Study of Innovative Building Integrated Photovoltaic (BIPV) Products and Solutions Based on Thin Film and c-Si Technologies

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Master Thesis

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Resumo

Atualmente, os recursos não renováveis ainda são dominantes na produção de eletricidade a nível mundial. Para que esta realidade se altere e se evitem as suas devastadoras consequências, é importante que haja um significativo aumento da utilização de energia solar fotovoltaica, em particular em edifícios, uma vez que estes representam uma parte muito significativa do consumo de eletricidade a nível mundial. Consequentemente, os produtos fotovoltaicos para integração em edifícios (BIPV) são fundamentais para uma mudança de paradigma, sendo que esta urgência deve ser acompanhada de inovação, incluindo a melhoria a nível estético, a diversidade de produtos BIPV, e o desenvolvimento de novas soluções BIPV. Neste trabalho estudaram-se duas inovações tecnológicas com abordagens diferentes, uma a nível de produto e outro a nível de solução: dimensionamento de módulos BIPV leves para fachadas ventiladas e dimensionamento de uma estufa fotovoltaica (GIPV), usando as tecnologias de silício amorfo de filme fino e de silício cristalino.

Em primeiro lugar, descrevem-se os fundamentos teóricos relacionados com as diferentes tecnologias de células fotovoltaicas e, caracterizam-se os principais componentes dos produtos e das soluções BIPV. É ainda feita uma referência aos fatores mais importantes para o dimensionamento de estufas.

Para o dimensionamento de módulos BIPV leves para fachadas ventiladas, foram encontradas as dimensões mínimas possíveis para os módulos, tendo em conta as normas aplicadas a fachadas ventiladas e a módulos fotovoltaicos. Foram igualmente avaliadas as dimensões de produtos comerciais leves para fachadas ventiladas. Posteriormente, foram identificadas as configurações mais competitivas que respeitam as normas aplicadas e produzidas algumas amostras. Finalmente, foi estudado o conceito *plug & play*, e como este pode ser aplicado a fachadas ventiladas, bem como avaliadas várias soluções já existentes que se aproximam deste conceito.

Para o dimensionamento da estufa fotovoltaica, especificaram-se os requisitos de projeto, sabendo que esta estaria dividida em duas partes iguais de cerca de 15 m^2 - uma com módulos BIPV semi-transparentes de a-Si e outra com vidros tradicionais transparentes - de forma a avaliar e comparar a produção agrícola nos dois espaços. Foram selecionados os tipos de produções agrícolas que se adequam ao clima de Soria e a correspondente transparência dos módulos BIPV. Outra parte do trabalho consistiu no desenho da estufa fotovoltaica, tendo em conta os requisitos. Uma vez definidas as dimensões, foi calculada a produção elétrica e eleito o sistema fotovoltaico mais adequado, independente da rede devido à baixa potência nominal. Posteriormente, foi desenhada uma nova estufa com as dimensões mínimas para que pudesse ser ligada à rede, calculada a sua produção elétrica e os custos totais de instalação.

No final do projeto, foram obtidos resultados muito positivos. Relativamente ao dimensionamento de módulos BIPV leves, foram encontradas várias configurações economicamente interessantes e as amostras produzidas não tiveram quase defeitos. Relativamente ao dimensionamento da estufa fotovoltaica, a configuração da estufa ligada à rede foi particularmente interessante, pois é a solução mais económica e capaz de albergar vários tipos de produtos agrícolas, conseguindo gerar eletricidade para satisfazer as necessidades de consumo da estufa. Os bons resultados associados às previsões de crescimento do mercado BIPV fazem com que seja interessante continuar a desenvolver o estudo realizado, com o objetivo de obter produtos comerciais finais.

Palavras-chave: BIPV, filme fino, a-Si, c-Si, materiais leves, *plug & play*, soluções fotovoltaicas para envolventes de edifícios, estufa, sistema fotovoltaico, sistemas autónomos, sistemas ligados à rede.

Abstract

Today, non-renewable energy sources are still dominant in the global electricity production. To change this reality and avoid its devastating consequences, it is crucial to increase the share of solar energy, particularly in buildings, which consume most of the generated electricity. Consequently, Building Integrated Photovoltaic (BIPV) products are fundamental for a change of paradigm, and must be combined with innovative developments, including the enhancement of aesthetics and diversity of BIPV products. Taking that into account, this study presents two technological innovations with different approaches, one at product level and another at solution level, using amorphous silicon (a-Si) thin film and monocrystalline silicon (c-Si) solar cells: design of lightweight PV modules and a Greenhouse Integrated Photovoltaic Glass (GIPV).

First, fundamentals related to PV technologies are described, and the components of BIPV products and solutions are characterized. An introduction to greenhouse's key factors is made.

For the design of lightweight BIPV modules, the standards applied to PV modules and construction materials for ventilated façades were taken into account to obtain the minimum possible dimensions of the PV modules. The configuration of the currently sold PV modules and equivalent products for ventilated façades were evaluated. After that, the most interesting BIPV lightweight PV solutions that at the same time comply with PV and building standards and are market competitive were identified and several samples were produced. Finally, the ideal characteristics of plug & play framing solutions for ventilated façades were defined and the most interesting products on the market were evaluated.

For the design of a GIPV, the requirements and specifications of this solution were evaluated. As a starting point, a 30 m^2 greenhouse was considered, divided in two 15 m^2 greenhouses, one integrating a-Si PV glass and another one with conventional clear glass, in order to evaluate and compare crop productions on both sides, and, consequently, to assess the influence of using PV glass in comparison with conventional glass in a greenhouse solution. The most adequate plants to be produced were selected, as well as the most suitable PV module transparency degree. Another part of the work consisted in designing the integrating photovoltaic glass, according to the requirements. Once the dimensions were defined, the energy production of the integrating photovoltaic glass was calculated and the most adequate energy management system was selected, which was a stand-alone PV system, due to the low nominal power of some façades. Following that, the minimum configuration for a grid connected PV system was drawn and the energy production as well as the cost of the integrating photovoltaic glass were calculated.

