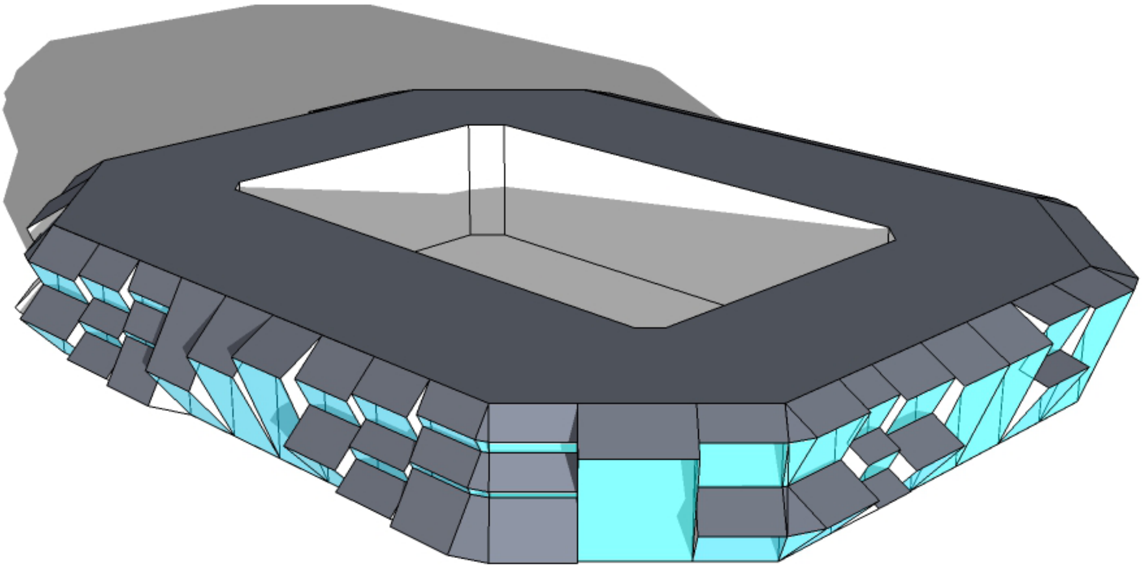
FOOTBALL STADIUM: SOLAR ENVELOPE AS AN ARCHITECTURAL TOOL



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Building integrated photovoltaics are becoming popular in the built environment due to the lack of space in the city. BiPV will allow the building to produce clean energy, thus making it sustainable without the need of additional space. However in many buildings, in which photovoltaic are used, is the architectural quality compromised. The technical requirements in those kind of buildings have a higher priority than the buildings appearance. This research paper focuses on the design of a solar envelope in which the solar energy production is optimized and at the same time enhances the architectural and spatial qualities. In other words, a solar envelope as an architectural tool is formulated. With the use of literature studies and research by design a solution has been found in which the technical requirements and the architecture enhance each other or at the very least are considered as equals. This is achieved by using the following guidelines:
-The use of a double façade principle.

- The use of different façade elements that are based on the accordion façade. The differences between these elements are the tilt values.

- The use of flat module shapes.

- In certain situation the program will determine the façade elements and in other situation the façade element will determine which program is situated behind the façade. This will create a strong relationship between the façade and the organisation of the building. In other words the buildings organisation is visualized externally thus making the solar envelope an architectural tool.

Keywords: Building integrated photovoltaic, solar envelope, accordion façade, architectural tool, multi-purpose building, football stadium, PV performance

I. INTRODUCTION

Football stadiums can be found in most parts of the world. They act as a theatre where the expression of civilization takes place. It is a place for social events with a high degree of social interaction. Most of the football stadiums in Europe are located in the city centre or densely populated urban areas. These stadiums have the potential of becoming exciting meeting places. They can give a new impulse to its surrounding area by creating new business opportunities. The Philips Stadium, located in the heart of Eindhoven, is a good example of the problems that most existing stadiums have in the city. First of all the building is used only two days a week and the remaining days it can be considered as a vacant building. The stadium itself cannot be considered as exciting meeting places due to the 'boring' and out of scale architecture. Furthermore, the design of the façade doesn't create any relationship with the surrounding area. The façade gives the building an introvert character, therefore excluding the city. The club owner PSV wants to expand the capacity of the stadium, thus creating an opportunity to solve these problems.

The Philip Stadium, like many other stadiums, needs also improvements regarding sustainability to make it more suitable for the 21st century. Two strategies can be implemented to make the stadium more sustainable: producing clean energy with wind, sun or water and/or reducing the energy demand. Space is required for the production of clean energy. However there is a lack of space in a densely built environment such as the city centre of Eindhoven. Integrating photovoltaic in the building envelope requires no additional infrastructure installation. The PV modules can replace the cladding materials of the roofs and the façade. A solar envelope will also make more efficient use of the unused spaces on the roofs and the façade. Furthermore a solar architecture will create more awareness for sustainability and efficient use of energy in the direct surroundings of the building. It is also my own fascination to design a solar envelope. I can use the knowledge that I have learned during my graduation project in my own country in the Middle East.

The aim of the graduation project is to reinvent the meaning and use of the football stadium in the city centre that fits in the 21st century. To achieve this objective, the Philips stadium must be transformed into a sustainable football stadium where other activities that are not related to football take place. This objective is translated into the following overall design question:

How to transform the existing Philips stadium into a solar powered stadium with a capacity of 45 000 seats and integrating the stadium with the city?

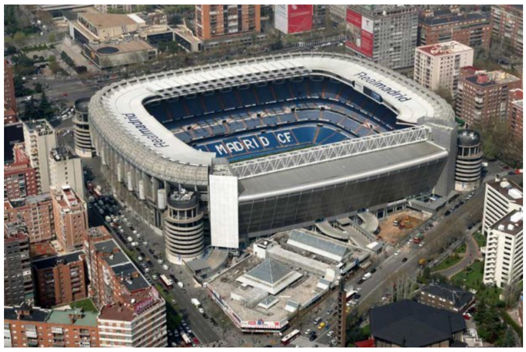


Fig. 1: Santiagio Bernabeau, Madrid
Low spatial and architectural quality,
(Cómo Llegar, n.d.)

Fig. 2: Philips Stadium, Eindhoven
Introvert character, weak relation with the surrounding (own image)

Fig. 3: Emirates Stadium, London
Extrovert character, lively stadium
(Ed G2s, 2009)

Fig. 4: Scheidegger Building, Bern
BIPV with low architectural quality
(Atlantis Solar System AG, n.d.)

Fig. 5: Dwelling, Thalheim
PV module maintain architectural quality
(Robert, 2011)

Fig. 6: High-rise hotel, unknown location
PV module integrated in the facade composition
(Solar Building Tech, n.d.)

An important aspect of the overall design question is the transformation to a solar powered stadium. The facade plays an important role of producing clean energy and creating a relationship between the stadium and the city. Most PV modules are not architecturally implemented in the design. In other words the architectural quality is compromised over the optimum PV power out. Therefore the following thematic research question has been formulated:

How to design a new building envelope that can optimize the solar energy production and at the same time enhances the desired spatial and architectural quality?

The research paper focuses on answering the thematic research question. The thematic research question is divided in two parts in order to answer the question. First a research is done to formulate the technical parameters that influence the PV power output. Secondly, formulating a design concept to use the solar envelope as an architecture tool.

In the second chapter an overview is given of the different research methods that have been used during the research. The third chapter is divided into sub-chapters that describe and elaborate the results of the research. The sub-chapters are the following:

- 3.1 Influences on the PV power output
- 3.2 PV integration opportunities in the building envelope
- 3.3 Design concepts for a PV façade
- 3.4 A solar envelope suitable for a multi-purpose building
- 3.5 Case studies of solar envelopes

Chapter 3.1 and 3.2 will help to formulate the technical parameters. Chapter 3.3 until 3.5 will help to formulate a design concept to use a solar envelope as an architectural tool for a multi-purpose building. The fourth chapter is the conclusion where an actual answer is given to the thematic research question. Furthermore the entire knowledge, discussed in the third chapter, is translated into a set of tools than can be used by other designers that face a similar design direction.

II. METHODOLOGY

Certain scientific research methods have been used to answer the research question. Using different types of research methods have the advantages of creating different perspectives. This will lead to discover more knowledge. The following research methods have been used: Literature study, case studies, research by design and on-site research

Literature study

Literature study has been primarily used to gain knowledge of the use of photovoltaic in buildings. Sources as books and articles were helpful to gain sufficient knowledge to adequately start the research. However most of the literature described the technical aspects of building integrated photovoltaic. A very limited amount of literature described about the architectural integration of photovoltaic.

On-site research

This research method is mostly used during the beginning of the research. By analysing the context on site, a better understanding of the problems at the location will be achievend and a better sense of scale. The insights cannot be gained by using only photographs on the internet or Google street view. On-site research method is more important for researching the architectural and spatial qualities of the area than formulating technical parameters.

Case studies

Case studies give insight in how the photovoltaic have been implemented in actual buildings. This will be very helpful to formulate a strategy when certain technologies are chosen. Furthermore they will also show the architectural and spatial qualities of the different integration possibilities of photovoltaic in buildings. Choosing the case study depends on the type of façade and not on the building type. It is important to discover the most suitable façade type for a certain building. The right case studies can help in finding the right façade type.

Research by design

This research method was crucial for researching how to use the solar envelope as an architectural tool. The gathered information from the previously described research methods formulates the parameters for doing the research by design. The designs are made with the computer 3d software Sketchup together with Autodesk Vasari. Autodesk Vasari, which is available for students, is used to make accurate and fast solar radiations analysis. For each model a calculation is made of the amount of solar radiation the envelope receives. In this way a scientific comparison based on specific data can be made. This will lead to an optimal performance design.

Fig. 7: Example of a monocrystalline silicone cell
Homogenous structure
(Direct Industries, n.d.)

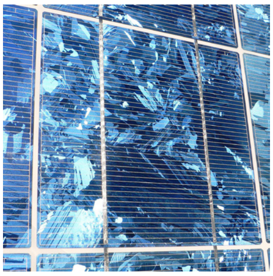


Fig. 8: Example of a polycrystalline silicone cell
Ice-patterned structure
(Solarvis Energy, n.d.)

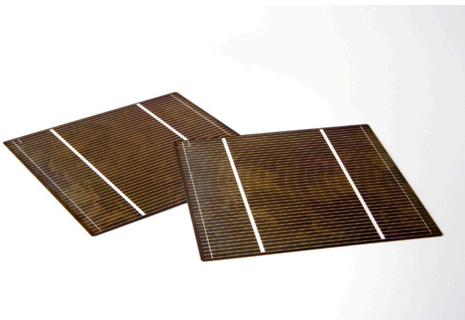


Fig. 9: Example of a thin-film cell
Homogenous structure
(Imec, (2010))

This chapter describes and elaborates the results of the thematic research. After each sub-chapter a conclusion is given.

