Architectural Photovoltaïcs

Research paper
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40% of all energy needs in Europe are in the building environment ("Rijksdienst voor Ondernemend Nederland ", 2014). This is a large percentage of all energy demand and there is a lot to be improved in this sector in terms of energy usage.

To encourage more use of renewable resources they have made a change in the guidelines of placing solar panels. New guidelines state that solar panels can also be placed in proximity of the building to be calculated in the EPC value("Rijksdienst voor Ondernemend Nederland ", 2014).

The vision of Amsterdam is to make the Brettenzone a buffer zone between the city and the harbor for leisure. The current situation is that the Brettenzone is a lifeless area, there are many wastelands and the functions are mono functional. This means that the area is only used little parts of the day.

The project anticipates to the fact that Sloterdijk can become the 2nd city center of Amsterdam. The largest need in the area is the need for a central square, where people can meet. This is why in the project a large canopy will be designed over a square in the Sloterdijk area.

In current projects PV panels are placed in straight lines on the roof, adding nothing to architectural expression. To answer the need to use more renewable resources, research is done to how PV technology can be made architecturally attractive to use in building design, without high production costs.

Keywords: PV technology, Architecture, Amsterdam, Brettenzone, Europe, guidelines, canopy, space frame, modular, building
**Background problem**

Renewable energy sources are becoming more and more important. This is due to depletion of fossil fuels and global warming. Projected is that all of our fossil fuels will be depleted by 2080, oil will even be depleted in 2040. Because of these shocking projections governments all around the world decided to act.

40% of all energy needs in Europe are in the building environment ("Rijksdienst voor Ondernemend Nederland ", 2014). This is a large percentage of all energy demand and there is a lot to be improved in this sector in terms of energy usage. This is why Europe decided to create guidelines with the goal that all new build buildings should be near energy neutral after 31 December 2020.

The Netherlands also has these guidelines and are working on realizing this goal. There even are guidelines that want government buildings to be near energy neutral in 2018, because they need to set an example for others. To measure if buildings are near energy neutral they use the EPC (energy performance coefficient) tool as a measuring system. Now buildings require an EPC of 0.6, this will be around 0 in 2020.

To get a low EPC value, buildings must take different aspects into account. The most important ones are ventilation, warm water, and air conditioning. They all relate to energy efficiency and making use of renewable resources like sun and wind energy. To encourage more use of renewable resources they have made a change in the guidelines of placing solar panels. The old guidelines stated that solar panels had to be placed on the building to be calculated in the EPC value. New guidelines state that solar panels can also be placed next (in proximity) of the building to be calculated in the EPC value.

Solar energy will be a very important factor in creating energy neutral buildings and replacing fossil fuels. The sun radiates enormous amounts of energy on the earth which we don’t use. The amount of energy the sun radiates in an hour can power the entire world for a year! This means the sun is a very powerful energy source we should use more.

The last years the market for solar panels has grown exponentially. The prices for solar panels are becoming lower and the efficiency higher. The full potential of this market is not reached yet, only 0.3% of the total energy production in the Netherlands is produced by solar panels. This is a very small amount, but it is growing fast. If the current growth will continue the market share of solar energy production in the total production will be around 3 - 6% in 2020 (Burger et al., 2014). That is a growth of 1000 – 2000% in 7 years. This is mainly due to the fact that solar panels are becoming profitable. This is because the manufacturing costs of solar panels get cheaper every year and the efficiency rises every year.

The biggest problem in solar panels is that they are often applied after a building is completed, which disrupts the image of the building. There are some companies and architects that use BIPV (building integrated photovoltaic) building, but there are few architectural methods to apply solar panels.

**Location**

The location of the project is the Brettenzone in Amsterdam. This area is already undergoing great changes. The vision of Amsterdam is to make the Brettenzone a buffer zone between the city and the harbor for leisure. The current situation is that the Brettenzone is a lifeless area, there are many wastelands and the functions are mono functional. This means that the area is only used little parts of the day.