In the end, it was possible to obtain very positive results. Concerning the design of lightweight BIPV modules, many economically interesting configurations were found and the produced samples had almost no defects. Regarding the design of an integrating photovoltaic glass, a particularly interesting grid connected PV system was obtained, which was capable of having many types of crop productions and generating enough electricity to power all electronic devices. Furthermore, the designed solution was the cheapest one. The great results combined with the very positive forecast of the BIPV market, point to the interest of further research in order to improve the already consolidated products and solutions and to develop new commercial ones.

Key-words: BIPV, thin film, a-Si, c-Si, lightweight, plug & play, BIPV click-&-go envelope solutions, GIPV, BIPV system, off-grid, grid connected.

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Contents

List of acronyms

Abbreviations

AC	Alternating current
AR	Aspect ratio
a-Si	Amorphous silicon
BAPV	Building attached photovoltaics
BIPV	Building integrated photovoltaic
BOS	Balance of System
CBD	Chemical bath deposition
CdS	Cadmium sulfide
CdTe	Cadmium telluride
c_e	Exposition coefficient
CIGS	Copper indium gallium selenide
Cl-O	Chlorine monoxide
CO2	Carbon dioxide
c_p	Eolic pressure coefficient
c_s	Suction coefficient
c-Si	Crystalline silicon
CVD	Chemical vapor deposition
DC	Direct flow electric charge
EArray	Energy at the end of the array
EnergyMatching	Adaptable and adaptive RES envelope solutions to maximise energy harvesting and optimize EU building and district load matching
EVA	Ethylene-vinyl acetate
GIPV	Greenhouse Integrated Photovoltaic Glass
KOH	Potassium hydroxide
Low-E	Low emissivity
LPCVD	Low pressure chemical vapor deposition
Mo	Molybdenum
NZEBs	Nearly zero-energy buildings
PAR	Photosynthetically active radiation
pc-Si	Polycrystalline silicon
PECVD	Plasma-enhanced chemical vapor deposition
PET	Polyethylene terephthalate
PV	Photovoltaic
PVB	Polyvinyl butyral
PVDF	Polyvinylidene fluoride
PVF	Polyvinyl fluoride

R&D	Research and development
Rezbuild	REfurbishment decision making platform through advanced technologies for near Zero energy BUILDing renovation
Si	Silicon
TCO	Transparent conducting oxide
UV	Ultraviolet
ZnO	Zinc oxide

Symbols

α	Absorption coefficient
μc-Si	Microcrystalline silicon

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1 Introduction

The present study was conducted at Onyx Solar, during five months, and aims to investigate about BIPV products and solutions and develop new ones, using a-Si thin film and c-Si PV technologies. This introductory chapter contains a brief description of the context and of the need to be addressed, as well as the presentation of the company where the research took place. In addition, the objectives are identified and a description of the methodology used is presented.

1.1 Thesis context, background and motivation

There is currently a great challenge to stop global warming and its devastating consequences. To reduce greenhouse gas emissions, which are the main cause of this phenomena, it is crucial to increase the usage of clean renewable energy resources, such as solar power. At the end of 2016, the share of renewable energy in global electricity production represented 24.5%, as shown in Figure 1.1, being the solar PV sector responsible for 1.5% of that production.

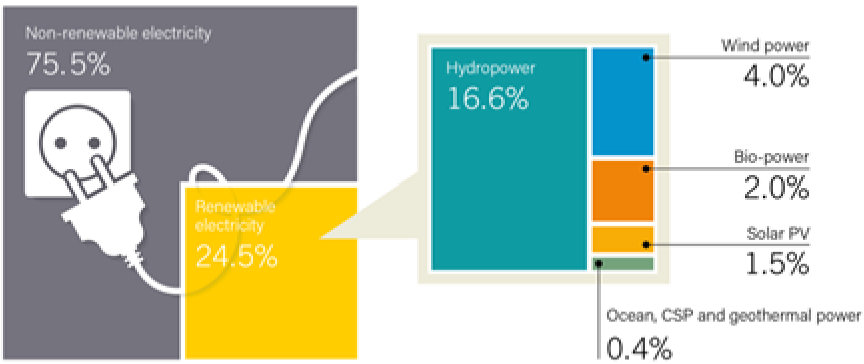


Figure 1.1 Global production of electricity at the end of 2016, by energy resource [1].

Even though there is a long path until most of the electricity is generated from renewable resources, there has been a very positive evolution of the global scenario, as it is possible to see in Figure 1.2 [2].

Figure 1.2 Global capacity growth of renewable technologies, from 1994 to 2022 [2].

In particular, Figure 1.3 shows that there has been a significant growth in the PV sector, from 6 GW in 2006 to 303 GW in 2016 [1].