3.1 INFLUENCES ON THE PV POWER OUTPUT

To formulate the technical parameters for a solar envelope, knowledge needs to be gained of the different influences on the PV power output. These influences can be used to optimize the solar energy production. The most important part of the research is the use of the solar envelope as an architecture tool. Therefore the influences on the PV power output will be described as simple as possible. The power output of the building integrated PV cells is determined by:
- Types of PV cells
- Orientation and tilt
- Temperature
- Shadowing: Shadowing of the PV cells cannot be prevented in an urban environment. The aim in a built environment is to minimize the shadowing of the PV modules

Types of PV cells
The first factor that influences the PV power output are the PV cell types. The efficiency of the PV cells depends on the structure, dimension and the colour of the cells, which vary depending on the type of cells. The majority of the cell types can be categorized into three main categories. These are monocrystalline silicone cell, polycrystalline silicone cell and the thin-layer cells (thin-film). The monocrystalline silicone cells are the most efficient PV cells currently available, with an average of 15 per cent efficiency (Reijenga & Ruoss, 2005, p.23). It has also the lowest degradation, losing its efficiency by 0,25-0,5 per cent per year (Right house, n.d.). The Polycrystalline silicone cells are similar to the monocrystalline silicone cell. It is has an average efficiency of 12 per cent (Reijenga & Ruoss, 2005, p.23). The polycrystalline has the benefit of an easy and fast production, making it more economical compared to the monocrystalline cell types. However both are considered as silicone cells and thus are more sensitive to an increase in temperature. The thin-film PV cells are the least efficient PV cells, with an average of under 10 per cent (Reijenga & Ruoss, 2005, p.24). The thin-film PV cells utilize diffuse and low light better than silicone cells and have good temperature efficiency. This makes the thin-film PV cells, compared to the silicone cells, more suitable for shaded areas or warm circumstances. Thin-film cells provide also flexibility in their form, making them more suitable for building integration applications (German Solar Energy Society, 2005, p. 31-32).

Orientation and Tilt

Due tot the rotation of the earth and its movement around the sun, the amount of solar radiation that falls on a surface varies on each location. In the northern hemisphere the maximum annual PV output can be achieved with a south orientation and a tilt from the horizontal equal to the latitude of the site minus 10 degrees – 20 degrees (Roberts & Guariento, 2009, p.33).

Temperature

PV cells transform approximately 20 per cent of the solar light into electricity. The remaining 80 per cent is transformed into heat, which increases the temperature of the PV modules. An increase in temperature will decrease the PV cell efficiency. A high temperature will also cause discomfort in the internal spaces and an increase in the cooling load (Thomas & Fordham, 2009, p.13). A high performance of the PV cells is maintained by cooling down the PV modules with natural ventilation or mechanical ventilation.

PV modules

PV modules consist of a number of PV cells that are identical in size and type. Only identical cells can be connected in series. Therefore the largest possible rectangular area determines the electrically effective area in an asymmetrical module shape (German Solar Energy Society, 2005, p. 31-32). Curved PV modules can be fabricated on a flexible material, with a minimum radius of 0,9 meters. However a curved module is not desirable. The performance of a curved module is reduced due to the non-uniformity of the sunlight intensity over the module surface (Roberts & Guariento, 2009, p.29). The type op PV modules and the module fixing depend on the type of integration and the requirements for the envelope. The most important requirements that determine the type of module fixing are the air-tightness and water-tightness of the envelope. Figure 13 shows the type of modules, from which it can be concluded that custom modules are the most suitable modules. However it will also be the most expensive option. Glass-Glass modules are very suitable for facade due to the semi-transparent attribute. Figure 14 shows the structural sealant glazing as the most suitable module fixing for PV modules. This type of fixing creates an appearance of a frameless module. The absent of a frame will also result in the absent of shadows on the PV cells that is otherwise created by the frames. Furthermore the structural sealant glazing can also be used for warm and cold facades. (German Solar Energy Society, 2005, p. 283-295)

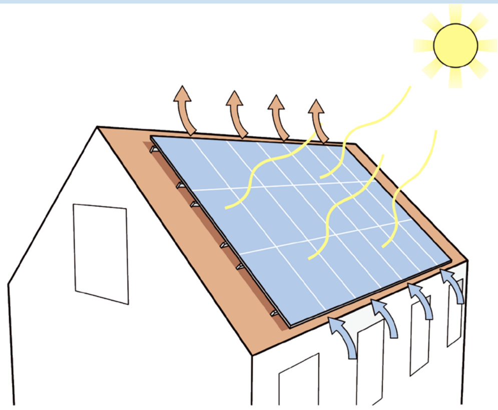


Fig. 10:Ventilated PV module
Maintaining high PV performance
(Roberts & Guariento, 2009, p.44)

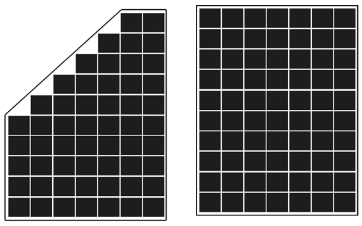


Fig. 11a: Flat PV modules,
PV cells need to have identical sizes
(own illustration)

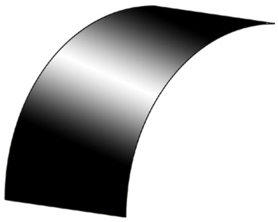


Fig. 11b: Curved PV module
Not efficient shape
(own illustration)

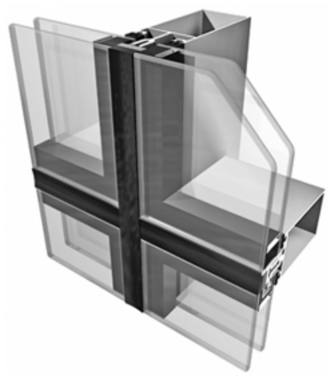


Fig. 12: Structural Sealant Glazing
No external frame profiles
(Metal Technology, n.d.)

Module construction technique	Typical dimension [cm²]	Application suitability				
		Sloped roof	Flat roof	Wall	Window	Shading
Standard modules with plastic or metal frame (glass multi-layer non-transparent back sheet)	33 x 130 45 x 100 55 x 115	+	o	o	-	o
Standard laminates as above without frames	33 x 130 45 x 100 55 x 115	+	+	+	-	+
Glass-glass modules with predefined transparency	all dimensions between 15 and 200	o	o	+	+	+
Glass modules with transparent plastic back sheet (predefined transparency possible)	all dimensions between 15 and 200	o	o	+	+	+
Modules with metal back sheet and plastic cover	15 x 150	+	+	+	-	+
Roofing modules (tiles/slates)	to fit with standard roofing systems	+	-	-	-	o
Custom-designed modules	various dimensions	+	+	+	+	+

+ = high suitability
o = low suitability
- = not suitable

Fig. 13: Types of PV module
Custom designed modules most suitable & least economical (Abbate-Gardner & Toggweiler, 2007, p.86)

To conclude, the orientation and tilt together with the ventilation of the PV modules are the most important parameters during the design of the solar envelope. The type of PV cell depends on the financial aspect of the client and the situation of the different parts of the solar envelope. For example the thin-film PV cell types will be chosen for a part of the solar envelope that has shadowing. The type of PV modules will also depend on the design of the solar envelope. When the design has a very complex shape with different curves, it will increase the probability of a custom PV module. The use of custom PV modules will increase the costs of the solar envelope compared with the standard PV modules. Therefore it is a smart move to take this into consideration during the design of the solar envelope.

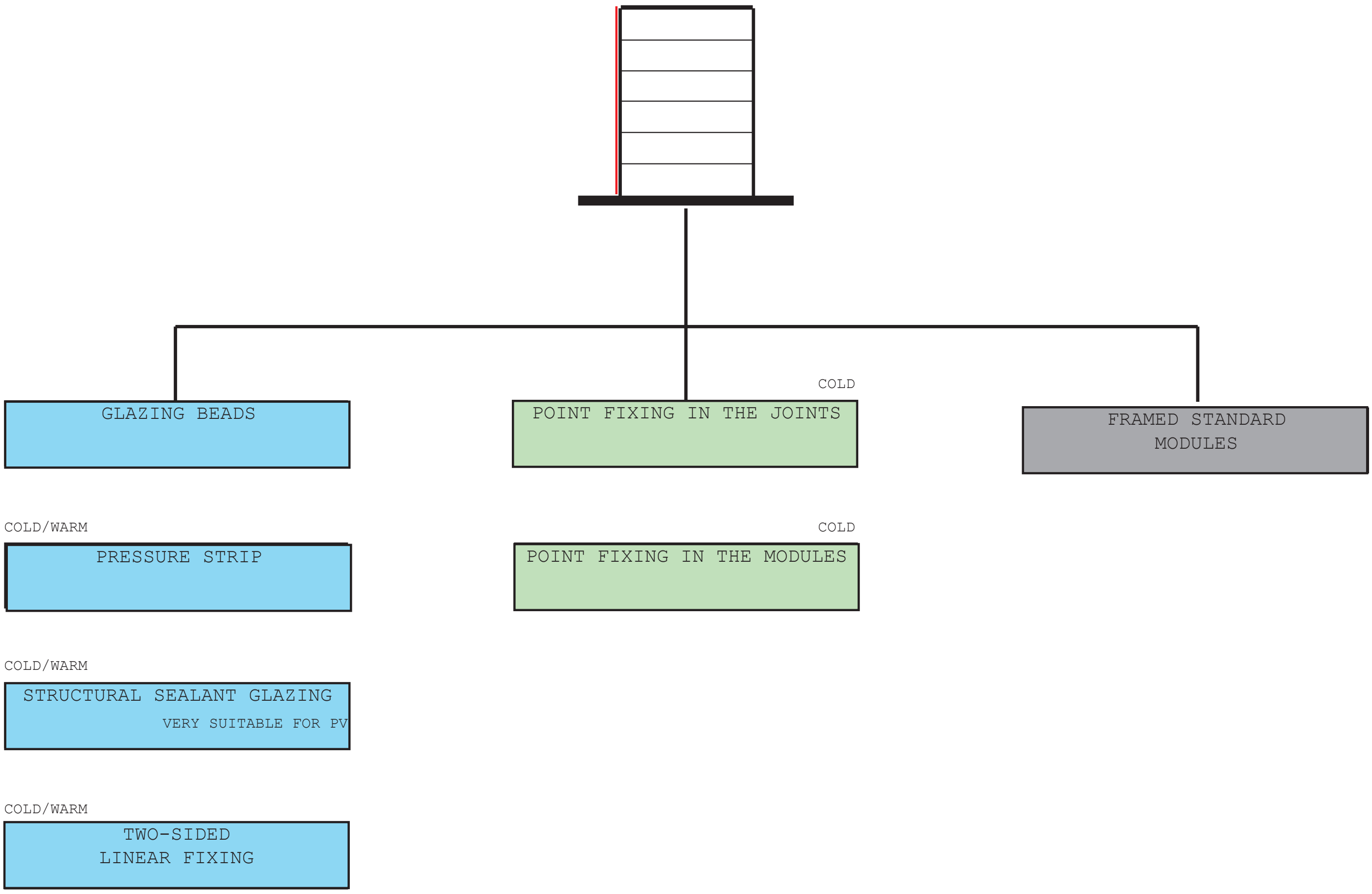


Fig. 14: Types of facade module fixing
(German Solar Energy Society, 2005, p. 283)

3.2 PV INTEGRATION OPPERTUNITIES

In this chapter the different possibilities of photovoltaic integration in buildings are described. Different combinations of the type of integration can be made. The types of PV integrations are:
- Shading devices
- Cold façade
- Warm façade
- Double skin façade
- Roof, atria & canopies

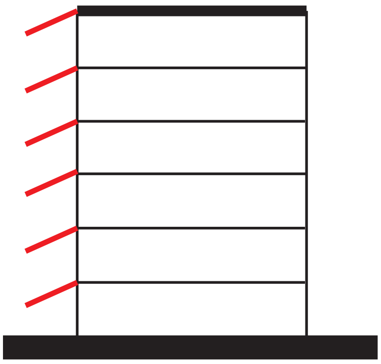


Fig. 15: PV module integrated in shading device

Shading devices
Shading devices are used to prevent overheating of the interior. They are a common application in facades with high transparency. These shading devices can for example be fixed or adjustable external louvers mounted in front of the façade. External shading devices are mostly tilted towards the sun, making it very suitable for PV modules. This will result in an optimum PV power output. External shading devices are also natural ventilated, thus maintaining a high performance of the PV modules by preventing an increase in temperature. On of the main issues of the integration of PV modules in shading devices is the weak resistance to wind loads. It is also difficult to access the PV modules for maintenance and cleaning. Furthermore external-shading devices may cause self-overshadowing, which will result in a lower PV power output (Roberts & Guariento, 2009, p. 46). Shading devices may also reduce the internal spatial quality by limiting or blocking the view to the outside. From an architectural point of view shading devices can have a lower aesthetic value.