The city is planning student housing around Sloterdijk, the main entrance of Sloterdijk (Orlyplein) is getting a facelift and there are new hotels being build. The presence of Sloterdijk station gives the area great potential. The station connects the area with the rest of Amsterdam and the Netherlands by bus, train, subway and tram. It is the second largest station of Amsterdam and the 9th largest station in the Netherlands. This potential is further increased if you take the future plans of Amsterdam into account. They want to connect Amsterdam North to the rest of Amsterdam by subway. This track will pass by Sloterdijk, which will further increase the flow of people passing by the area and raises attractiveness of the area due to its great connectivity. In potential Sloterdijk can become the 2nd city center of Amsterdam.
The area around Sloterdijk consists mostly of offices, which is why the area is not very active during the day. Many office employees flee the area when they are on a break or when the work day has ended. This is because the area in general is very unattractive. There are only few places to get a nice lunch and almost no places to sit outside under shelter. The area also has a lot of empty office spaces, this is a national problem, but in an area which is so well connected this is strange. This is largely due to the negative image the area has.

**Project description**

The project anticipates to the fact that Sloterdijk can become the 2nd city center of Amsterdam. To make this happen, there have to be some changes in the area. The largest need in the area is the need for a central square, where people can meet. This is why in the project a large canopy will be designed over a square in the Sloterdijk area. Because the canopy will be so large, architecture plays a big part in the design. This, in combination with the large roof space and the background story, gives answer to why PV technology will be used. For PV to become a really interesting option for architects and other designers, they need to see that PV can be more than placing rectangle squares on a roof for generating energy. These architects should be shown that PV can be used architectonic and can be beautiful. To show that PV technology can not only be beautiful, but also affordable and flexible, a modular construction system will be designed for the canopy. The modular system can be used to add PV technology to a building and can be used in the design of a new building. Also, the system can be used to create multi-use areas, so an area can create energy and give, for example, shelter to cars or people. Because the canopy is covering a large square, there should as less columns as possible. This will make the square more flexible and the system more self-supporting and one product. The project will be the ultimate showcase for this system. It will show how the system can work on large scale, to convince people that every scale can be possible. It will show that PV can be beautiful and yet affordable and flexible.

**Technical design question**

To translate my project in a technical design question (without taking context into account), a few subjects are important to integrate in the question; Important is to make architectonic use of PV technology. This technology is applied to a canopy over the square, which is the architectural typology. The way this canopy is constructed is by a modular, large span system. For the technical design question these are the most important subjects to create the question. By doing research to these subjects a tool-set will be created with which a design for the canopy can be made. To formulate the subjects into a technical question:

*How can PV technology be architectonically integrated in the design of a canopy, constructed by a modular, large span construction system?*

To answer this question it will be divided it into several sub-questions. These sub-questions will isolate a subject and formulate what I need to research for this subject;

**PV technology (and its architectural use)**
- What different PV panels are there?
- How are these PV panels produced?
- How can these PV panels be shaped?
- How are PV panels used in the building environment?

**Canopy**
- What different types of canopies are there?
- How are these types constructed?
- How are canopies used in the building environment?
Modular system (large span)
- What are modular building systems?
- What different kinds of modular building systems are there?
- What spans can these kinds of modular building systems make?
- How are modular systems used in the building environment?

By answering these questions a tool-set will be created by which the main technical question can be answered and a design for the project can be created.

Methods
Every subject will use one or more research method(s). For these research methods there will be explained why this method is used and what parts of the subject can be answered with this research method. In the end the sub-questions should be answered by the research done. There are different research methods I used; Literature research refers to the research I got from other papers, technical documents or websites from manufactures. Case studies refer to projects where a neutral party did research in. References refer to projects where analysis was done in and conclusions were made focused on the research question. Finally, research by design is the research done by design to create boundaries and conclusions to add to the tool-set for the design of the canopy.

For the research in PV technologies literature will be used to describe what PV technology is and what it does. It will also be used to identify which PV panels are used the most and what material is used for these. Literature will also be used to look into the efficiency, costs and production process of these PV panels. Also possible design dangers will be researched. In the end, the PV panels will be compared to see which fits the project best.

Case studies will be used to see how PV technologies are applied now in the building environment.

For the research in canopies, references will be used to determine what different typologies there are. For these typologies it will be determined how the canopy is used, what function(s) it houses and how the canopy is constructed. This will give an overview in how the canopy can be used in the project.

For the research in modular constructions literature will be used to describe what modular constructions are and what different types of modular systems there are. Literature will be used to determine the maximum spans of these different modular systems. It will also be used to determine what the advantages and disadvantages are of modular systems. References will be used to see how modular elements connect to each other and to see how modular systems are used in the build environment.

With these research methods the sub-questions from every subject can be answered and used to create the tool-set needed to make a design for the project.
Results
The research began with 3 main subjects; Canopy research, PV research and Modular construction research. After the research of these subjects there will be an answer to the main technical question, which will give architectural methods to design the canopy. Some of these design methods will need additional research to fit in the tool-set for the design of the canopy.