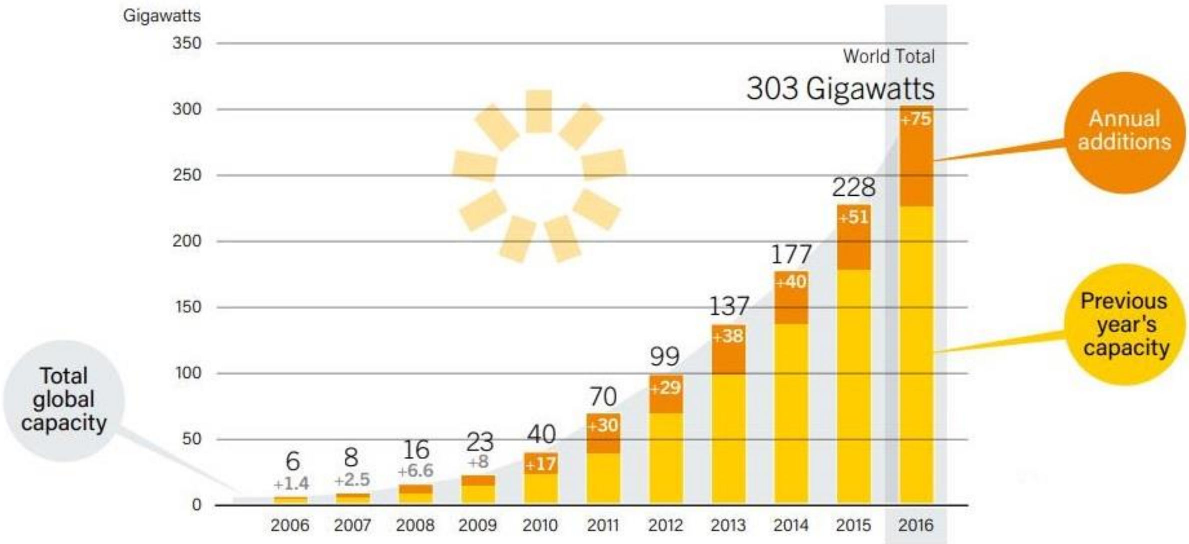


Figure 1.3 Global capacity and annual additions of the solar PV sector, from 2006 to 2016 [1].

For an effective enhancement of the share of renewable resources, buildings must play an important role, since they represent a very significant part of the worldwide energy consumption, and particularly of electricity consumption, as Figure 1.4 and Figure 1.5 show, respectively.

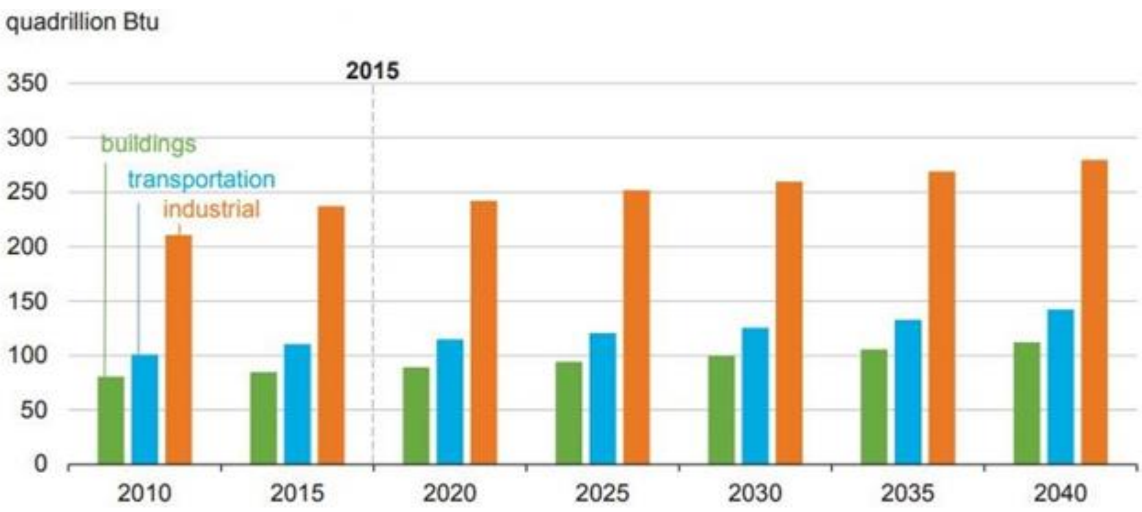


Figure 1.4 Graph about world energy consumption by end-use sector [3].

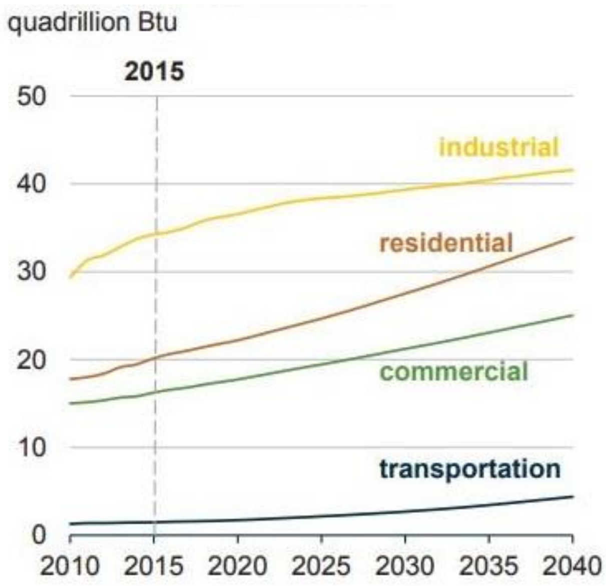


Figure 1.5 Graph about world electricity use by sector [3].

All the data above mentioned support the idea that a significant growth in BIPV sector is crucial to face climate change. It would also diminish significantly the energy costs of buildings, since electricity consumption represents more than 60% of the total energy consumption in U.S. buildings, as it can be seen in Figure 1.6.

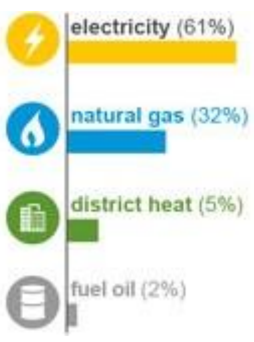


Figure 1.6 Share of energy consumption in buildings in U.S. (2016) [4].

Furthermore, BIPV solutions would reduce the total energy consumption on buildings, since a great part of the energy consumed is used in space heating, refrigeration and ventilation systems, as Figure 1.7 shows, and BIPV solutions improve significantly buildings thermal insulation.