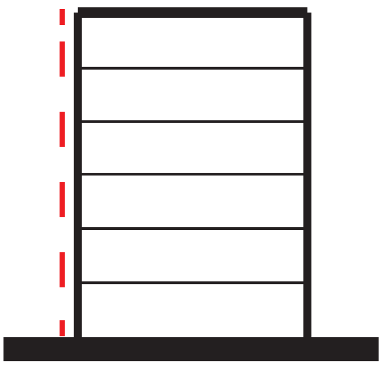


Fig. 16: PV module integrated in cold facade

Cold Façade
Cold façade, also called cavity walls, consist of two skins with a cavity in between. The inner layer is an insulated loadbearing structure, while the outer layer is a protection against the different weather conditions. The outer layer is also the architectural appearance of the building (German Solar Energy Society, 2005, p. 275). PV modules can be integrated in the outer layer of cold facades by replacing the cladding or by placing the PV modules in front of the cladding. The cavity can be ventilated thus allowing the air to cool down the PV modules to maintain a high performance. There is also sufficient space in the cavity for the cable routes (Roberts & Guariento, 2009, p. 47). Furthermore the integration of PV in a cold façade is also one of the most economical options. However cold facades are massive and closed facades, making them unsuitable for buildings that require a high transparency.

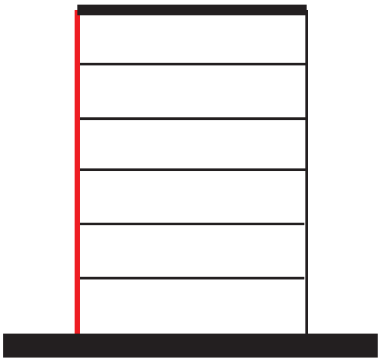


Fig. 17: PV module integrated in warm facade/ curtain wall

Warm Facade

Curtain wall systems, also called warm facades, consist of one layer that protects the interior from the different weather conditions and provides the thermal insulation. The PV modules can be integrated in warm facades by replacing the insulated panels. Depending on the requirements, these modules can be opaque or transparent. Curtain wall systems are not ventilated at the rear side, making them less suitable for the integration of PV modules (German Solar Energy Society, 2005, p. 275-276). However a decrease of the performance of the PV cells can be limited by using PV modules with Teflon encapsulation. Teflon encapsulation ensures adequate cooling of the PV cells when the rear side is poorly or not ventilated (German Solar Energy Society, 2005, p. 53).

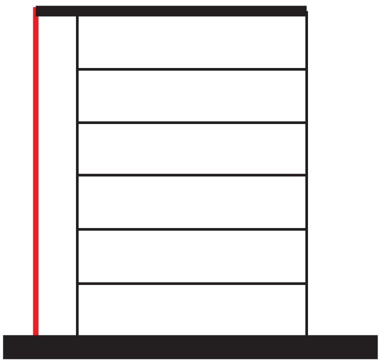


Fig. 18: PV module integrated in double facade

Double skin façade

Double skin façade follows the same principle of a cavity wall. Unlike a cavity wall a high transparency can be achieved with the use of a double skin façade. The advantage of double skin façade is the ability to regulate heat, cold, light and wind without the use of complex and expensive technologies, thus reducing the energy demand (German Solar Energy Society, 2005, p. 276). The inner skin of the double skin façade provides the thermal insulation. The outer skin is made from single glazing allowing daylight entering the cavity. The cavity can be naturally or mechanically ventilated and acts as a thermal buffer. This configuration makes the double skin façade very suitable for the PV modules. PV modules can replace the single glazing of the outer skin. The heat that builds up in the cavity can be collected for heating the interior. This will result in a lower heating load during the winter periods (Roberts & Guariento, 2009, p. 51). Furthermore the PV modules can also act as shading devices, giving the PV modules the function of protection and production. Unlike the cavity walls or the cold facades, catwalks in the cavity allow easy access for maintenance and cleaning.

Roofs, Atria & Canopies

PV modules can also be placed on the roof of a building. The roof has the advantages of being free from overshadowing. The roofs suitability does not depend on the buildings orientation due to the horizontal surface of the roof. A sloped roof can be used to maximize the PV power output. A high performance of the PV module is easy to maintain due to the fact that PV modules on roofs are easy to ventilate. In atriums PV modules can be used to regulate the amount of daylight entering the interior by adjusting the proportion of opaque PV areas. Roofs have also some important issues regarding the integration of PV modules. PV modules on a roof have the risk of the accumulation of dirt on top of the PV module. There is also the risk of condensation on the interior side of a glass-glass PV module (Roberts & Guariento, 2009, p. 51).

To conclude, the double skin façade is the most suitable for the integration of PV modules. The PV modules in the other type of integrations function as protection and production in the building envelope. PV modules in a double skin façade have also an important role in the climate control of the interior. The PV module in combination with the cavity of the double skin façade will help to reduce the heating load of the building during the winter periods. This is highly desirable in cool climates as the Netherlands.

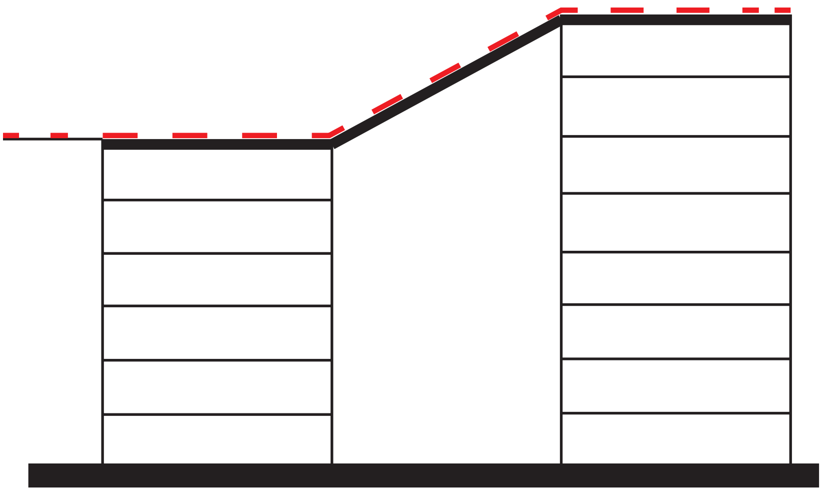


Fig. 19: PV module integrated in roofs,atria & canopies

3.3 DESIGN CONCEPTS

This chapter discusses the different design concepts from an architectural point of view. The design concepts are focused only on the façade. A separate research has been made of the different types of roof structure for a football stadium and their suitability for the integration of PV modules. However this separate research is not applicable for a general paper about solar envelopes due to the specificity of the research. Therefore the choice is made to exclude this separate research in this paper. The different design concepts of the façade are:

- PV vertical curtain wall
- PV vertical structural glazing
- Vertical and horizontal Saw-tooth PV façade
- Accordion PV façade
- Sloped and stepped PV façade

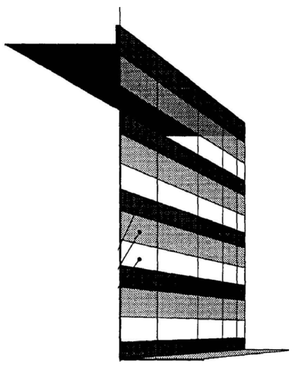


Fig. 20A: Vertical PV façade (Abbate-Gardner, Toggweiler, Kiss, Schoen, & Hullmann, 2007, p.97)

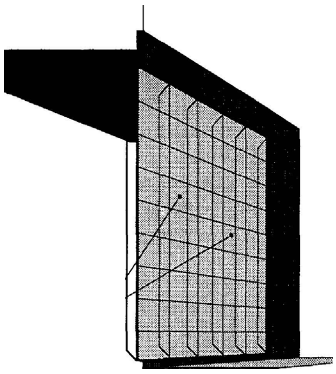


Fig. 20B: PV vertical structural glazing (Abbate-Gardner, et al., 2007, p.103)

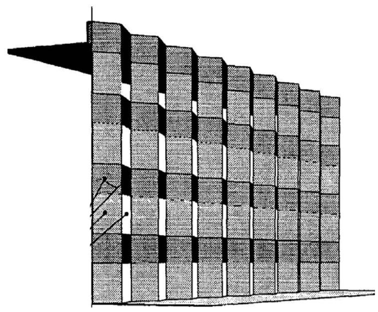


Fig. 20C: Vertical saw-tooth PV façade (Abbate-Gardner, et al., 2007, p.99)

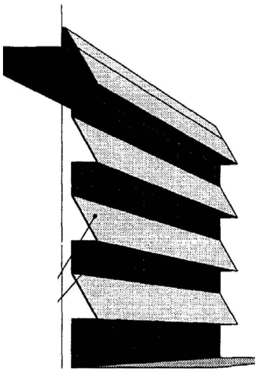


Fig. 20D: Horizontal saw-tooth PV façade (Abbate-Gardner, et al., 2007, p.98)

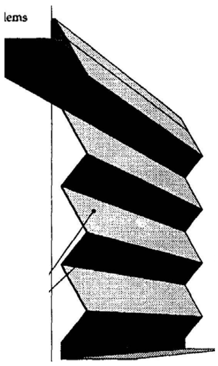


Fig. 20E: Accordion PV façade (Abbate-Gardner, et al., 2007, p.100)

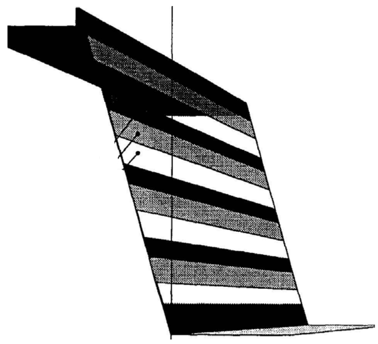


Fig. 20F: Sloping PV façade (Abbate-Gardner, et al., 2007, p.101)

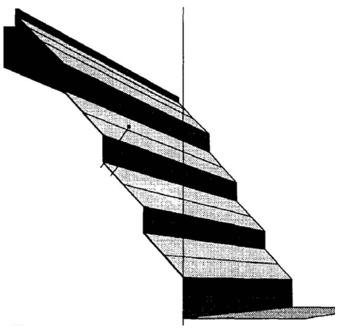


Fig. 20G: Stepping PV façade (Abbate-Gardner, et al., 2007, p.102)

Vertical PV façade

The curtain wall and the structural glazing are both considered as a vertical façade. The vertical façade is a common type of façade in the built environment due to the economical and fast construction attributes. This type of façade cannot be considered as a solar envelope. The PV modules are not tilted to achieve an optimum PV power output. Furthermore the PV modules are more an addition to the façade. The vertical façade has also a low architectural quality because visually striking appearances cannot be created with this type of façade. Additional shading devices may be required, which might result in blocking or limiting the view to outside. This will reduce the internal spatial quality and weaken the relationship between outside and inside. However the vertical façade allows easy access for maintenance and cleaning.

Fig. 21: A reference of a vertical PV façade
Xicui entertainment complex, Beijing
The visual striking appearance is not achieved by the shape of the facade but by implementing new technologies in the facade (Giostra, 2008)

Fig. 22: A reference of a vertical PV façade
Company building Tobias Grau, Hamburg
(Schaer, n.d.)