Photovoltaics
Photovoltaic is the method of generating electrical power by converting solar radiation into electricity. It does this by making use of solar energy absorbing materials. The most used materials are: Mono-crystalline silicon, Poly-crystalline silicon, cadmium telluride, amorphous silicon and copper indium gallium selenide. The materials absorb the sun’s energy and create a stream of electrons, which is caught by conductors and transported as electricity (Basnet, 2012).

The photovoltaic materials can be produced into panels, thin films or combinations. These all have their advantages and disadvantages. These different products are categorized in different groups with their materials, costs, production process and efficiencies.

Mono-crystalline PV panels have the highest efficiency on the market. This is due to the fact that the cells in mono-crystalline panels are cut from a single, round, continuous crystal. This means that the cells have a continuous molecule structure, which makes the material absorb more sunlight. Therefore it has a high efficiency, high heat resistance and a long life span. Unfortunately the panels have bad resistance to shadowing. If shadow falls on the panel it can break down and it will need to be replaced. The round, continuous crystal is cut into round wafers. To fit these optimally in the panel the edges are cut off, which means there is waste. The process of creating the continuous round crystal is an expensive process. This in combination with the fact that there is waste makes this product have high production costs. Mono-crystalline panels normally appear as a solid black or blue color. Other colors are possible, but have lower efficiency (Basnet, 2012).

Poly-crystalline PV panels have a lower efficiency than mono-crystalline PV panels. Poly-crystalline cells are also made from silicon, but this is melted and poured into a square mold. This means that the molecule structure is not entirely continuous, which causes the lower efficiency. The upside is that because it is poured into a square mold, there is no waste material. The quality of the silicon is also lower, which means the poly-crystalline panels have lower production costs. The poly-crystalline panel is also sensitive to shadowing, which can result in damage to the panel. It has a lower heat resistance than mono-crystalline panels (Basnet, 2012). The overall appearance of the panel looks fractured and is colored blue.

Thin Film PV panels are made of other materials than silicon. The most used materials are cadmium telluride (CdTe) and copper indium gallium selenide (CIGS). Thin film panels have slightly lower efficiencies than poly-crystalline panels, but have the highest potential efficiency. They are produced by spraying different layers of coatings, this way there is no waste and it makes the production process more flexible (“Manufacturing process First Solar,” 2014). This cheap process in combination with low material costs, make thin film panels have low production costs. Thin film panels have high resistance to shadowing and have high heat resistance (Basnet, 2012).

Case studies (see attachment 2) show that addition of PV panels to the build environment often go in a linear and mono-tone fashion. They are added to buildings which want to lower their energy costs and gain a higher energy label. The panels are often placed on the roof, which results in just lines of PV panels, disconnected from the architectural design (“PV Database “, 2014).

A method that tries to tackle this problem is Building Integrated PV (BIPV). Architects who use this method design a building integral with PV technologies. This results in improved aesthetics, lower costs and wider distribution. But most of these methods still do little with the shape and appearance of the PV panel. It usually means creating a PV façade or integrating PV cell into glass.
Although the PV panels all have their advantages and disadvantages, the CdTe thin film panel shows most connection to the technical question. The fact that the production process allows for alterations in panel design is very important. This in combination with the low cost and the high resistances make it the best choice for this project. (For additional information on CdTe thin film technology, see attachment 1)

**Canopy**

A canopy is an overhead roof, or else a structure over which a covering is placed, able to provide shade or shelter. A canopy usually has multiple purposes, but the main purpose always remains to provide shelter. The canopy makes it possible to practice activities under bad weather conditions; too much sun or too much rain. For architecture this means it can make an outdoor public space active throughout the entire day. The secondary purpose is often used to emphasize the function of the public space or to generate energy for the environment. Canopies can be independent or attached to buildings. Canopies that are attached to buildings often indicate an entrance or a waiting area. Canopies which are independent have three scales: The small public space, the large public space or the public area or square. The canopy over the small public space is often used as waiting or meeting area or as an artwork. The canopy over the large public space is often used to shelter activities, such as sports or small events. The canopy over the public area is used to shelter markets, events, squares and stations. These canopies are automatically landmarks, due to their scale, and are designed as such.

The Cubierta Cazuca (see attachment 3) is a great example of how a canopy can shelter an activity from sunlight. The canopy is situated in Colombia, where the temperatures can be high. This is why the canopy is designed over a soccer field, to provide shelter to the users. The canopy has a lightweight steel construction with fabric as roof cover. The hexagonal spheres are similar constructed and rest on steel columns (“Cubierta Cazuca,” 2014).

