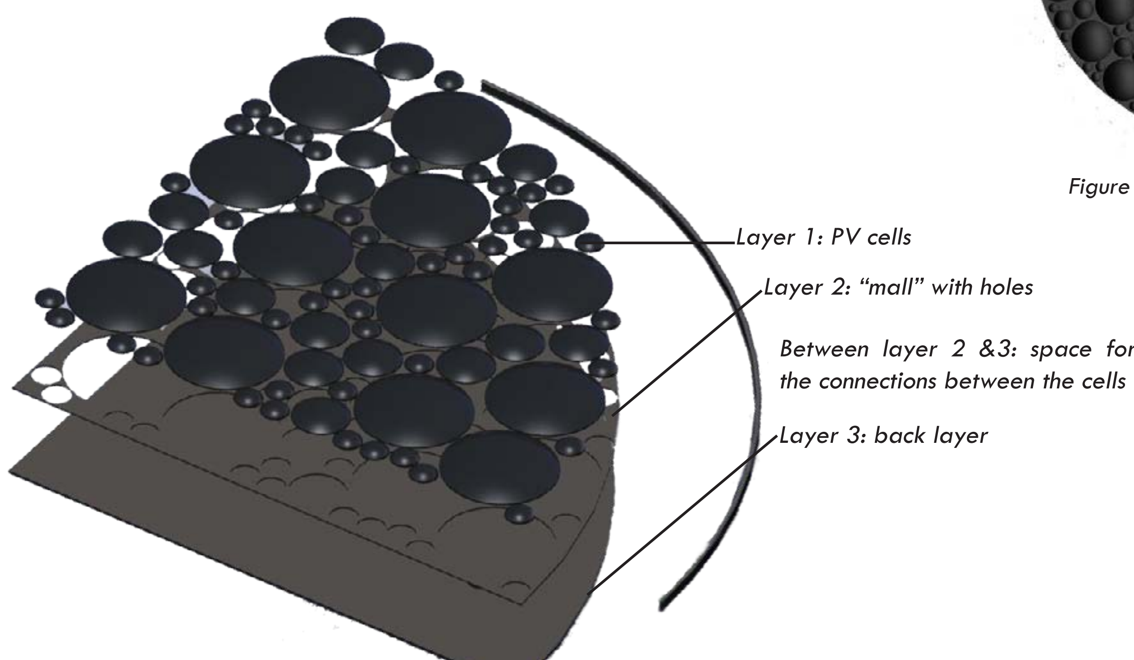


Figure 32: exploded view layers PV module

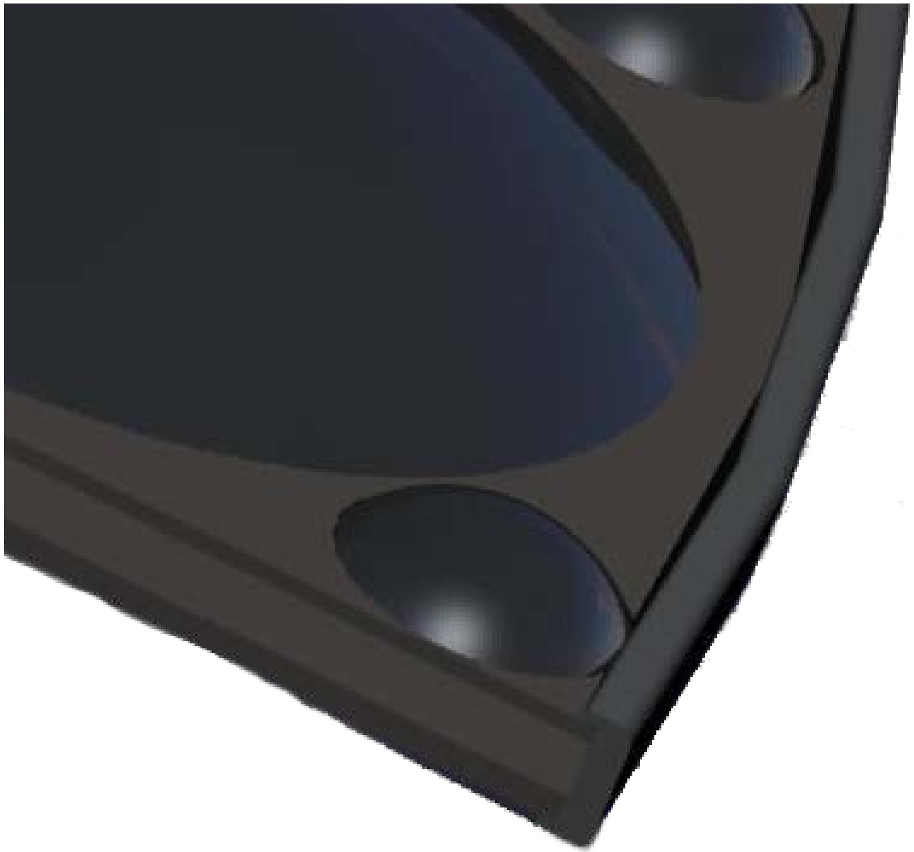


Figure 33: render cross-section module

Figure 34: render and Photoshop adaptation of PV bubble modules on the Selfridges building in Birmingham

As showed in the page before this one, the PV bubble module will be build-up out of three parts, a lot of PV cells and wiring.
The back layer and the “mall” layer will be made of PP (homopolymer, clarified/ nucleated), that was already selected in chapter 5.3.
The surfaces that will be exposed to the environment, will be treated with a UV resistant coating.
The edge of the module will be made of aluminum, because this material has already proved to be strong but light and therfore it has been used in many other PV modules.

7.6 CHECKING THE REQUIREMENTS

Now all aspects are determined, the requirements that where already defined, can be checked. This will be done one by one.

Requirements

- *Dimensions*

The preferred dimensions of the cells were set on 40 – 250 millimeters. The cells used in the PV bubble module have diameters of 200, 100 and 50 millimeter. The desirable dimension of the module was set on 2*2 meters. The module will have a diameter of 2 meters. Under a module of 2*2 meters a rest space of 83,9 millimeters is accepted on a building with a curvature of r=6 meters. The connection part of the design will ensure that the module can be placed directly on the roof, so the rest-space will never be more than the calculated space.
>> All requirements concerning the dimensions are met.

- *Adaptability*

The module should be suitable on building surfaces with a minimum radius of 6 meters.
In this context the word 'suitable' means that the modules have a reasonably close fit on the building and the mounting system allows to be fixed on every surface.
A connection part is used between the modules and the advantage of this part is that it is possible to position the modules closely to the roof and so the shape of the PV system can be totally adapted to the roof. The second advantage is that this connection part can be used to connect the modules to the roof, and so the modules do not have to contain this mechanical aspect.