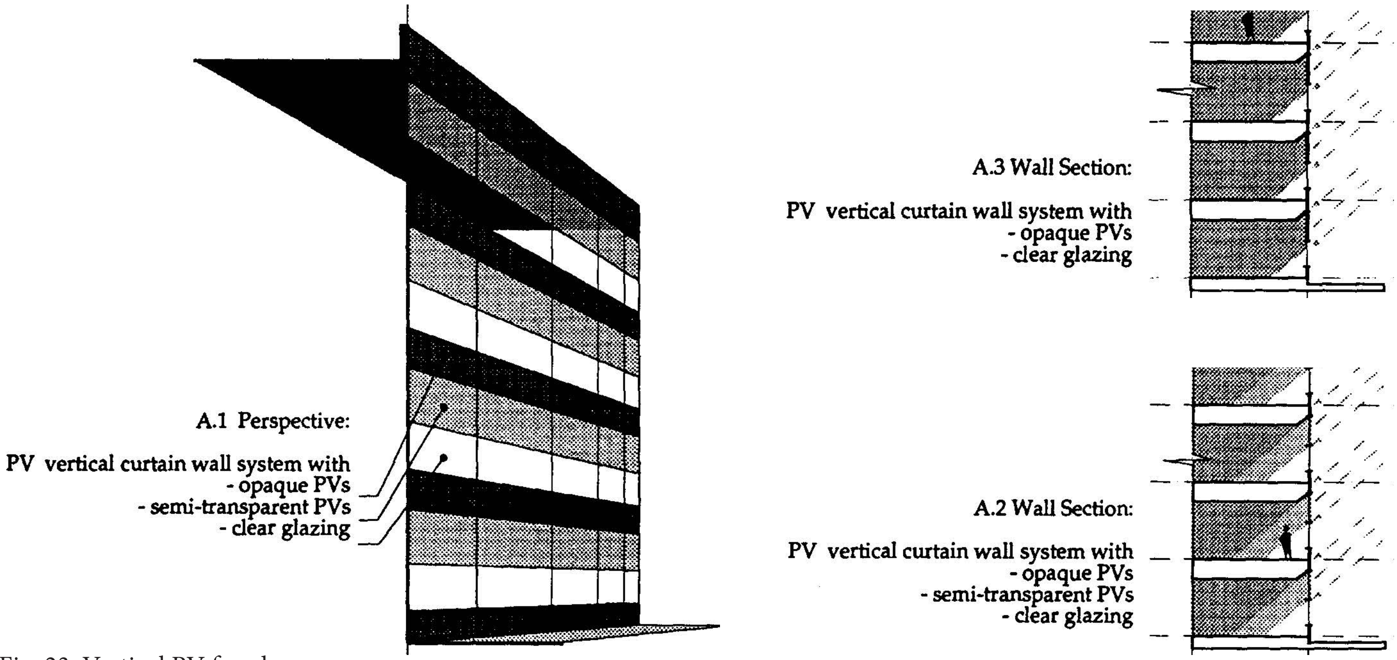


Fig. 23: Vertical PV façade
- Standard, economical, standard construction
- No optimal PV power output
(Abbate-Gardner, et al., 2007, p.97)

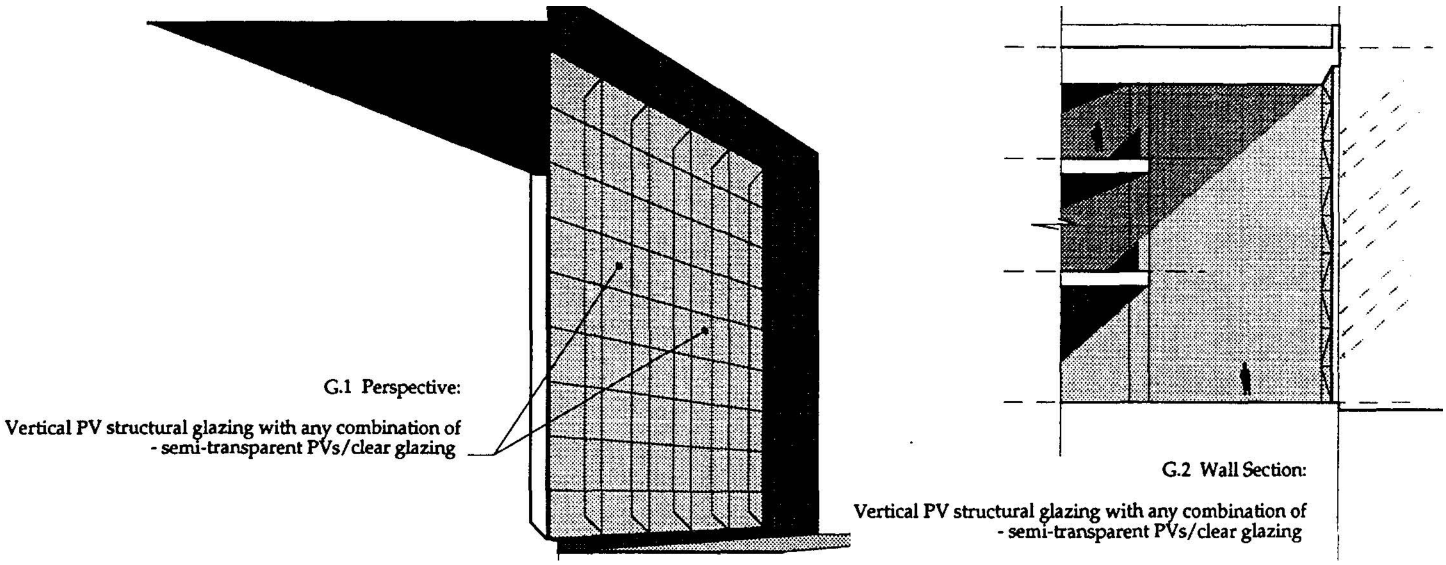


Fig. 24: PV vertical structural glazing
- Standard, economical, standard construction
- Difficult sealing problems for PV edges
(Abbate-Gardner, et al., 2007, p.103)

Saw-tooth façade

The PV modules in the horizontal saw-tooth façade are tilted to achieve an optimum PV power output and act as passive shading devices. The view will remain unobstructed, thus enhancing the internal spatial quality and the relationship between outside and inside. The main issues of the horizontal saw-tooth façade are the complex structure and the potential cleaning and maintenance problems. The vertical saw-tooth PV façade does not have these issues, but it is only suitable for a west or east orientation. The architectural appearance of the saw-tooth façade is also more striking than the vertical façade. A combination of a south oriented horizontal saw-tooth façade with a west and east oriented vertical saw-tooth façade is discouraged. This will lead to an unbalanced design as a whole. It is preferable to use on type of façade that can be used for all the different orientations to maintain a unity in the design

Fig. 25: A reference of a vertical saw-tooth façade. This not a BiPV façade, but it shows the architectural potential
Bronx criminal court complex, New York
(Seward, 2006)

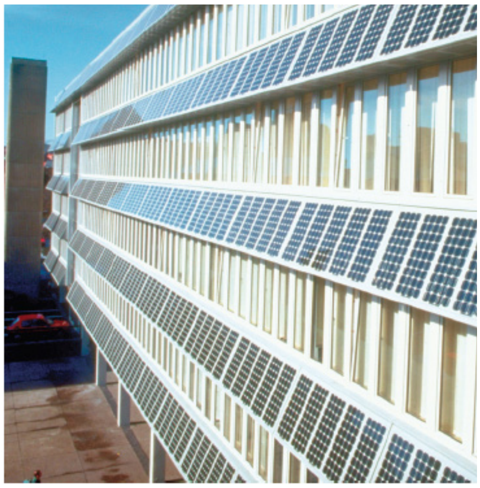


Fig. 26: A reference of a horizontal saw-tooth façade
Northumberland building, Newcastle upon Tyne
(Roberts, & Guariento, 2009, p. 166)

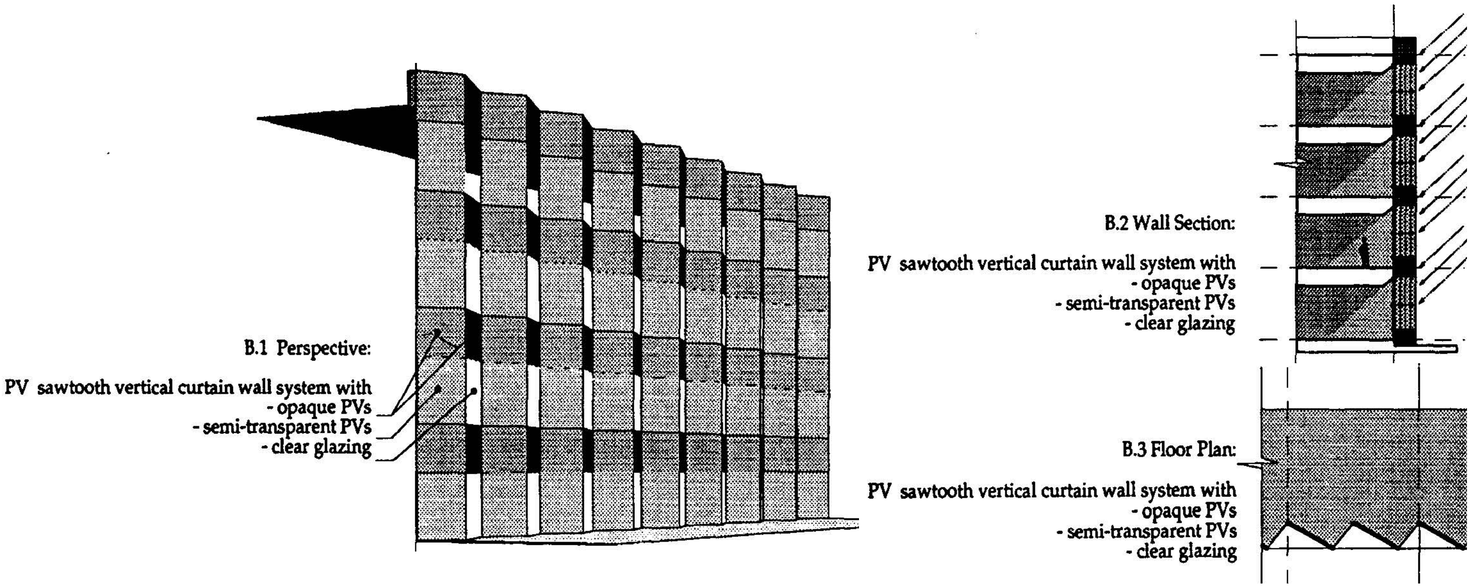


Fig. 27: Vertical saw-tooth PV façade
- Minimal additional construction cost
- Good solar performance in certain orientations
- Creates multiple corner windows
(Abbate-Gardner, et al., 2007, p.99)