The Marseille vieux port pavilion (see attachment 4) is a good example of a canopy under which multiple functions can take place. The pavilion is open on all sides and it is supported by slender columns. The canopies polished, mirrored surface reflects the surrounding port and tapers towards the edges, minimizing its profile and reducing the structures visual impact (“Marseille vieux port “, 2014).

The Mercat Encants (see attachment 5) in Barcelona is a good example of a canopy over a large public space, in this case a market. The projects main objective was to maintain the open nature of the current outdoor markets in Barcelona. Its design intends to avoid building multiple floors, thus rejecting the model of a commercial center. Instead of that, a continuous commercial area was designed, with slightly inclined planes intertwining and generating an endless loop which links stalls and small shops. The visitor’s experience is similar to a stroll through a pedestrian road. The great casing, suspended as a canopy, is almost 25 meters high and is a prominent landmark. The casing is carried by thin columns. It protects shopkeepers and users from the sunlight. Its underside presents different inclinations and becomes a mechanism of reflection of the city into the market (“Mercat encants “, 2014).

The Metropol parasol in Sevilla (see attachment 6) is another good example of a canopy over a large public space. In this case the canopy houses several bars, restaurants, a market, a museum and an elevated plaza. Its role as a unique urban space within the dense fabric of the medieval inner city of Seville allows for a great variety of activities. It is realized as one of the largest and most innovative bonded timber constructions with a polyurethane coating, the parasols grow out of the archaeological excavation site into a contemporary landmark, defining a unique relationship between the historical and the contemporary city. Metropol Parasols mix-used character initiates a dynamic development for culture and commerce in the heart of Seville and beyond (“Metropol parasol “, 2014).
The majority of the build canopies are constructed in two ways, either as a roof surface supported by columns or as a uniform object supporting itself. There is a lot of repetition in the construction of most canopies, which is why modular construction fits this typology well. The canopy always has an open identity, because the boundaries of the canopy are all open. This fits well with the functions of markets, bars, restaurant and other outdoor activities. The canopy creates a feeling of being outdoors, but still provides shelter from the elements. The space under the canopy is very flexible, especially when no columns are used. This makes the canopy a good typology for sheltering city squares. The demands of the public space are constantly changing, so the flexible space under the canopy can always be changed to fit these demands. This is why the canopy is a good instrument for creating an active public area.

**Modular construction**

Modular construction uses three-dimensional or volumetric that are prefabricated and are essentially fully finished in factory conditions, and are assembled on site to create complete buildings or part of buildings. Modular construction is one of the four degrees of prefabrication, which are; materials, components, panels and modules (see attachment 7) (Smith, 2010). The definition of components, panels and modules can be confusing. For example: panels for interior building are often referred to as modular wall systems. This is not the same as modular building, which is the use of entire finished building modules. The categorization simply describes if a prefabricated element is more or less finished when it arrives on site.

Modular construction is generally used to create cellular-type buildings, which consist of similar size modules with a suitable size for transportation. Multiple modules with two, or more, open sides can be used to create one bigger space. Modular units can also be manufactured to create higher value components of the building, such as; bathrooms, lift and stair-units, mechanical serviced units and prefabricated roofs (Lawson, Ogden, & Goodier, 2014).

The benefits of modular construction can be focused to certain market sectors, where there is a demand for speed of construction, economy in manufacture or for reducing disturbance of the building process. The key advantages of modular building in the context of cost, quality and time are (Lawson et al., 2014):

- Shorter building time, which lead for lower site costs.
- Superior quality by factory based construction process.
- Economy in scale of production, especially larger or repeated projects.
- Excellent acoustics, insulation and fire protection due to double skin nature of modules.
- Reduced design cost.
- Lightweight, less material use, less waste.
- Increased productivity in factory and reduced labor on site.
- Fewer disturbances to the neighborhood during construction.
- Ability to dismantle the building and re-use.