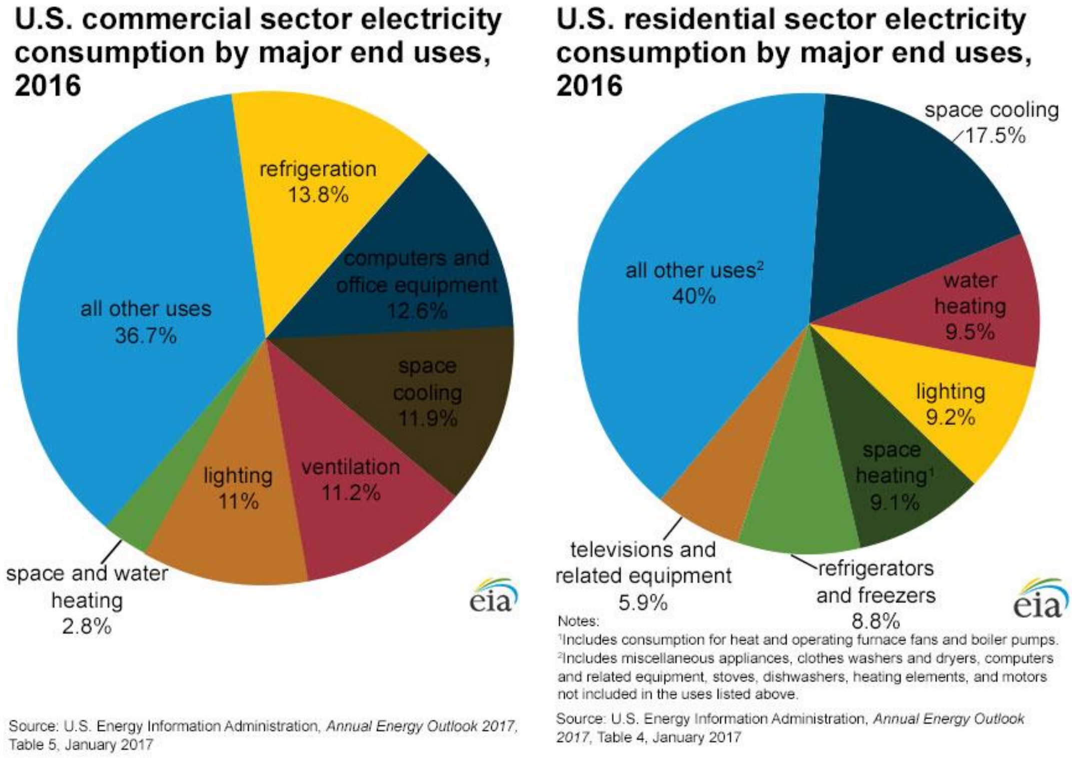


Figure 1.7 U.S. electricity consumption by major end uses, 2016. A) Commercial sector. B) Residential sector [5].

It is possible to conclude that there is a positive scenario for the BIPV sector, which is estimated to have an exponential growth, being expected that at the end of 2022 there will be a BIPV shipment of 16.24 GW, as Figure 1.8 shows.

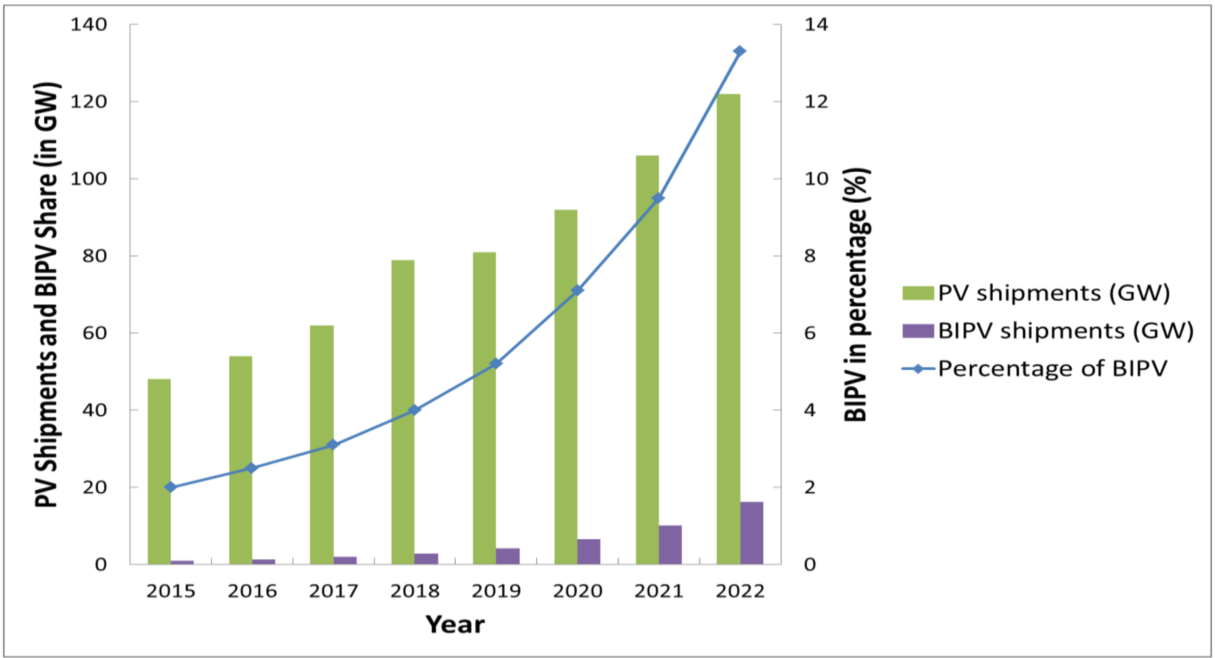


Figure 1.8 Share of BIPV products in the PV shipment [6].

In order to make BIPV market growth possible, it is now crucial to continue enhancing products in order to satisfy architects' needs and to develop innovative solutions according to the latest trends of the BIPV market. Those are the main objectives and the strategy of the research and development (R&D) department of Onyx Solar, and that explains the importance of the present research work. On one hand, at product level, by investigating lightweight BIPV modules and plug and play framing solutions, expecting to enhance aesthetics, diversify products and diminish installation costs. On the other hand, at solution level, a prototype of a Greenhouse Integrated Photovoltaic Glass (GIPV), with the objective of obtaining a competitive and interesting solution to help farmers coming towards a more economic and sustainable agriculture production.

1.2 Presentation of the company

The research work was conducted at Onyx Solar, a SME funded and established in Ávila, in the region of Castile and Leon, in Spain, as part of the projects of the R&D department.