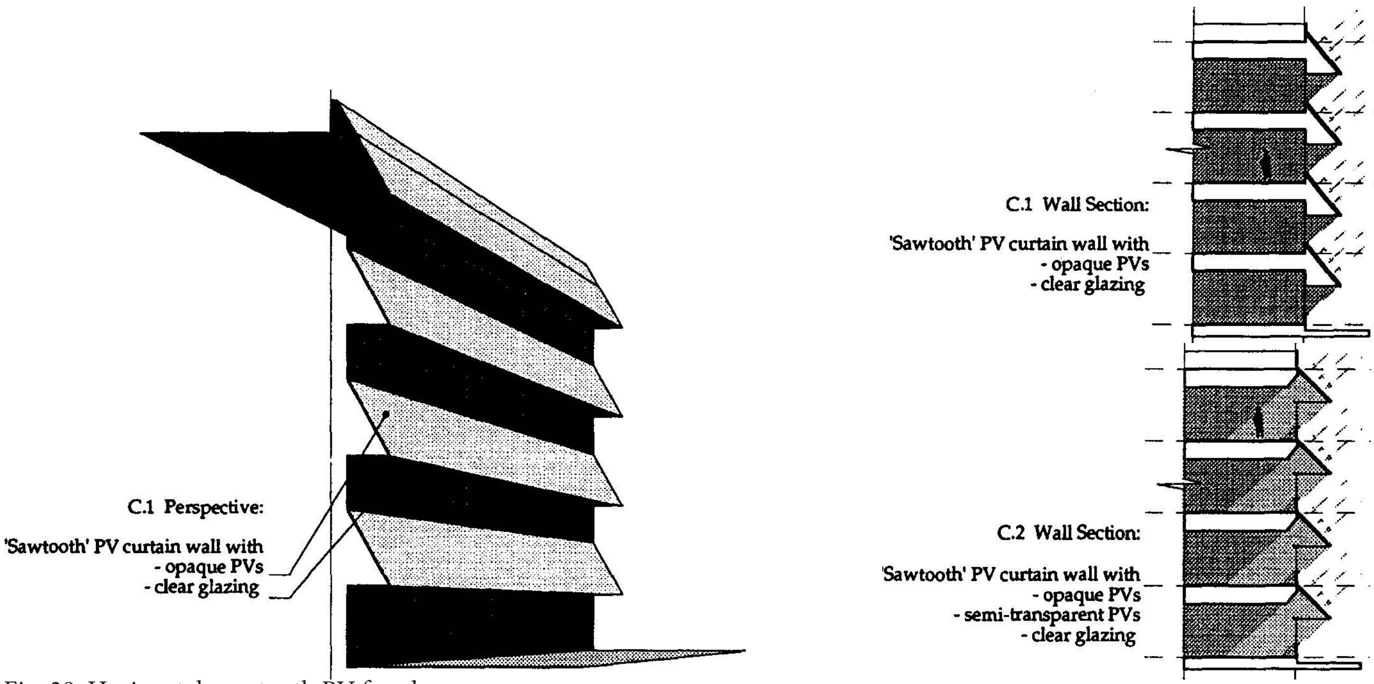


Fig. 28: Horizontal saw-tooth PV façade
- PVs as building skin
- Complex curtain wall construction
- Good PV efficiency
- Passive shading/daylight control
- Potential cleaning problems
(Abbate-Gardner, et al., n.d., p.98)

Accordion PV façade

The accordion façade makes full use of the PV modules and is considered as a solar envelope. The PV modules are truly integrated into the skin instead of being an addition to the façade. The accordion façade has also a high architectural quality. The design of the façade is very dynamic and visually striking, thus creating a unique architecture in the built environment. The internal spatial qualities and the relation to the outside are also enhanced due to the unobstructed view. The PV modules are tilted to achieve an optimum PV power output. The glazing is angled downwards towards the ground to minimize the amount of solar radiation and glare entering the interior. This combination creates a better passive solar protection compared to the horizontal saw-tooth façade. During winter periods the sun can penetrate the skin and heat the interior. This will reduce the heating and cooling load of the building (Building Design + Construction, 2014). Furthermore it is also possible to integrate the double façade in this design concept. However the accordion façade is the least economical façade type due to the complex structure and the potential cleaning and maintenance problems.

Fig. 29: Reference accordion façade
Endesa Pavilion, Barcelona
(Archdaily, 2012)

Fig. 30: Reference accordion façade
Korean Tower, Seoul
(Building Design Construction, 2014)

Fig. 31: Reference accordion façade
Design of a hotel/office building
(Cliento, 2009)

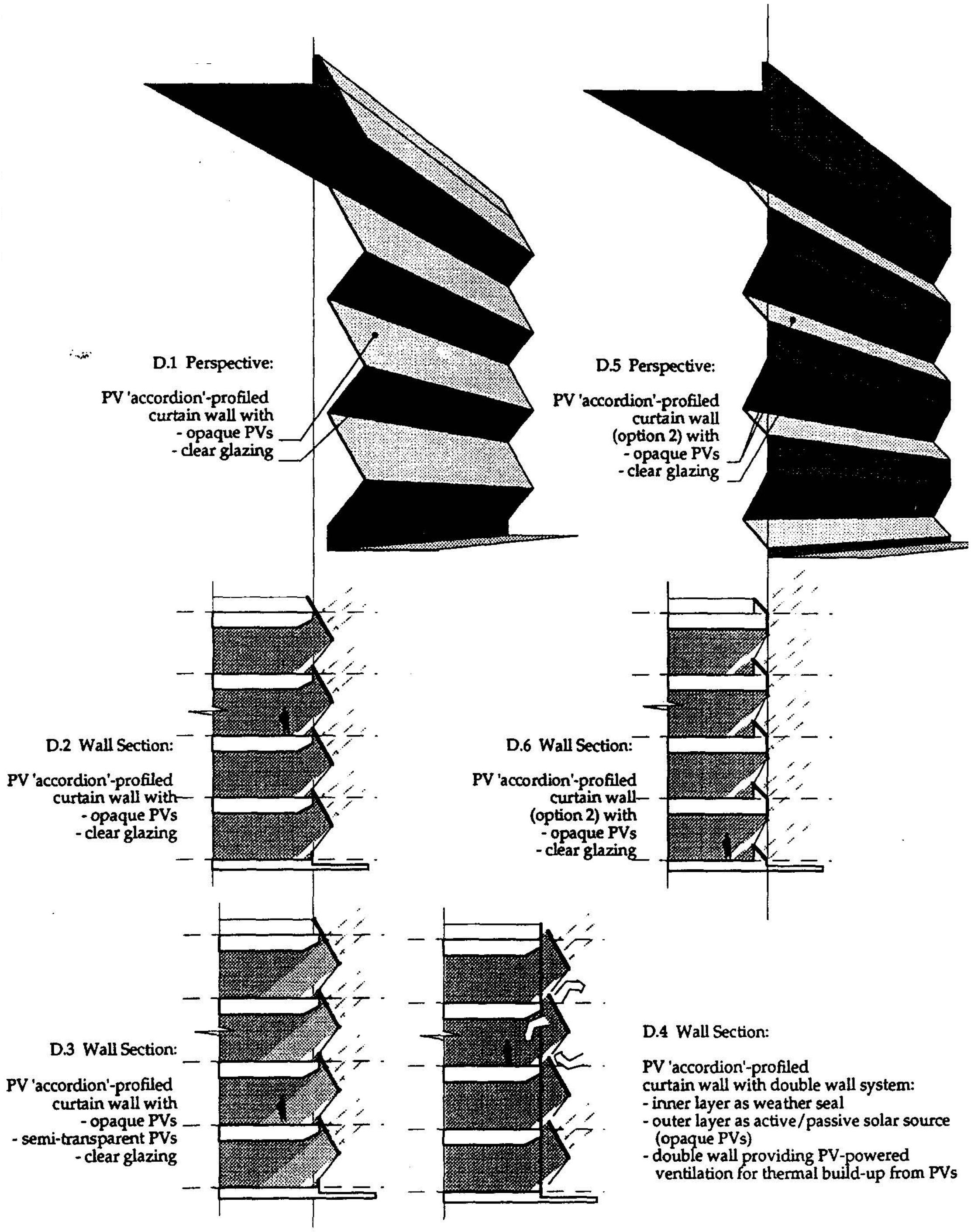


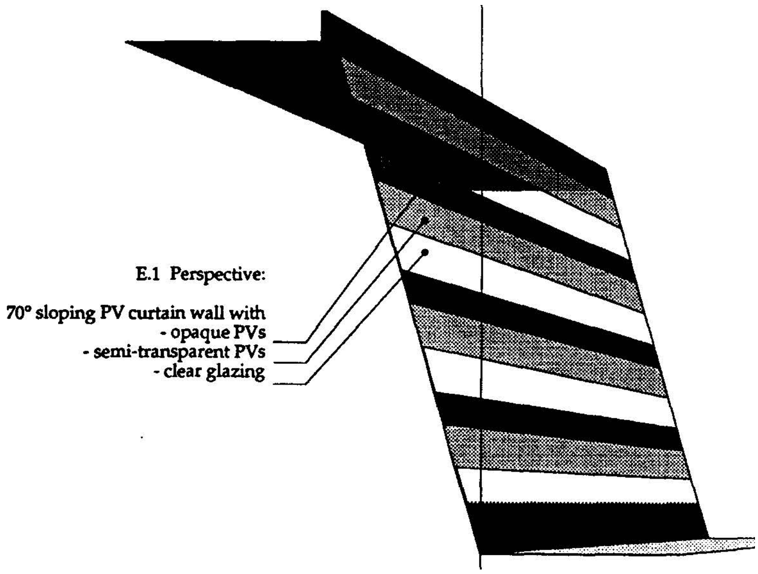
Fig. 32: Accordion PV façade
- PVs as building skin
- Complex curtain wall construction
- Good PV effiency
- Potential cleaning problems
- Passive shading/daylight control
- Good architectural potential
(Abbate-Gardner, et al., 2007, p.100)

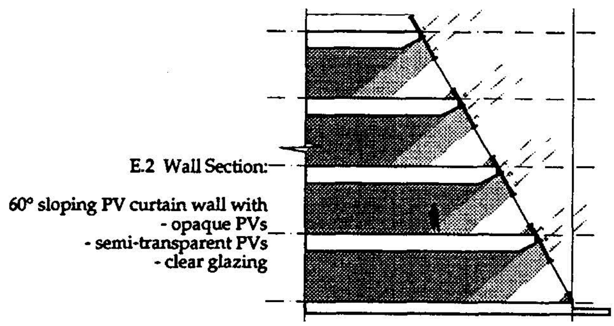
Sloped & stepped façade

The stepping façade is a more complex variant of the sloping façade, but both can be considered as one type. The sloping façade, compared to the other design concepts, has the largest surface area suitable for PV modules with an optimum power output. However the view of this façade is less ideal, because of the orientation towards the sky. A major issue of this design concept is the potential overheating of the interior due to the amount of solar radiation that can enter the interior. It has also a less striking appearance than the saw-tooth and the accordion façade. Furthermore this design concept does not make efficient use of the building footprint. However it has fewer problems with maintenance and cleaning compared to the accordion and the horizontal saw-tooth façade.

Fig. 33: Reference sloping façade
Hahn & Kolb headquarters, Ludwigsburg
(Franck, 2013)

Fig. 34: Reference sloping façade
Solar Office Doxford, Sunderland
(Studio E Architects, n.d.)