Because the canopy project has the need for a large span, a system which fit this criterion had to be found. This search ends with the space fame, a structure system of linear elements that are arranged in such a way that forces are transported in a three-dimensional manner (Lan, 2005). The space frame can be formed on either a flat or a curved surface. The earliest form of space frame structure is single-layer grid. By adding intermediate grids and including rigid connection to the joist and girder framing system, the single-layer grid is formed. The major characteristic of grid construction is the omnidirectional spread of the load as opposed to the linear transfer of the load in an ordinary framing system. Since such load transfer is mainly by bending, for larger spans the bending stiffness is increased most efficiently by changing to a double-layer system (Lan, 2005). The load transfer mechanism of a curved surface space frame is essentially different from the grid system that is primarily membrane-like shaped.
One of the most important advantages of a space frame structure is that it is lightweight. This is due to the fact that material is distributed spatially in such a way that the load transfer is primarily axial, tension or compression. Most space frames are now constructed with steel or aluminum, which decreases considerably their self-weight. This is especially important in the case of long-span roofs. The units of space frames are usually mass produced in the factory so that they can take full advantage of the industrialized system of construction. Space frames can be built from simple prefabricated units, which are often of standard size and shape. Such units can be easily transported and rapidly assembled on site by semi-skilled labor. This means that space frames can be built at a lower cost. A space frame is usually sufficiently stiff in spite of its lightness. This is due to its three-dimensional character and to the full participation of its elements. The space frames allow greater flexibility in layout and positioning of columns (Lan, 2005). Space frames possess a versatility of shape and form and can utilize a standard module to generate various flat space grids, latticed shell, or even free-form shapes. Desire for openness for both visual impact as well as the ability to accommodate flexible space requirements often call for space frames as the most favorable solution.

To make large spans possible, double-layered space frames are used. These are space frames that consist of two planar networks that are parallel to each other. These networks are interconnected with each other by diagonal members. The layers are connected with hinged joints, which means that the system can only resist tension or compression. Double layered space frame are constructed in three ways; with planar latticed trusses, as pyramids with square bases (octahedron) or as pyramids with triangular bases (tetrahedron) (see figures 1 & 2) (Lan, 2005). These systems all have recommended methods of support (see attachment 8) (Lan, 2005).
(Fig 1&2: three basic construction methods of space frames)
Patterns

An architectural way of designing the canopy by repetition and prefabrication is by basing the repetition on a pattern. The combination of patterns and colors can make interesting designs. Patterns can be used for the expression of the architect. With patterns architecture can be made which looks fractured or uniform, colors can further emphasize these. Because both the canopy and the space frame rely on repetition, patterns can be an interesting way to give it an architectural design strategy.

Figure 3 and 4 show some studies of patterns based on the space frame system. There is also some testing in color done, to show how this can create depth in the pattern. These patterns are not yet based on the production method of thin film PV panels. It is important in the design to keep the production method into account.

(Fig 3: pattern studies)

(Fig 4: pattern studies)
Conclusion

Photovoltaic materials can be produced into panels, thin films or combinations. These all have their advantages and disadvantages. Mono-crystalline and Poly-crystalline PV panels have the highest efficiency on the market. They have high efficiency, high heat resistance and a long life span. Unfortunately the panels have bad resistance to shadowing. If shadow falls on the panel it can break down and it will need to be replaced. Mono-crystalline wafers have more waste in the production process due to the fact that they are made from round crystals and the edges have to be cut off. Poly-crystalline wafers are made from square crystals, which is why they have no waste, but slightly lower efficiency. Mono-crystalline panels normally appear as a solid black or blue color, poly-crystalline panels have a fractured blue appearance. Other colors are possible, but have lower efficiency. Thin Film PV panels are made from cadmium telluride (CdTe) or copper indium gallium selenide (CIGS). Thin film panels have slightly lower efficiencies than poly-crystalline panels, but have the highest potential efficiency. They are produced by spraying different layers of coatings, this way there is no waste and it makes the production process more flexible. This cheap process in combination with low material costs, make thin film panels have low production costs. Thin film panels have high resistance to shadowing and have high heat resistance. Case studies show that addition of PV panels to the build environment often go in a linear and mono-tone fashion, disconnected from the architectural plan. A method that tries to tackle this problem is Building Integrated PV. This results in improved aesthetics, lower costs and wider distribution. But most of these methods still do little with the shape and appearance of the PV panel. It usually means creating a PV façade or integrating PV cell into glass.

Although the PV panels all have their advantages and disadvantages, the CdTe thin film panel shows most connection to the technical question. The fact that the production process allows for alterations in panel design is very important. This in combination with the low cost and the high resistances make it the best choice for this project.

The canopy makes it possible to practice activities under bad weather conditions; too much sun or too much rain. For architecture this means it can make an outdoor public space active throughout the entire day. The secondary purpose is often used to emphasize the function of the public space or to generate energy for the environment. Canopies can be independent or attached to buildings. Canopies that are attached to buildings often indicate an entrance or a waiting area. Large canopies are automatically landmarks, due to their scale, and are designed as such.