Onyx Solar is a global leader in the BIPV sector, selling aesthetic energy producing solutions that provide thermal, visual and acoustic comfort. This company offers fully customized solutions and works together with architects and building constructers to adequate its innovative solutions to best fit clients' needs. Onyx Solar has completed over 150 projects in 5 continents, having an annual production capacity of over 200.000 m^2. It was the first company to produce both transparent and low-e BIPV solutions. Due to its continuous work of excellence, Onyx Solar has won more than 50 awards [7].

Onyx Solar has an important R&D department, having participated in more than 15 R&D projects with the objective of keeping up with the most cutting-edge technology and adapt current products to completely satisfy architects' needs. Currently, one of the challenges is to produce cost effective technologies for refurbishment of existing building stock to turn them into NZEBs. The design of lightweight BIPV modules for the integration in plug & play solutions comes as a response to this challenge, to reduce installation costs and enable a more flexible façade's aesthetic design. On the other hand, the design of a GIPV comes as response to specific needs of the agriculture building sector, with the objective of both creating self-sufficient greenhouses and opening a new market niche for Onyx Solar.

1.3 Objectives of the project

The main objective of this thesis is to understand the importance of BIPV, learn about current technologies, materials, manufacturing processes of this field of work as well as market needs, in order to be able to work and solve two real needs of the BIPV market, one at product and other at solution level.

At product level, on the study and development of aesthetically advanced and lightweight BIPV products based on a-Si thin film and c-Si PV technologies using glass-glass and glass-backsheet as substrate, collaborating on the design phase, analysing different possibilities and on the development of the final products. Apart from that, the identification of plug & play commercial framing solutions adequate to lightweight BIPV modules has been done.

At solution level, on the design of innovative and competitive GIPV solutions based on a-Si technology, by studying the most adequate transparency degree, dimensions, PV system as well as estimating electricity production and costs.

1.4 Project methodology

For the design of the PV modules, the wind actions were calculated using the Spanish Standard *Structural security – Actions on buildings*. In addition, in order to define the minimum dimensions of the PV modules, IEC 61730 and UL 1703 were used to guarantee PV modules' electrical insulation.

Concerning the design of the GIPV, the software *PVsyst* [8] was used to estimate electricity production and PV system efficiency. The software was also used to identify the adequate inverters for the grid connected PV system.

For both parts of the research work, at product and solution level, AutoCAD software was used for the drawings.

1.5 Structure of the Thesis

The first chapter presents the context of the research work and how it fits into the overall context of sustainable development. It also presents the company where the research took place as well as project's objectives and methodology.

The second chapter gives an overview of the BIPV field of work, describes the currently commercially used PV technologies, the most important components of the BIPV products, the main BIPV solutions along with an introduction to greenhouse's key factors.

The third chapter aims to design lightweight BIPV glass. For that, requirements are identified and then the most competitive solutions are selected. After that, experimental samples are analysed.

The fourth chapter discusses the concept of plug & play framing solutions and several commercial approximations to this concept.

The fifth chapter focuses on the design of a GIPV prototype with a surface area of approximately 30 m^2, to be located in Soria (Spain). Two alternatives are defined, one with a standalone PV system and other with the minimum dimensions so that it is possible to connect it to the grid. Electricity production is estimated and an approximation of the total costs of the most market competitive alternative is presented.

2 Literature review

This chapter is a brief introduction to the most important aspects of the BIPV sector and to the most used PV technologies, as well as their main characteristics. Apart from that, BIPV most important components are referred, as well as the current Onyx Solar's standard products, as a starting point to the design of the lightweight BIPV modules. At the end, BIPV current solutions are identified, including their main elements, and the greenhouse's key factors are pointed out, as an introduction to the design of the GIPV.

2.1 BIPV

BIPV solutions are PV solutions for the building envelope. In contrast to building attached photovoltaics (BAPV), such as PV solar collectors, BIPV products have at the same time PV properties and the technical characteristics of the construction materials they are substituting. In that way, BIPV provide structural solutions that offer at the same time electricity production as well as aesthetical, thermal and acoustic insulation (active and passive properties).

2.1.1 Most used PV Technologies on BIPV solutions

2.1.1.1 Silicon Solar cells

c-Si solar cells

c-Si solar cells are part of the first generation of PV technologies, with an increasingly higher efficiency of commercial cells over time, of 6-10% in the 1950s and currently of 15-22%, combined with progressively lower prices, as Figure 2.1 shows [9]. Currently, prices of 156 x 156 mm^2 cells can be as low as 0.59 US$ [10].

Figure 2.1 U.S. photovoltaic module shipment value of c-Si solar cells (US$/Wp) [9].

Polycrystalline silicon (pc-Si) solar cells have increased their efficiency over time, currently between 12-15% [11], and have low prices, as Figure 2.2 shows [9]. Currently, the price range is around 16 US$/Kg, having lower prices when compared to c-Si solar cells [10].