>> The adaptability requirements are met.

- *Energy generation*

The area requirement is set on 90% of 60 Wp/m^2 = 54 Wp/m^2. Out of the table with electrical information can be concluded that the total power will be 148 Wp.
>> The requirement concerning energy generation is met.

- *Installation total system*

It should not take too much time to install the modules on the roof, connect the modules and the inverters. The requirement is that it should only take 1,5 times the time it takes to install a standard crystalline module system.
To install the standard crystalline module system, an aluminum frame needs to be connected to the roof and for this special mounting parts need to be fixed to the roof. For the PV bubble module you will also need special mounting parts to fix to the roof, before you will be able to connect the modules to the roof. An advantage is that you are allowed to choose to only fix the connection parts you prefer to the roof.
>> Because of this reasons, it is assumed that it will not take more time to connect the PV bubble modules to the roof than to connect a standard crystalline module system.

- *Coverage*

A total building surface coverage of 70% is aimed at. The connection parts will take up 7% of the total surface so the cells need to cover 77% of the total surface of the circle. 2,46 square meters of the total surface of 3,14 square meters is filled and this is 78%.
>> The requirement of covering 70% of the building surface is met.

[3] The total power can be calculated by taking the sum of the value for the power of every string of cells with the same size. The formula for the power of one string of the same cells is P = I (total) * U (total).

- *Aesthetics*

The PV module should be designed with high architectural quality. The requirements coming from the IEA were:

- The system is naturally integrated; the PV system completes the building.