The majority of the build canopies are constructed in two ways, either as a roof surface supported by columns or as a uniform object supporting itself. There is a lot of repetition in the construction of most canopies, which is why modular construction fits this typology well. The canopy always has an open identity, because the boundaries of the canopy are all open. This fits well with the functions of markets, bars, restaurant and other outdoor activities. The canopy creates a feeling of being outdoors, but still provides shelter from the elements. This is why the canopy is a good instrument for creating an active public area.

Modular construction uses three-dimensional or volumetric that are prefabricated and are essentially fully finished in factory conditions, and are assembled on site to create complete buildings or part of buildings. Modular construction is one of the four degrees of prefabrication, which are; materials, components, panels and modules.

The benefits of modular construction can be focused to certain market sectors, where there is a demand for speed of construction, economy in manufacture or for reducing disturbance of the building process. The key advantages of modular building lie in the context of cost, quality and time. A system that will fit the project well and can be prefabricated is the space frame. The units of space frames are usually mass produced in the factory so that they can take full advantage of the industrialized system of construction. Space frames can be built from simple prefabricated units, which are often of standard size and shape. Such units can be easily transported and rapidly assembled on site by semi-skilled labor. This means that space frames can be built at a lower cost. To make large
spans possible, double-layered space frames are used. These are space frames that consist of two planar networks that are parallel to each other. These networks are interconnected with each other by diagonal members. The layers are connected with hinged joints, which means that the system can only resist tension or compression.

With the knowledge found in the research the technical question can be answered. Every notion in the technical question is researched and the sub-questions are answered. The research led to a flaw in the technical question. Because the research states that modules are a degree of prefabrication, the technical question has to be changed to prevent confusion in the design process.

*How can PV technology be architectonically integrated in the design of a canopy, constructed by a prefabricated, large span construction system?*

The research showed modules are finished building parts, which is something that is not certain in the project yet. This is why the definition in the technical question is changed into prefabricated system. This way the question leaves open if the prefabricated parts are (partially) assembled in the factory or on site.

The technical question can be answered based on the research. The Thin film PV technology can be changed easily in its production process, so other shape than rectangle is possible. This opens opportunities to create a design that looks non-standardized, while using repetition. This repetition of elements should be based on the system of the space frame that is used. This way the PV panels can connect properly to the construction system. Space frames can be prefabricated and can make large span construction, so this way the entire system of construction and PV panels can be prefabricated. To translate this in an architectural way of designing the canopy, by repetition and prefabrication, a pattern can be used. The combination of patterns and colors can make interesting designs. Patterns can be used for the expression of the architect. With patterns the architecture of the canopy can look fractured or uniform, color can further emphasize this. To answer the technical question in one sentence; To use PV technology in the context of an architectural design of a canopy, constructed by a prefabricated, large span construction system, the PV technology can be shaped into panels which together create a pattern, based on the construction system of the space frame, that is the basis of the architectural design of the canopy. Below is the principle that will be used in the design.

(Fig 5: principle of system design)
**Literature**


Images

Fig 3 & 4: own image
Fig 5: Own image
Fig 6: Own image
Fig 49 & 50: Lawson, M., Ogden, R., & Goodier, C. (2014). *Design in Modular Construction*: CRC Press pp 9
ATTACHMENT 1 – PV types

(fig 6: diagram of cost, production and efficiency)
**ATTACHMENT 2 – Vidursolar**

Name project VIDURSOLAR: Glass-glass PV module for architectural integration
Country Spain, Catalonia - Barcelona
Year 2006-03-15 (Start of market availability)
PV application Façade - transparent PV façade

**Product summary**

The PV module Vidursolar offers to architects extraordinary possibilities of design, both of the buildings outer skin as well as of the building interior space, by means of its selective light transmission properties. The functional characteristics of Vidursolar PV modules allow its use in multiple applications where both aesthetics and functionality are necessary: sunscreens, façades, curtain walls, glass flat roofs, roofs skylights, pergolas, verandahs, etc. Designed as a high technology construction element, it can substitute conventional construction elements by assuming the same functions in terms of safety, solar protection, thermal and acoustic insulation; besides these properties, the PV modules also incorporate innovative, aesthetical and ecological components. They are custom-designed elements, in order to provide maximum flexibility to an innovative architecture with a wide range of possible finishes, shapes and electrical configurations.