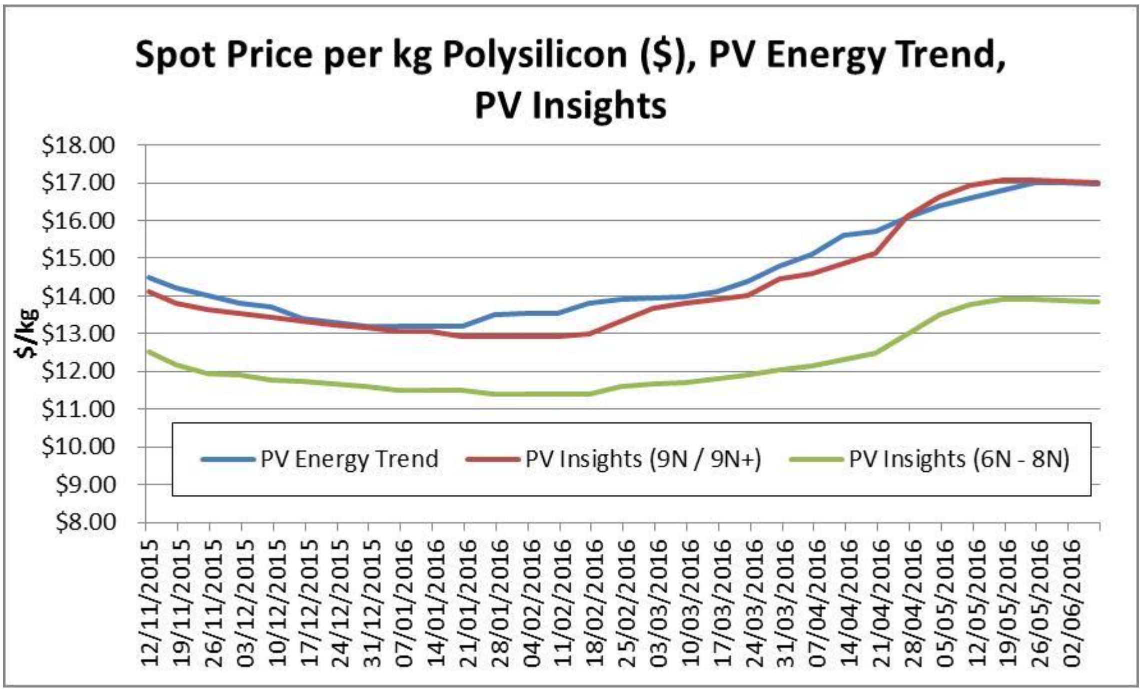


Figure 2.2 Price evolution of pc-Si cells (US$/Kg) [9].

Architecture of the Solar Cell

Both c-Si and pc-Si solar cells consist of a p-n junction, which is usually a layer of silicon doped with boron and another doped with phosphorus, respectively, each with a metal contact, as Figure 2.3 shows [12].

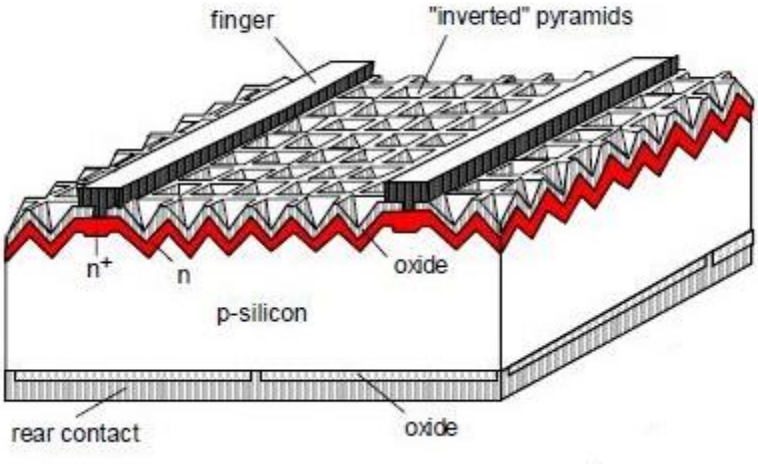


Figure 2.3 c-Si/pc-Si p-n junction [12].

Boron is used in the p-silicon layer since this atom only has three valence electrons. By doping silicon, which has four valence atoms, with boron, a hole is created. The opposite occurs when silicon is doped with phosphorous, which has five valence electrons, creating an extra electron. Figure 2.4 shows the atom structure of pure silicon, p-type and n-type silicon.

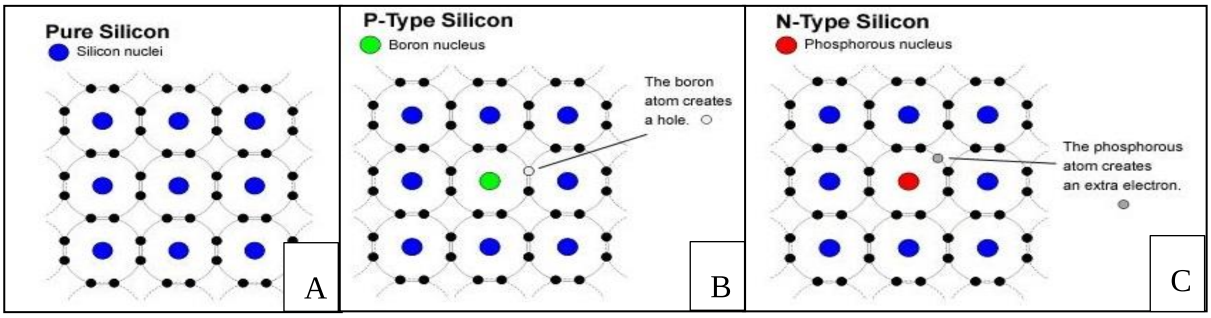


Figure 2.4 A) Atom structure of pure silicon. B) P-type silicon. C) N-type silicon [13].

The working principle of the p-n junction is the same of a diode. When p- and n-type are connected, the diffusion of some electrons from n-type to p-type region and the diffusion of some holes from p-type to n-type region occurs. As Figure 2.5 shows, an "electron-hole free region" called depletion region appears at the interface [14].

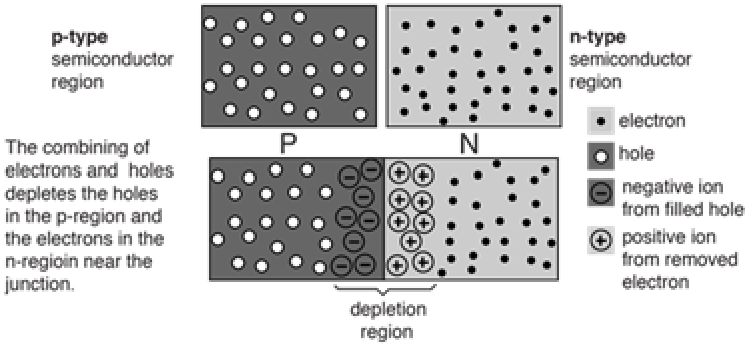


Figure 2.5 Depletion region [15].