>> The cells on the module have a natural pattern and the total system allows to exactly fit the building surface, so the system is naturally integrated.

- The PV system adds eye-catching features to the design.

>> The total PV system changes the look of the building. The modules and the pattern of the cells in the modules will be an eye-catcher for the environment. Using LED's between the cells can even increase this effect.

- Color and texture of the building should be in harmony with the other materials.

>> Natural colors in gray-scale can be used, but you can also choose for a color. So the appearance of the materials used, will not differ from the materials that are used in the buildings.

- The sizing of the PV system matches the sizing and grid of the building.

>> The idea is to fill every part of the building surface that catches sunlight. Only on places when the curvature is too sharp, it is not possible to place modules. That is why the sizing of the PV system will match the sizing and grid of the building.

- The total image of a building should be in harmony with the PV system.

>> This requirement is very case dependent. But in most of the times, the total image of the building will be in harmony with the PV system.

- *Price*

The price of the installation of a PV system of bubble modules should be only 1,5 times the average price of the installation of a crystalline silicon system.

>> It is assumed that this requirement will not be met. The reasons for this are that the technique to make the PV cell needs to be optimized, all parts in the module are so specific that they need to be fabricated in the right shape and the connection part is something extra in comparison to the crystalline silicon system.

- *Material*

- The PV module should be resistant to fresh water, deterioration and of course to UV radiation.

- According to the IEC requirements, the maximum service temperature should be 90°C.

- It is allowed to be easily flammable and to contribute strongly to the spread of fire.

>> Glass and PP are both resistant to fresh water, deterioration and to a temperature of 90°C. PP will be made resistant to UV radiation by treating it with an UV resistant coating.

- *Sustainability*

- The material should be sustainable. This will be compared to the embodied energy of primary production of aluminum, which is about 200 MJ/kg. The embodied energy for the primary production of the outside material of the PV module may not be higher than this value.

>> The embodied energy for PP is 98.7 MJ/kg and for glass this is 27 MJ/kg. Further aluminum will be used. So all the materials will not have a bigger value for embodied energy than 200 MJ/kg.

Wishes

- *Customizable*

The positioning of the PV cells is adaptable, the color of the module can be adapted to the demands, there are light, warmth and movement sensors integrated in the system and LED's are integrated.

>> The color of the module can be adapted. The rest of the requirements are not met in the PV bubble module in the way it is presented right now, but there is space left between the cells and between the modules, so it would be possible to integrate LED's and sensors.

CONCLUSION AND DISCUSSION

The objective of this assignment was to develop a new PV module in which spherical cells are used, which can be integrated in the current Blob architecture. The result of the assignment is a concept for a PV module with sphere cells, that can be used on the curved envelope of Blob architecture and that can be customized in order to meet the requirements of every customer. In the concept, customisation of the color of the module is possible. In conclusion, the purpose of the assignment has been met. But this will not give the certainty of social acceptation of the new concept. It can be read in the survey that not every architect believes in PV modules on every kind of building envelope. From the chapter “Products” it can be concluded that there are already companies that believe in the possibilities of selling innovative PV products. So it is assumed that there is a market for the PV bubble module, but it still needs some effort to make more architects enthusiastic.

Not everything is been developed in great detail. For further development people with more expertise in the different mechanical, technical, material and production areas are needed.
In the first place more research should be done to the working of the spherical cells. Because, as said in chapter one, the cells are not performing very well at the moment due to the disuniformity of the thickness. Because of the use of a big number of cells of three different sizes, the wiring is very complicated. This should be developed in greater detail and it should be tested, in order to be sure about their performance.
The use of this big number of cells bring two more problems: the coverage cannot be optimal because of the rest space and it possibly will be hard to maintenance the PV system after installation. This is because the surface is not equal in height and so it could be hard to keep it clean and so receive all sunlight’s insolation.