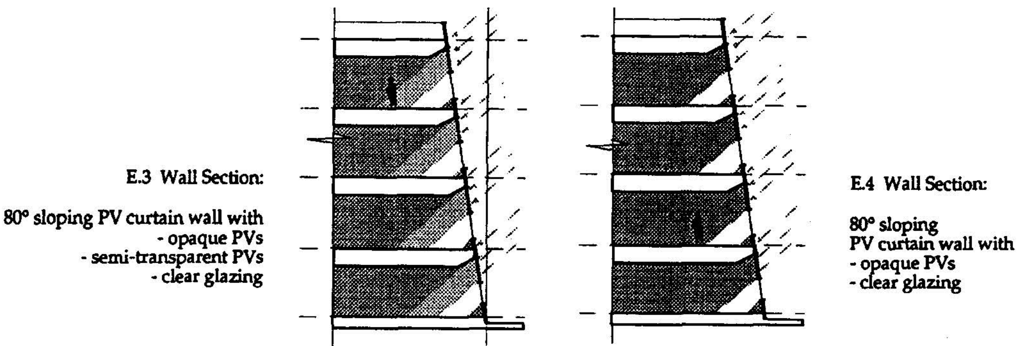


Fig. 35: Sloping PV façade
- Good PV efficiency
- less efficient use of building footprint
(Abbate-Gardner, et al., 2007, p.101)

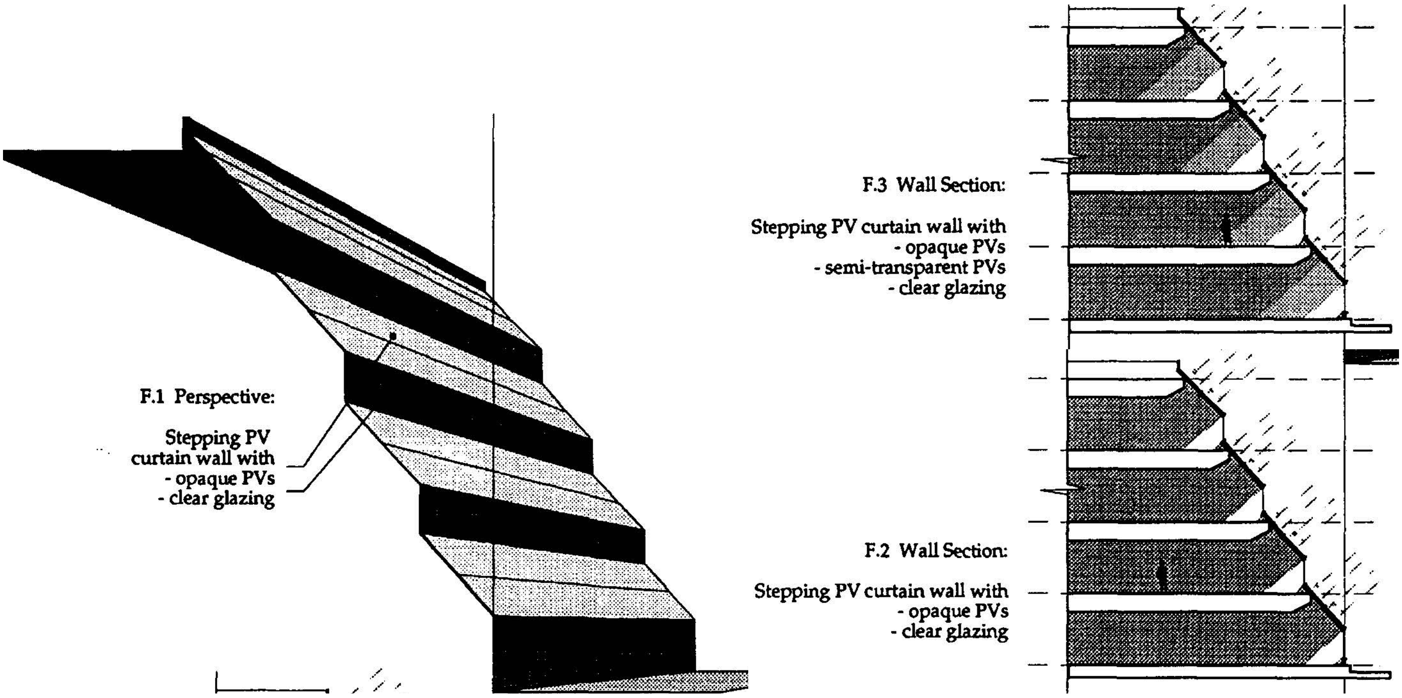


Fig. 36: Stepping PV façade
- Good PV effiency
- Less efficient use of building footprint
- Complex curtain wall construction
(Abbate-Gardner, et al., 2007, p.102)

CONCLUSION

Table 1 shows the differences between the different design concepts. The accordion facade has the highest scores regarding the architectural and spatial quality (view). It has also one of the highest PV efficiency. Therefore the accordion facade meets the requirement of the thematic research question. An other important attribute of the accordion facade is the potential for reducing the energy demand. This attribute can also be found in the horizontal saw-tooth facade. However all the discussed design concepts are not yet suitable for a multi-purpose building. This issue will be further discussed in the next chapter.

	VERTICAL CURTAIN WALL	STRUCTURAL GLAZING	VERTICAL SAW-TOOTH	HORIZONTAL SAW-TOOTH	ACCORDION FACADE	SLOPING FACADE	STEPPING FACADE
ARCHITECTURAL QUALITY	+	+	++	+	+++	++	++
VIEW	+	+	+	+++	+++	+	+
PV EFFICIENCY	+	+	+	+++	+++	+++	+++
ECONOMICAL	+++	+++	++	+	+	++	+
STRUCTURAL COMPLEXITY	+++	+++	++	+	+	++	+
MAINTENANCE	+++	+++	++	+	+	++	+
SOLAR ENVELOPE	NO	NO	YES	YES	YES	YES	YES

Table 1: Comparison between the design concepts
Most important attributes are
- Architectural Quality
- View
- PV effiency

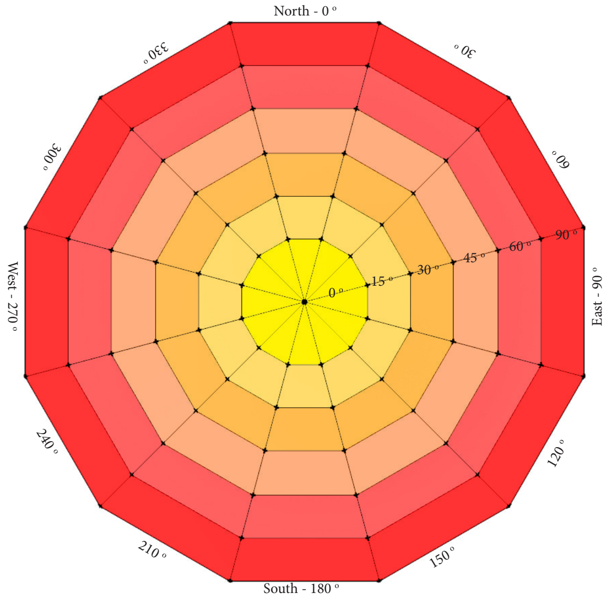
\+ = bad
++ = medium
+++ = good

3.4 SOLAR ENVELOPE FOR A MULTI-PURPOSE BUILDING

The discussed design concepts have a uniform design making them suitable for a single purpose building. For example, the façade of an office building needs to meet only the requirements of the office spaces that are situated behind the façade. A multi-purpose building has different functions situated behind the façade, which may create conflicting requirements. For example a public function requires a high transparency, while a private function favours a closed façade. A uniform façade is therefore not suitable for a multi-purpose building.

The accordion façade is transformed into façade elements with different amount of angles and different slopes. This will make it suitable for a multi-purpose building. The amount of angles and the different slopes varies depending on the location and orientation of the design project. In this paper the location of the graduation project is chosen to illustrate how the accordion façade can be transformed to make it suitable for a multi-purpose building. The same steps can be taken for a different location.

The first step is making a dome with different tilted surfaces and different orientations. The dome gives information of the amount of solar radiation that falls on the surfaces. This will act as guidelines when designing and comparing the different façade elements. The used dome for the graduation project has surfaces that are stepwise tilted by 15 degrees. This will generate façade elements with four different slopes within the same envelope. Each slope will have different amount of angles. Figure 37 shows the different elements that are derived from the accordion PV façade with the guidelines of the dome. The façade elements vary in amount of surface area that is suitable for PV modules and the quality of the transparent surfaces. A lower slope value will result in a larger transparent surface, but the amount of surface suitable for PV modules will decrease. Adding more angles will give more surface area suitable for PV modules and create multiple smaller transparent surfaces. The choice of each façade element depends on the requirements of the functions that are situated behind the façade. The façade elements of one or two angles with 15 degrees or 30 degrees slope are most suitable for public functions. These elements have the largest transparent surfaces, thus enhancing the relationship between outside and inside. The façade element of four angles with 60 degrees slope creates a closed façade, making it more suitable for private functions. This approach allows the designer to create a strong relationship between the façade and the program.



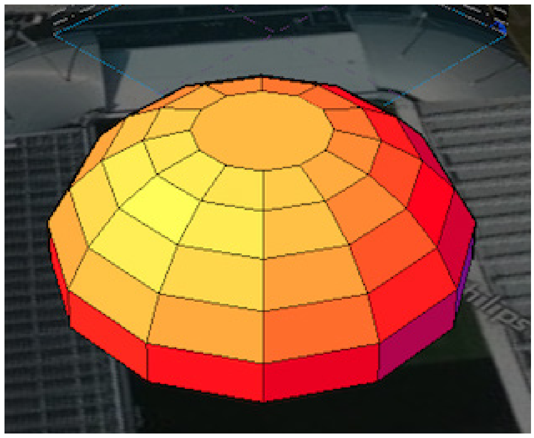


Fig. 36: Different orientations & angles of the guiding dome,

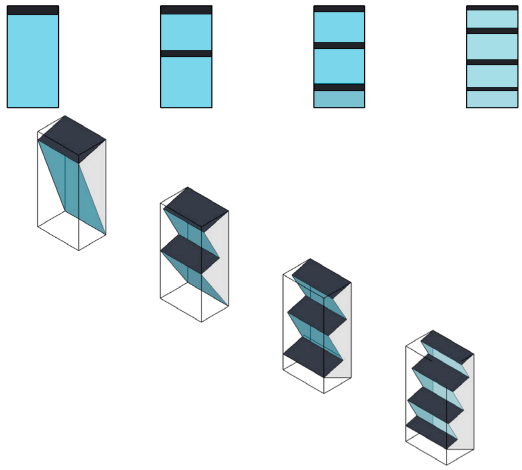


Fig. 37A: Facade elements 15 degrees slope
Left to right; one angle, two angles, three angles and four angles

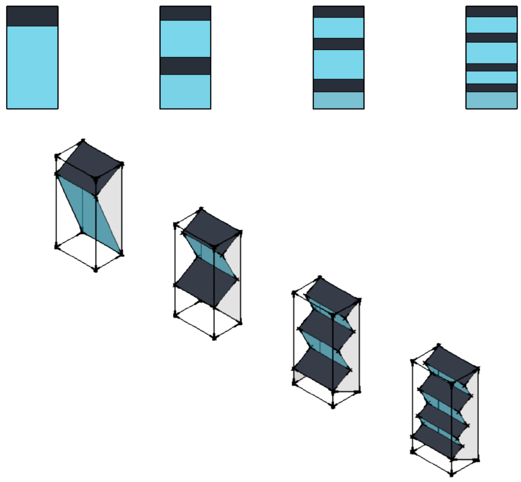


Fig. 37B: Facade elements 30 degrees slope
Left to right; one angle, two angles, three angles and four angles

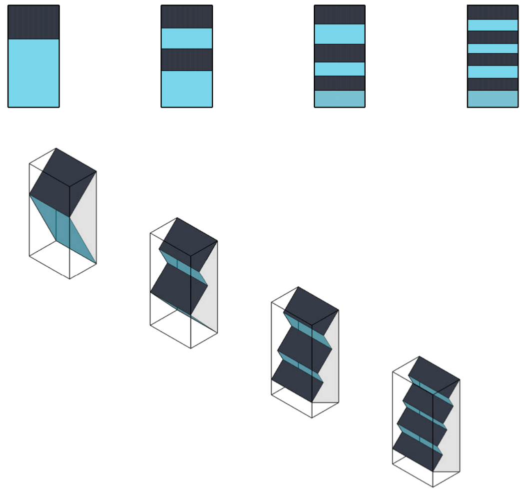


Fig. 37C: Facade elements 45 degrees slope
Left to right; one angle, two angles, three angles and four angles

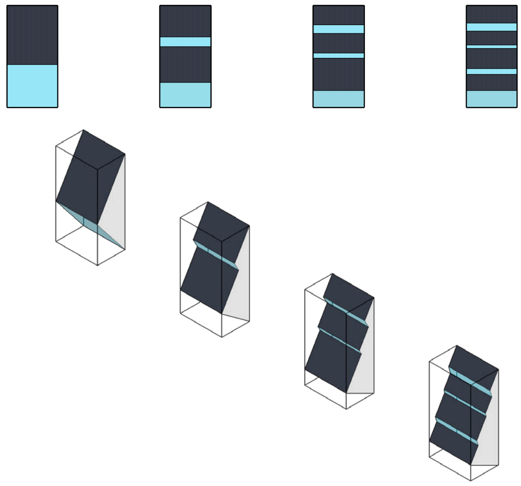


Fig. 37D: Facade elements 60 degrees slope
Left to right; one angle, two angles, three angles and four angles