Source: (“PV Database “, 2014)
**ATTACHMENT 2 – BMW Welt**

Name project: BMW Welt München  
Country: Germany  
Year: 2007-10-17 (Start operation date)  
PV application: Flat roof - integrated  
PV power total: 824 kWp  
Location: München, Bayern

**Project summary**

On the immense roofage of the BMW World (about 16.000m²) SunStrom installed a roof integrated photovoltaic system with 3660 modules and a nominal power of 824 kWp. Alone the outward appearance is unique. One special function of the photovoltaic system is that it works like the “fifth façade” of the building. Through its exposed position next to the Olympia Tower and to the BMW Group-Building the BMW World is always visible from top. Therefore the architectural design of the roof was planned with great care. Between the black glimmering module fields there were constructed small ways covered with stainless steel plates. These ways cross the whole roof and generate a reticular pattern.

Source: ("PV Database ", 2014)
ATTACHMENT 2 – La Vaguada

Name project  “Madrid-2 La Vaguada” Commercial and leisure Center  
CountrySpain  
Year  2007-04-01 (Start operation date)  
PV application Flat roof - mounted & ballast fixing,  
Inclined roof - transparent roof  
PV power total  100.4 kWp  
Location Madrid, Madrid

Project summary
PV system architecturally integrated in one of the most visited commercial and leisure centres of Madrid (25 million visitors per year). Special emphasis has been put on architectural integration of PV modules in glass areas of the building, as well as on educational aspects of visitors through monitoring and information of the benefits produced by the PV system (electricity and CHG emissions savings).

Source: (“PV Database ”, 2014)
**ATTACHMENT 2 – Lamela HQ**

Name project  Headquarters of the "Studio Lamela Architects" (Leitner Building)
Country  Spain
Year  2007-11-30 (Start operation date)
PV application  Flat roof - mounted & mechanical fixing
PV power total  31.5 kWp
Location  Madrid, Madrid

**Project summary**
The new headquarters of the "Studio Lamela Architects" has been designed following a detailed environmental strategy. The building floors are elevated, with a basement open configuration. Building envelope is a double skin, with an inner glass surface protected with horizontal lamellas for direct solar protection and a metallic framework (tramex) for maintenance of glass surface and lamellas. Materials selected are natural (stone, wood) and recycled (aluminum, façade glass and concrete for the building foundations). The energy strategies include reducing air conditioning needs with a double skin for sun protection, increasing efficiency through the use of centralised and flexible systems, lighting sensors and the use of renewable energies (6 m2 of solar thermal and 250 m2 of photovoltaics).

Source: ("PV Database ", 2014)
**ATTACHMENT 2 – PV canopy**

Name project     PV Canopy in Telefonica “C District”  
Country      Spain  
Year           2006-09-01 (Start operation date)  
PV application    Flat roof – mounted & mechanical fixing  
PV power total    2874 kWp  
Location        Madrid, Madrid

**Project summary**

PV plant of 2.9 MWp integrated in the canopy of the new headquarters of Telefonica company (called “C District”) in Madrid. The PV modules, which occupy more than 21000 m² are distributed in such a way that they form the letter “C” that constitutes the name of the building ensemble. The PV plant is divided into 24 independent 100 kW PV plants, connected to the distribution grid through 5 Transformation Centers of 630 kVA each.

Source: (“PV Database ”, 2014)
Fig 27, 28, 29, 30, 31, 32: (“Cubierta Cazuca,” 2014)
ATTACHMENT 4 – Marseille vieux port, Foster and partners

Fig 33, 34, 35, 36: (“Marseille vieux port “, 2014)
ATTACHMENT 5 - Mercat dels Encants, b720

Fig 37, 38, 39, 40, 41, 42: ("Mercat encants ", 2014)
ATTACHMENT 6 – Metropol Parasol, John Mayer

Fig 43, 44, 45, 46, 47, 48: (“Metropol parasol”, 2014)
ATTACHMENT 7 – Modular building

![Table 1.1 Illustration of various levels of building technologies in the context of off-site construction](image)