Concerning the connection part, there are also aspects that need improvement. The mechanical part that cares for the movement in X and Y direction as you can find it in chapter six, only gives a representation of the working. The elaboration should be more in detail in order to be able to use it. The way the connection module should be connected to the roof needs even more further development. There has been thought about the fact that some connection modules have a bigger distance according to the roof than others, due to the curvatures in the envelope of the Blob buildings. Therefore a part needs to be designed which can be height-adjustable.

Further the electrical connection between the module and connection part is not been elaborated exactly. It should work like a so-called “plug-and-play” system: only one small action should connect the modules electrically. This principal is been used a lot already, so it is assumed that it will be a good solution for the problem of electrical connection.

The material used for the module will be PP and the performance of this material, in combination with the UV-resistant coating, should be tested, because this is not been proved yet.

The production methodology needs to be defined in more detail in order to be able to produce the PV bubble module.

Only the possibility to customize the color of the module is present in the current design. In order to be able to adapt the module to your demands, more research has to be done to the possibility of placing LED’s and sensors.

Finally, a cost-benefit analysis need to be made in order to be sure that the PV bubble module will produce enough energy at the long-term.

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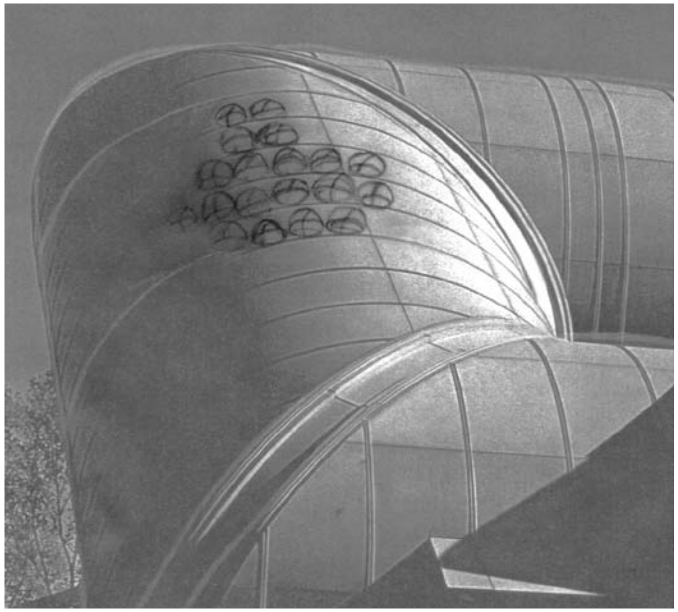
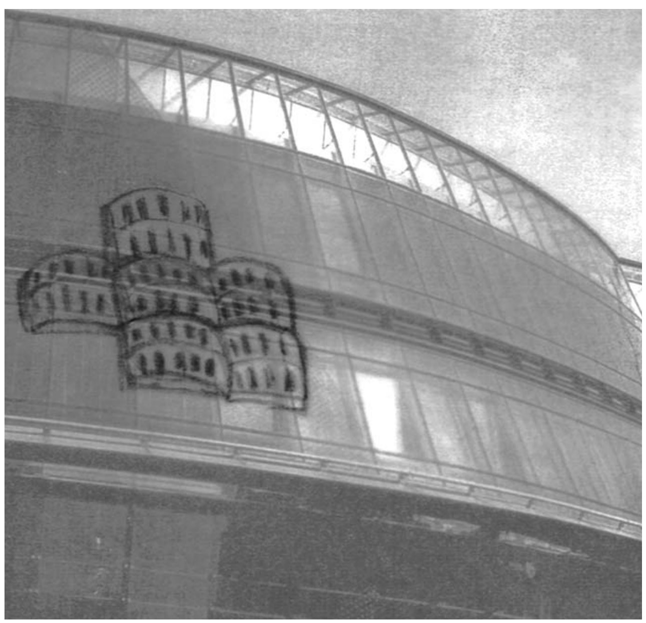
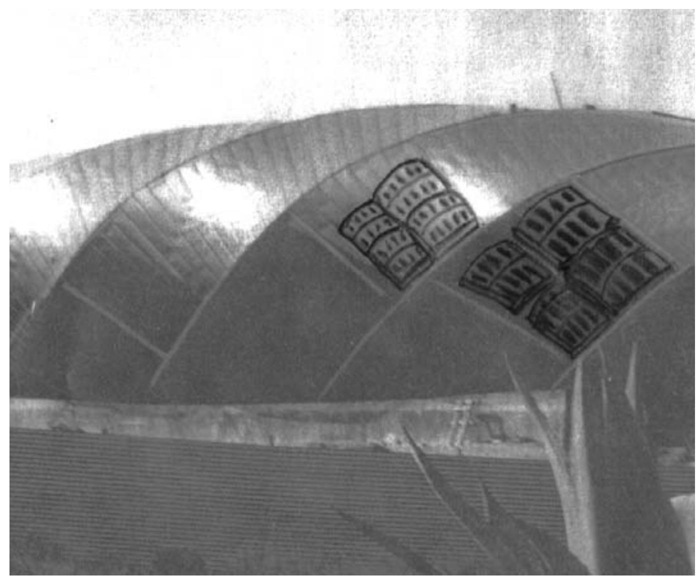
APPENDIX I: MODULES ON BUILDING