When a photon with energy higher than first ionization energy strikes the PV cell, it "creates an electron hole pair", i.e, "a free electron and a free hole". In fact, the free electron is extracted from n-side of depletion region (p-silicon layer) and goes to n-side of the junction (n-silicon layer), and from that to the p-side of the junction (p-silicon layer) through metal contacts, generating electric current [14] [16].

Fabrication Technology

In c-Si solar cells, to obtain p-silicon layer, melted purified silicon is mixed with small pieces of silicon doped with boron, around one part per million, "which a seed crystal is dipped and slowly withdrawn". With this crystal growing process, called Czochralski, it is possible to obtain a cylindrical c-Si ingot. After that, the ingot is "squared-off" and cut in thin wafers, as Figure 2.6 shows.

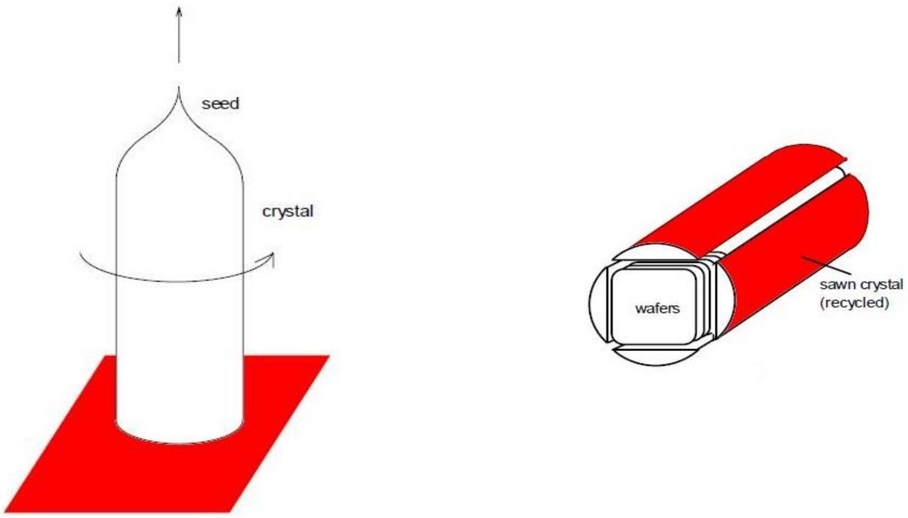


Figure 2.6 A) Czochralski growing process. B) Squared-off Czochralski ingot [12].

pc-Si wafers are fabricated in rectangular ingots, where molten silicon solidifies, as Figure 2.7 shows, from "bottom to upwards". Ingot dimensions can be as large as 60 cm x 60 cm x 20 cm [12].

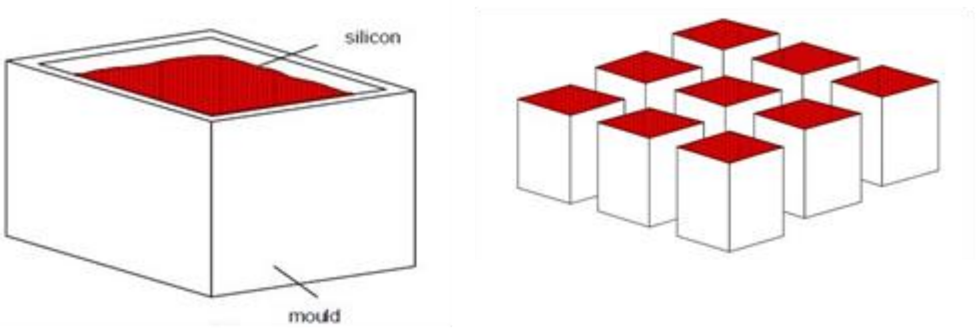


Figure 2.7 pc-Si ingot [12].

In both technologies, wafers are usually wire-cut using slurries, although diamond-coated wires are being increasingly used, which enables cutting speeds to be six to eight times faster [17]. Figure 2.8 shows "as-cut slurry and diamond wire sawn wafer" [18]. The cut wafers have a typical thickness of 180 μm. Once the wafer is cut it has to be chemical etched, with potassium hydroxide (KOH) and acidic solutions, for c-Si and pc-Si, respectively. Since the reflectance of pc-Si wafer after this process is higher than c-Si ones, an antireflection coating is applied [17]. These treatments are applied with the aim of reducing reflection's losses and consequently improving solar cells' efficiency [19]. After surface texturing, the wafers are cleaned.

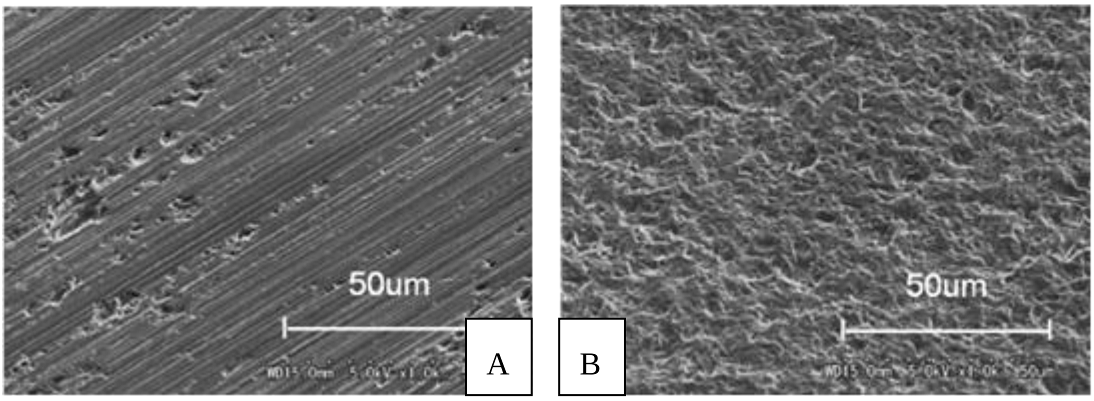


Figure 2.8 Sawn wafer. A) Using slurry. B) Using diamond-coated wires [18].