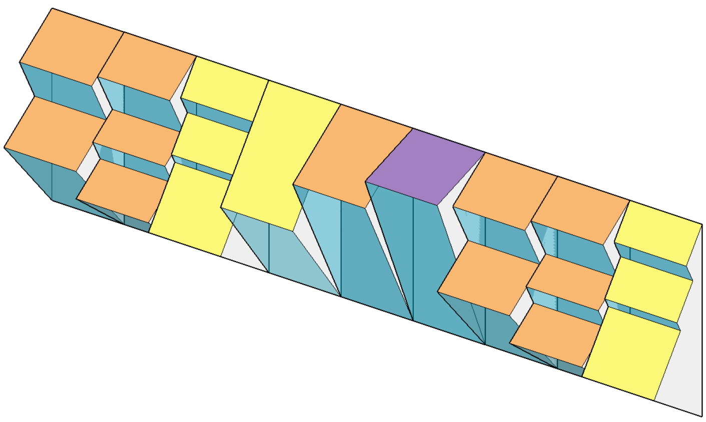


Fig. 38A: Variant 1 south orientation
A stepwise transition from a three angled 60 degrees element (yellow) to the one angle 30 degrees element (purple)

Cumulative solar radiation: 1 732 419 kW

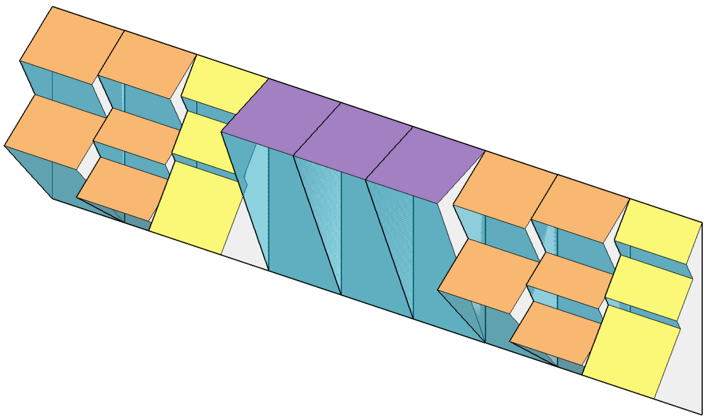


Fig. 38B: Variant 2 south orientation
No stepwise transition from a three angled 60 degrees element (yellow) to the one angle 30 degrees element (purple)

Cumulative solar radiation: 1 659 905 kW

15 ^{0} Angle　45 ^{0} Angle　30 ^{0} Angle　60 ^{0} Angle

The combination of different façade elements, with different slopes and different amount of angles, will cause self-overshadowing. It is therefore important to minimize the self-overshadowing. This can be achieved by using a stepwise transition of the amount of angles and the different slopes. Figure 39 shows the stepwise transition of the different slopes for a south orientation. This approach will cause self-overshadowing in only one direction instead of two directions. However an overall stepwise transition cannot always be achieved in the façade as it can be seen in figure 38. It is still important to implement a stepwise transition as much as possible. Figure 38 shows two variants of the same façade with a public function located in the middle. On the left side of figure 38A a stepwise transition has been made from the three angles of 60 degrees façade element to the one angle of 30 degrees façade elements. This approach will reduce the self-overshadowing and increase the amount of surface suitable for PV modules. Figure 38B shows no such transition, thus reducing the PV module performance. For the east and west orientation a stepwise transition from south to north will minimize the self-overshadowing, as it can be seen in figure 40. Figure 41 shows three systems of façade combinations. It can be concluded from this figure that a stepwise transition of the slope value will minimize the self-overshadowing in the east and west orientation.

The scale of the façade elements depends on the design requirements. Therefore a general guideline cannot be formulated for the best scale of the façade element. Larger façade elements will create a more complex structure, thus increasing the cost of the façade. However the described steps are a good starting point of making the accordion façade suitable for a multi-purpose building.

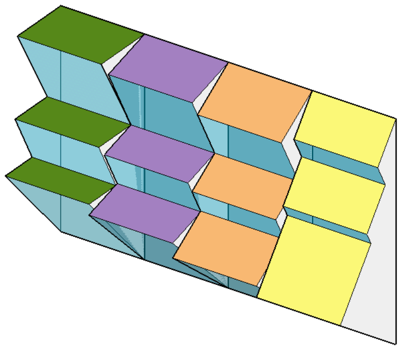


Fig. 39: Stepwise transition

Fig. 40A: East orientation
Stepwise transition north to south

Fig. 40B: East orientation
Stepwise transition south to north

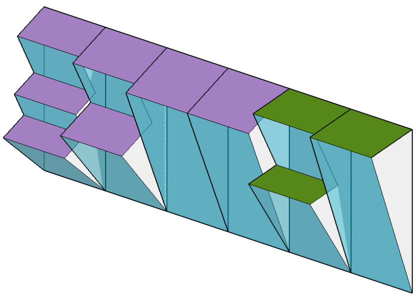


Fig. 41A: Variant 1 east orientation
Stepwise transition of the different slopes
Cumulatieve solar radiation: 674 033 kW

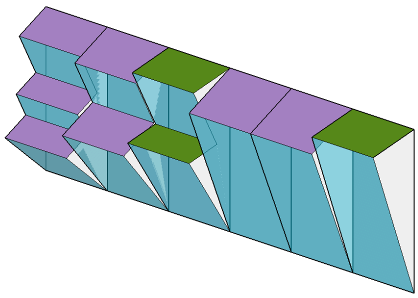


Fig. 41B: Variant 2 east orientation
Stepwise transition of amount of angles
Cumulatieve solar radiation: 672 514 kW

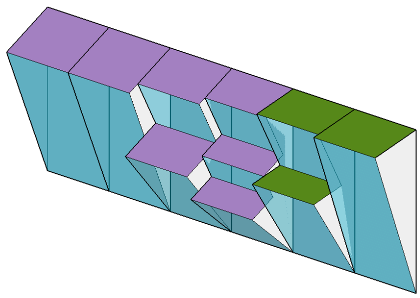


Fig. 41C: Variant 3 east orientation
A variant of 1, a “wave” transition
Cumulatieve solar radiation: 662 454 kW

15 ⁰ Angle

30 ⁰ Angle

45 ⁰ Angle

60 ⁰ Angle

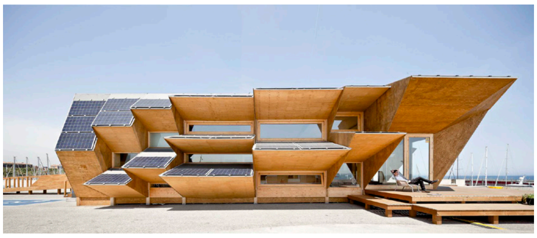


Fig. 42: South façade
(Archdaily, 2012)

3.5 CASE STUDIES

Endesa Pavilion
The Endesa Pavilion is designed from the concept 'form follows energy' with the aim of optimizing the solar energy production (Archdaily, 2012). The façade is made up from different modules that vary depending on the location, inclination of the sun and the relationship with the surrounding area. The sun, when it is high during the summer, will be blocked to avoid heat gain. During the winter the sun is lower, thus possible to enter interior. This will reduce the heating load of the building during the winter (Contemporist, 2012). Each module has also a different window size on different positions. This makes the interior livelier by creating a variety of perspectives to the outside. The façade creates also a very unique and lively architecture. The type of façade that is used in the Endesa Pavilion can be considered as a variant of the accordion façade.

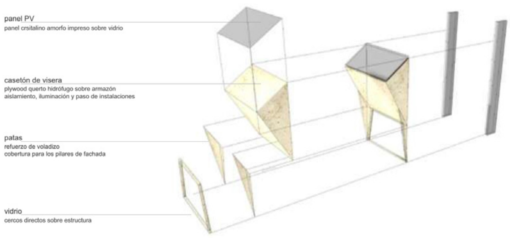


Fig. 43: Façade element
(Archdaily, 2012)

LOCATION: Barcelona
ARCHITECTS: Rodrigo Rubio
YEAR: 2011
TYPE: Pavilion
MODULE SHAPE: rectangular
TECHNOLOGY: Amorphous Crystalline (Thin-Film)
VENTILATED: yes
TYPE OF INTEGRATION: on top of cladding (cold facade)
MODULE FIXING: point fixing in the joints
DESIGN CONCEPT: Accordion façade

Fig. 44: Lively interior
(Archdaily, 2012)

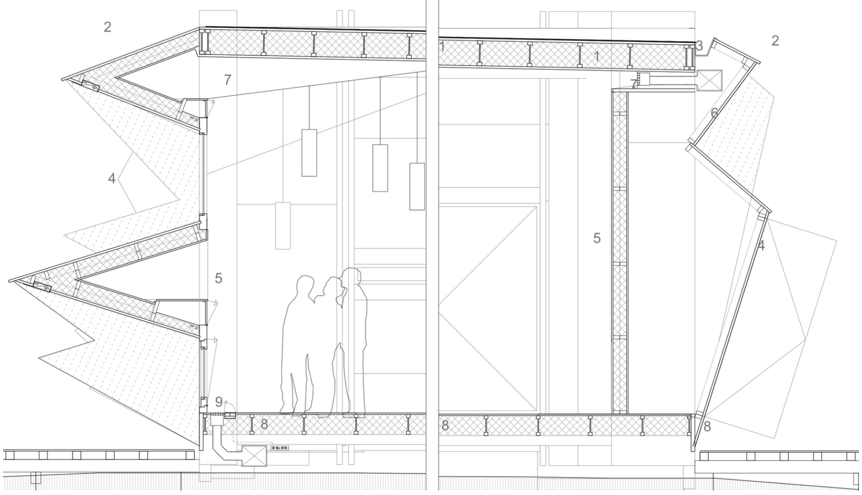


Fig. 45: Section
(Archdaily, 2012)

Korean Tower
The Korean tower is a 50-storey office tower with a smart solar façade. The PV modules are tilted 30 degrees towards the sun to maximize the PV power output. The PV modules also act as passive solar shading. The glazing is angled 15 degrees downwards towards the ground (Building Design + Construction, 2014). The angled glazing will reflect a large percentage of the summer sun to reduce the cooling loads. During the winter the sun still enters the interior, which will also reduce the heating load (Michler, 2010). This configuration of angled glazing and tilted PV modules creates also a dynamic architecture that is visually striking in the building environment. The façade of the Korean tower is a perfect example of the accordion façade type. Unlike the Endesa Pavilion, is the façade of the Korean Tower made from a single facade element. This creates a uniform façade, which is suitable for a single purpose building. Furtermore this accordion facade has only one angle at each floor.