In order to get to know more about the advantages and disadvantages of the flexible thin-film module, Sphelar, ETFE and Solyndra, are being tried out on buildings. Sphelar and ETFE are shown on different buildings that are curved two-sided.



APPENDIX II: SURVEY PV BUBBLE MODULE

INTRODUCTION

In order to create a concept for the bubble photovoltaic (PV) modules that are likely to be used in the future, the wishes of architects should be taken into account.

The International Energy Agency (IEA) Task 41 has already dealt with the issue of general barriers that architects are facing concerning integrating PV technologies in their design. Outcome of the survey was that economic issues were the largest barriers.

During my project, I want to get more into detail by developing a product that enables architects to integrate PV in architecture more easily. Consequently, I would like to ask you to fill in the following questions about barriers, wishes and solutions concerning PV products to be used in architecture and in architecture with curved envelopes.

The answers can be written below the questions. If there are options to choose between, please delete the answers that you don't think are suitable.

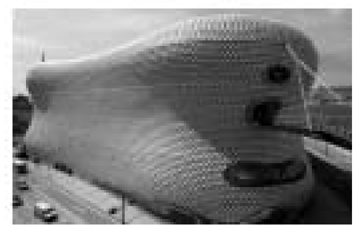
TERMS USED

Where 'standard PV module' is said, rigid, square, flat, dark coloured modules are meant.

Below a picture of a flexible thin-film module and of a building with a curved envelope is shown.

'Standard PV module'

Flexible thin-film module



Building with a curved envelope

1. GENERAL

- In how many projects have you been involved as an architect?
- In which architectural projects did you use PV modules?
- Please give the two most important arguments for deciding not to use PV modules in a project.
- Did you ever feel limited in designing a building because the use of PV was necessary? Yes / No
- If yes, why?

2. BARRIERS AND WISHES

How important do you consider the next five barriers concerning the use standard PV modules in architecture? Please use the 1-5 scale with the following statements and delete the answers you think are not suitable.

1=strongly disagree, 2=disagree, 3=not sure, 4=agree, 5=strongly agree

The lack of suitable products for quality building integration is an important barrier for using PV in buildings.
1 2 3 4 5

Integrating PV modules in the building is difficult because the colour or the sort of material of the modules is often not in harmony with the building. 1 2 3 4 5

Integrating PV modules in the building is difficult because the shape of the modules is often not in harmony with the building. 1 2 3 4 5

It is too expensive to find a solution for PV modules in architecture. 1 2 3 4 5

Material, colour, structure and/or shape of the building is/are no longer in harmony with the environment of the building when applying standard PV modules. 1 2 3 4 5

There are more problems, that is (please fill in)...

Should a PV module be customizable? Yes / No. If yes, please choose between:
Different shapes / different colours / positioning of the cells / integrate LED / other, which is...

If you have any more wishes considering the design of PV modules, please write them down here.

3. CURVED ENVELOPES

Do you have wishes concerning the use of PV panels in 'curved' architecture? If yes, please write them down here…

What do you consider to be the three largest barriers in using a 'standard' PV panel in architecture which contains curved envelopes? Please choose between: lack of products / integration with the building / price / integration with the environment / other, which is ….