**Table 1.1** Illustration of various levels of building technologies in the context of off-site construction

<table>
<thead>
<tr>
<th>Level</th>
<th>Components</th>
<th>Description of technology</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Materials</td>
<td>Basic materials for site-intensive construction, e.g., concrete, brickwork</td>
</tr>
<tr>
<td>1</td>
<td>Components</td>
<td>Manufactured components that are used as part of site-intensive building processes</td>
</tr>
<tr>
<td>2</td>
<td>Elemental or planar systems</td>
<td>Linear or 2D components in the form of assemblies of structural frames and wall panels</td>
</tr>
<tr>
<td>3</td>
<td>Volumetric systems</td>
<td>3D components in the form of modules used to create major parts of buildings, which may be combined with elemental systems</td>
</tr>
<tr>
<td>4</td>
<td>Complete building systems</td>
<td>Complete building systems, which comprise modular components, and are essentially fully finished before delivery to the site</td>
</tr>
</tbody>
</table>

*Source: Adapted from Gibb, A.G.F., Off-site Fabrication—Pre-Assembly, Pre-Fabrication, and Modularisation, Whittles Publishing Services, Dunbeath, Scotland, 1999.*

![Fig 49, 50: (Lawson et al., 2014)](image)

**Fig 49, 50: (Lawson et al., 2014)**
**ATTACHMENT 8 – Space frames**

**Group 1: composed of latticed trusses**
A. Two-way orthogonal latticed grids (square on square). This type of latticed grid has the advantage of simplicity in configuration and in joint detail. All chord members are of the same length and lie in two planes that intersect at 90 degrees to each other. Because of its weak torsional strength, horizontal bracings are usually established along the perimeters.
B. Two-way diagonal latticed grids. The layout of the latticed grid is exactly the same as in type A, except that it is offset by 45 degrees from the edges. The latticed trusses have different spans along two directions at each intersecting joint. Since the depth is all the same, the stiffness of each latticed truss varies according to its span. The latticed trusses of shorter span may be considered as a kind of support for latticed trusses of longer span, hence more spatial action is obtained.
C. Three-way latticed grids. All chord members intersect at 60 degrees to each other and form equilateral triangular grids. It is a stiff and efficient system that is adaptable to odd shapes like circular and hexagonal plans. The joint detail is complicated by numerous members intersecting at one point, with 13 members in extreme cases.
D. One-way latticed grids. It is composed of a series of mutually inclined latticed trusses to form a folded shape. There are only chord members along the spanning direction, therefore one-way action is predominant. As in type A, horizontal bracings are necessary along the perimeters to increase the integral stiffness.

**Group 2A: composed of square pyramids**
E. Orthogonal square pyramid space grids (square on square offset). This is one of the most commonly used framing patterns with top-layer square grids offset over bottom layer grids. In addition to the equal length of both top and bottom chord members, if the angle between the diagonal and chord members is 45 degrees, then all members in the space grids will have the same length. The basic element is a square pyramid that is used in some proprietary systems as prefabricated units to form this type of space grid.
F. Orthogonal square pyramid space grids with openings (square on square offset with internal openings, square on larger square). The framing pattern is similar to that of type E, except that the inner square pyramids are removed alternatively to form larger grids in the bottom-layer. This modification will reduce the total number of members and consequently the weight. It is also visually effective as the extra openness of the space grids network produces an impressive architectural effect. Skylights can be used with this system.
G. Differential square pyramid space grids (square on diagonal). This is a typical example of differential grids. The two planes of the space grids are at 45 degrees to each other, which will increase the torsional stiffness effectively. The grids are arranged orthogonally in the top layer and diagonally in the bottom-layer. It is one of the most efficient framing systems with shorter top chord members to resist compression and longer bottom chords to resist tension. Even with the removal of a large number of members, the system is still structurally stable and esthetically pleasing.
H. Diagonal square pyramid space grids (Diagonal Square on square with internal openings, diagonal on square. This type of space grid is also of the differential layout but with a reverse pattern from type G. It is composed of square pyramids connected at their apices with fewer members intersecting at the node. The joint detail is relatively simple since there are only six members connecting at the top chord joint and eight members at the bottom chord joint.

**Group 2B: composed of triangular pyramids**
I. Triangular pyramid space grids (triangle on triangle offset). Triangular pyramids are used as basic elements and connected at their apices, thus forming a pattern of top-layer triangular grids offset over bottom-layer grids. If the depth of the space grids is equal to the root of 2/3 chord length, then all members will have the same length.
J. Triangular pyramid space grids with openings (triangle on triangle offset with internal openings). Like type F, the inner triangular pyramids may also be removed alternatively. As in the figure shown, triangular grids are formed in the top-layer, while triangular and hexagonal grids are formed in the bottom-layer. The pattern in the bottom-layer may be varied depending on the ways of removal. This type of space grids has a good open feeling, and the contrast of the patterns is effective.