Fig. 46: Render of the building
(Building Design + Construction, 2014)

LOCATION: Seoul
ARCHITECTS: Adrian Smith & Gordon-Gill Architecture
YEAR: Not yet build
TYPE: Office
MODULE SHAPE: Rectangular
TECHNOLOGY: Unknown
VENTILATED: Unknown
TYPE OF INTEGRATION:Curtain Wall
MODULE FIXING: High propability Pressure strips
DESIGN CONCEPT: Accordion façade

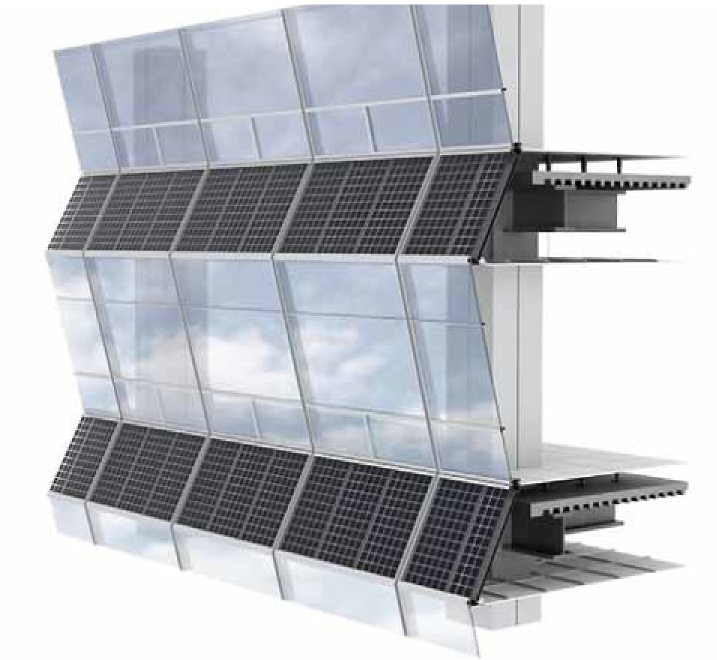


Fig. 47: Detailed view of the façade,
The floors have sufficient space for the installations of the necessary hardware of the PV modules
(Building Design + Construction, 2014)

Fig. 48: Detailed view of the façade
(Building Design + Construction, 2014)

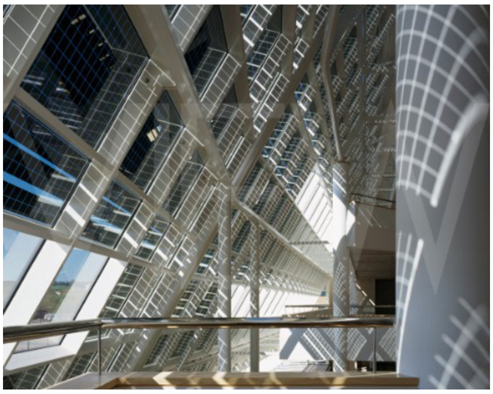


Fig. 49: Interior south façade
Light effect created by the PV cells
(Prasat & Snow, 2005, p.158)

Solar Office, Doxford international

The solar office of DOXFORD International uses the sloping PV façade to regulate the ventilation of the internal spaces. Earlier this façade was considered as a weak option for a PV façade. However this case study shows a different strategy that can be implemented for a PV façade to reduce the energy demand. The heat from the PV façade creates a stack effect that helps to draw out the air from the adjacent office spaces. The depths of the offices have a maximum of 15 meters to make the natural cross ventilation possible. Mechanical vents have been installed at the PV façade to help the natural airflow. The mechanical vents function also as a cooling mechanism for the PV façade (Prasad & Snow, 2005, p.156).

Fig. 50: South (sloping) façade
(Prasat & Snow, 2005, p.154)

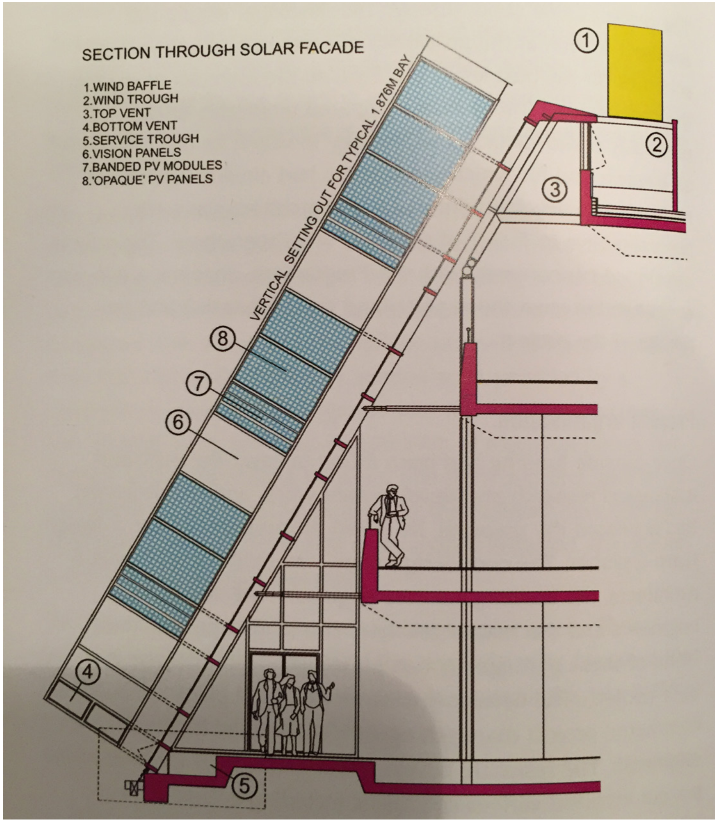


Fig. 51: Detailed section south façade
(Prasat & Snow, 2005, p.157)

LOCATION: Sunderland
ARCHITECTS: Studio E Architects
YEAR: 1998
TYPE: Commercial
MODULE SHAPE: rectangular
TECHNOLOGY: Polycrystalline silicone
VENTILATED: yes
TYPE OF INTEGRATION: Curtain Wall
MODULE FIXING: Pressure strips
D**ESIGN CONCEPT**: Sloping façade

IV. CONCLUSION

How to design a new building envelope that can optimize the solar energy production and at the same time enhances the desired spatial and architectural quality?

Figure 52 shows the different possibilities of designing a solar envelope. It's a set of layers from which the designer can choose different combinations. Each layer has its own options that can be combined with the option from another layer. The combinations of the different layers depend on the requirements that are formulated by the designer. Every combination of the different layers is possible, but each combination creates its own set of problems. The designer must then solve these problems. For the graduation project the focus was on optimizing the solar energy production and the use of the solar envelope as an architectural tool. Therefore the choice has been made to design a solar envelope based on the accordion façade. Figure 52 shows the combination that formulates the answer to the thematic research question. It also shows the different routes of the case studies to illustrate the possibilities of different combinations.

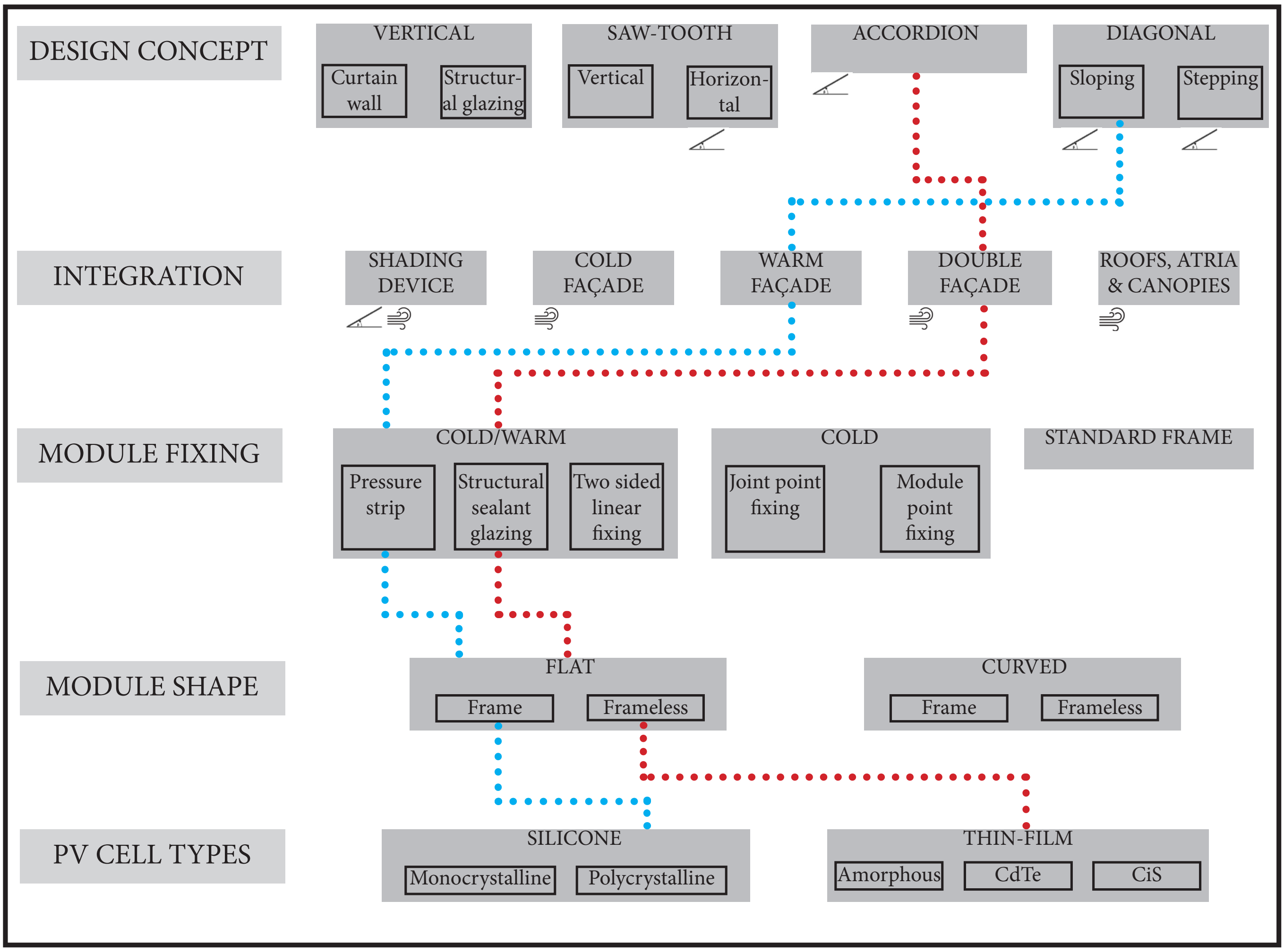


Fig. 52: The different layers of a solar envelope Showing the combination of the Graduation Project and as an example the combinations of the Solar Office Doxford.

Tilted PV module :
Ventilated :

Route Graduation Project/Aswer THQ :
Route Solar Office Doxford :

As it was stated earlier, the accordion façade has the potential of optimizing the solar energy production and at the same time enhances the architectural and spatial quality. The accordion façade creates visually striking appearances, thus enhancing the identity and therefore the architectural quality of the building in the built environment. The accordion façade doesn't require additional shading devices, resulting in an unobstructed view to the outside. Therefore an increase in the spatial quality is gained and a stronger relation between outside and inside is achieved. It is possible to have different type of programs situated behind the façade by combining accordion facades of different slopes and angles. It is possible to even combine contrasting programs, such as public functions and private functions, behind the same façade. This will result in a stronger relationship between the solar façade and the program. In other words the façade shows the situation of the different programs that are located in the building. Therefore the solar envelope will truly become an architectural tool and at the same time enhances the PV power output. However this solar envelope has a complex structure, making it less economical and creating potential problems for the maintenance and cleaning. A further study needs to be made to solve these problems.

In some cases the technical parameters and the architectural requirements may cause conflicting situations. From a technical point of view shadows need to be prevented and the façade needs to be ventilated to maintain a high PV cell performance. It is not always possible to meet all those requirements. As it was shown in chapter 3.4, the façade will cause self-overshadowing. In some cases the program prevents to use a stepwise transition of the façade elements and therefore minimizing the self-overshadowing becomes limited. It can therefore be concluded that a balance should be found in optimizing the PV power output and the desired architectural quality. This research paper focuses more on use of the solar envelope as an architectural tool. Therefore in some cases a compromise in the energy output has been made over the architectural quality.

The thematic research question focuses mainly on producing clean energy with a PV façade. However the research showed that a good sustainable and integrated design of a PV façade is achieved by using the PV modules as multifunctional elements and not only to produce clean energy. The PV modules can help to reduce the energy demand by reducing the heating and cooling load. Furthermore the PV module can help to regulate the ventilation of the internal spaces. This strategy will lead to solar architecture instead of using the PV modules as additions to the façade.

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