Do you consider small (up to 150x150mm) PV modules as a solution for the problems of using PV in architecture with curved envelopes? Yes / No. Explain why (not):

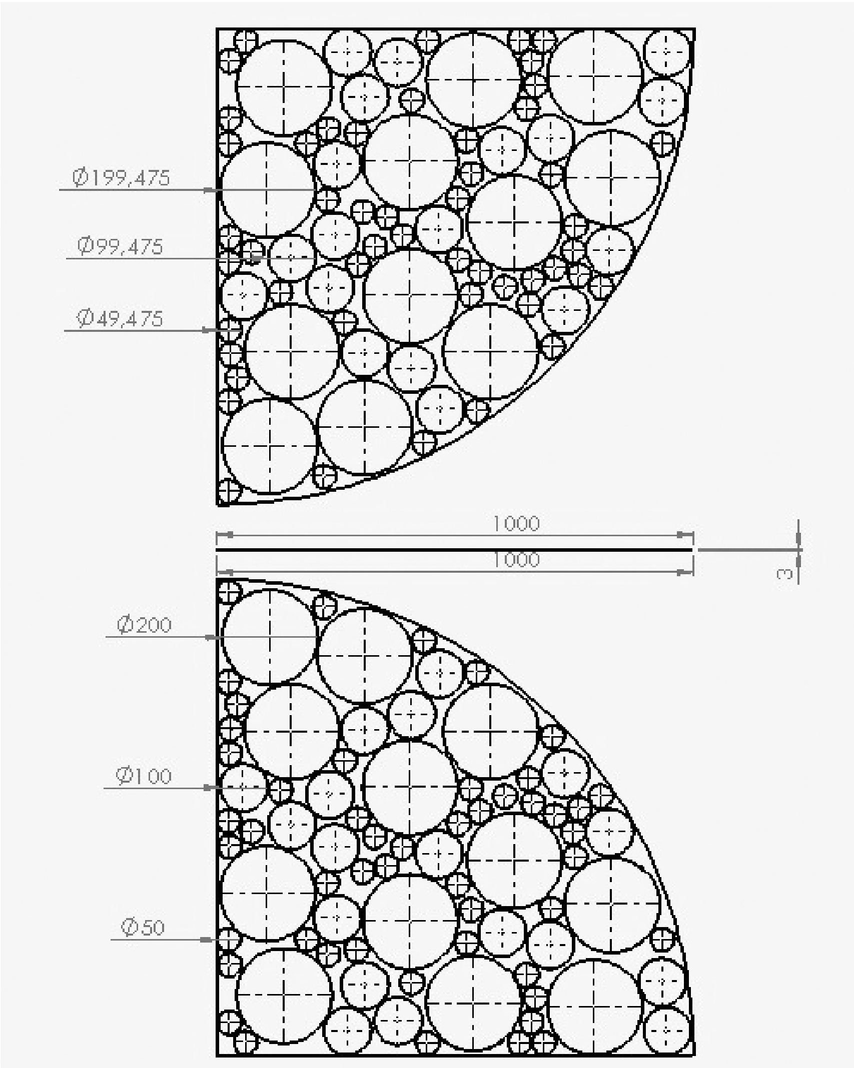
Do you consider flexible thin-film PV modules as a solution for the problems of using PV in architecture with curved envelopes? Yes / No. Explain why (not):

Do you have any other solutions concerning the use of PV panels in 'curved' architecture?

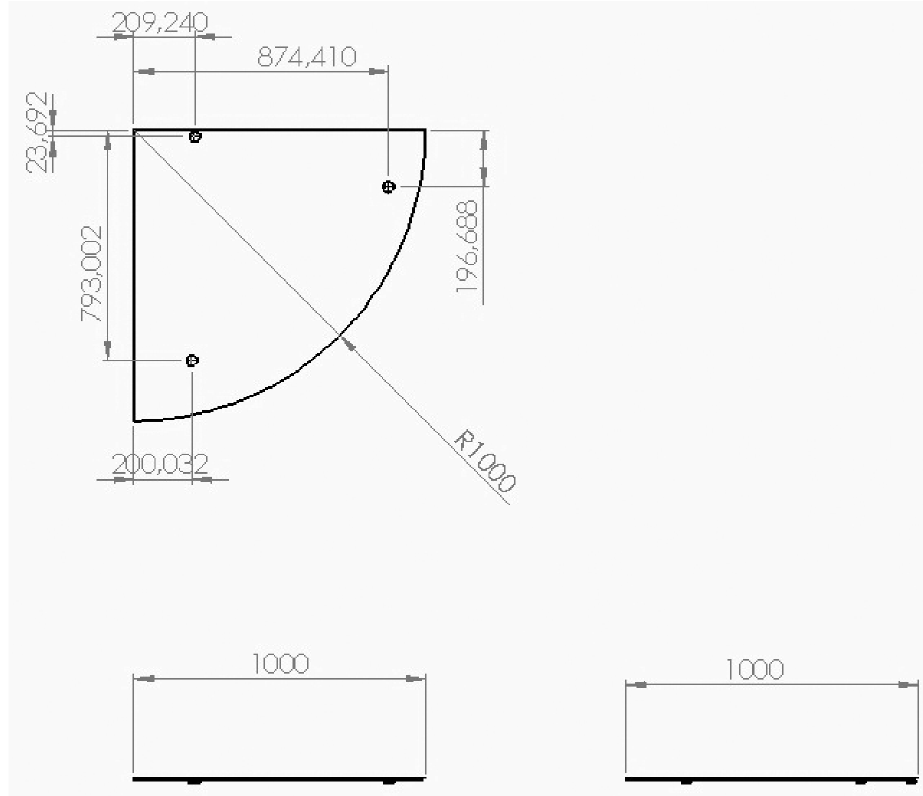
I would like to thank you very much for your collaboration!

Would you like to collaborate in another survey of this project? Yes / No

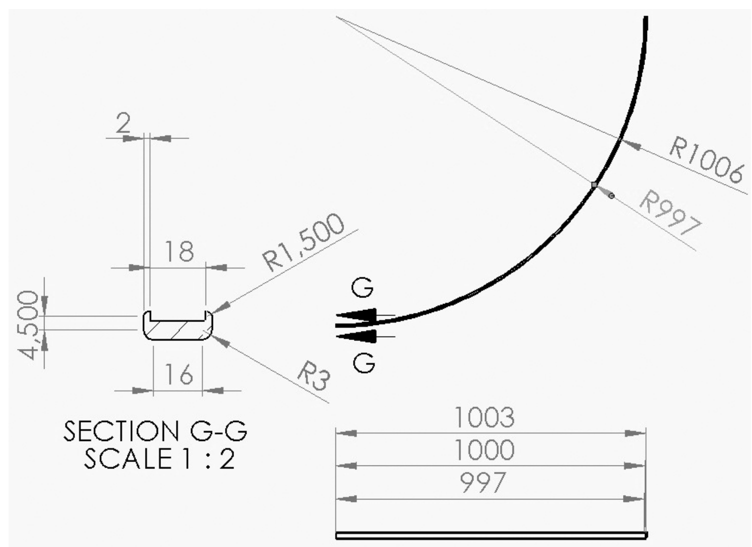
APPENDIX III: DIMENSIONAL DRAWINGS



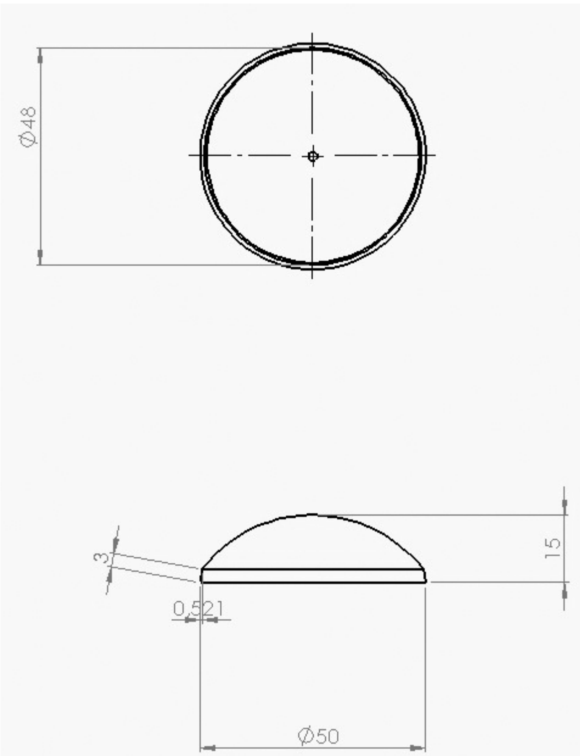
Dimensional drawing "mall" (layer 2)



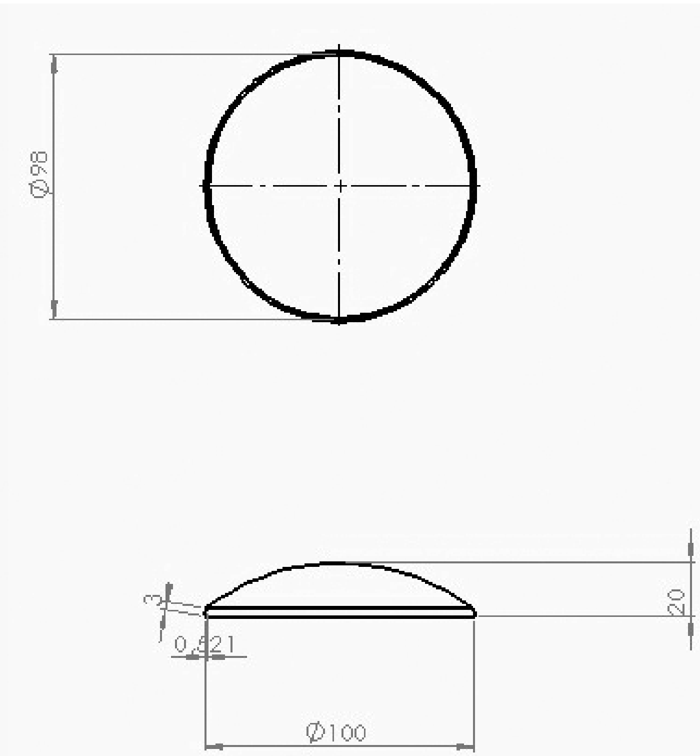
Dimensional drawing back layer (layer 3)



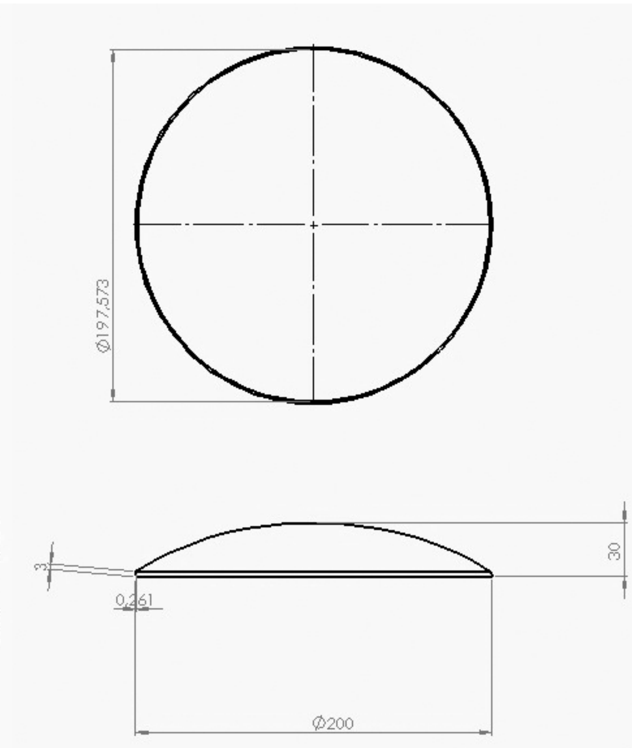
Dimensional drawing edge



Dimensional drawing 50mm cell



Dimensional drawing 100mm cell



Dimensional drawing 200mm cell