Once with the p-silicon wafer, a fraction of a micron of silicon doped with phosphorus (n-silicon) is diffused into the surface, forming the p-n junction. Additionally, opaque metal contacts are screen printed into both p- and n-silicon surfaces [4]. Figure 2.9 shows the final aspect of c-Si and pc-Si solar cells' front view, where it is visible the front contacts, which are usually called ribbons [20]. The area occupied by ribbons must be optimized, so that electric current is maximized and efficiency loss minimized.

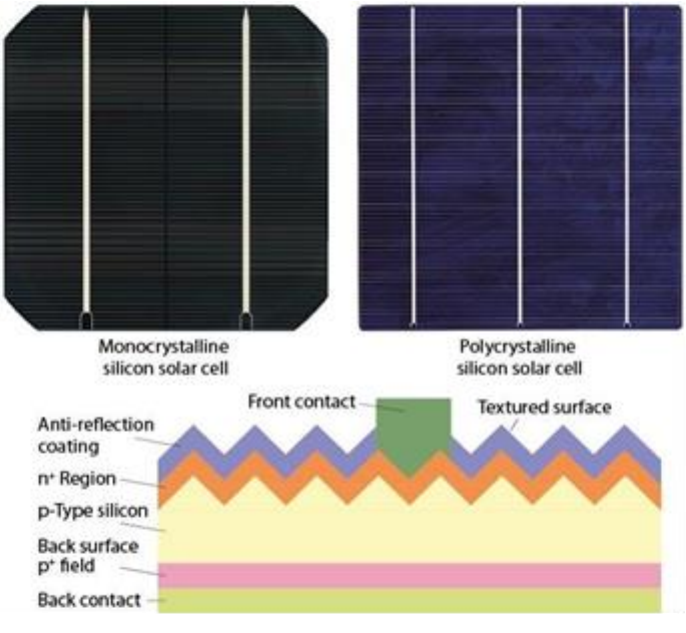


Figure 2.9 Final aspect of the front view of c-Si and pc-Si solar cells [20].

2.1.1.2 a-Si thin film solar cells

Thin film a-Si has the capacity of having some transparency degree, by laser etching, removing some portion of a-Si layer. For that reason, a-Si PV technology is very suitable for BIPV solutions, since the final module is aesthetic and homogenous as well as it can be used in solutions where some grade of transparency is required, such as curtain walls, skylights and some ventilated façades.

a-Si thin film solar cells are part of the second generation of PV technologies. Even though the market share of c-Si was 94% of total production in 2016, with pc-Si solar cells representing around 70%, the market share of thin film solar cells is growing, representing in 2016 6% of the total production [21]. Concerning the different thin film technologies, since the beginning of the century, a-Si presence has been constantly decreasing, as Figure 2.10 shows [21], representing 0.5% of 2016 PV total production. These results can be explained by the declining prices of c-Si solar cells, as Figure 2.1 shows, combined with the appearance of CIGS and CdTe commercial solar cells, which are more cost competitive and have higher efficiencies. However, a-Si thin film PV modules are still the most aesthetic PV technology for BIPV solutions where some transparency degree is required.

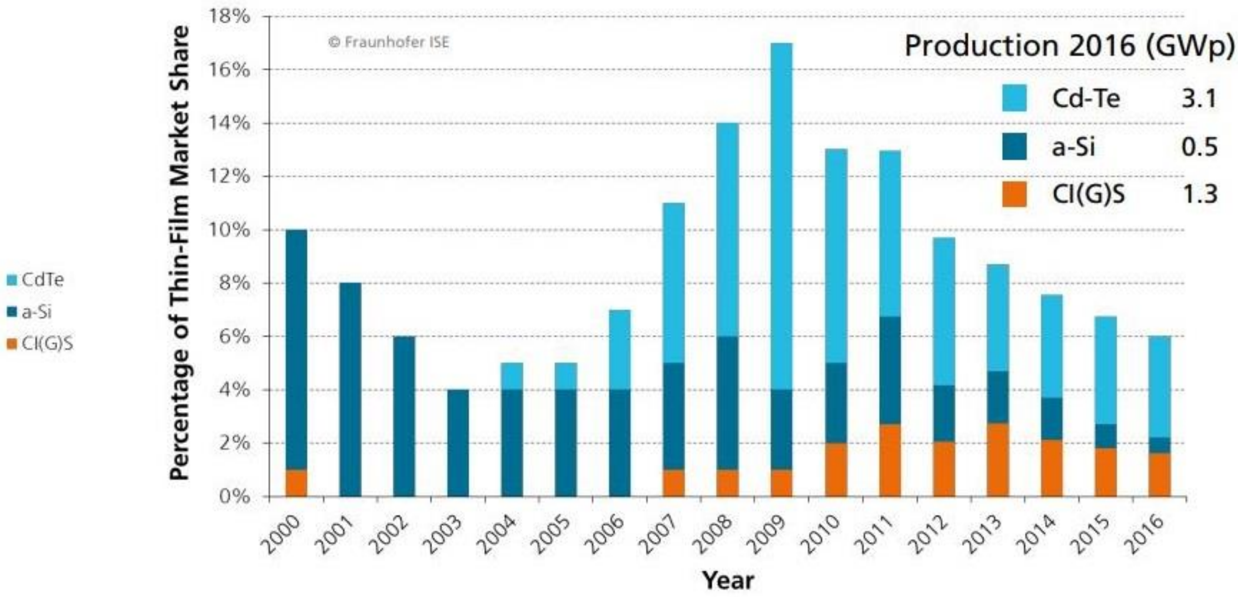


Figure 2.10 Total Global PV Production (%) [21].

The efficiency of a-Si thin film commercial modules is around 7-10%, while its minimum production costs can be 0.35–0.40 US$/Wp [22].

<u>Architecture of the Solar Cell</u>

The basic architecture of an a-Si solar cell is a “p–i–n” junction, as Figure 2.11 shows.

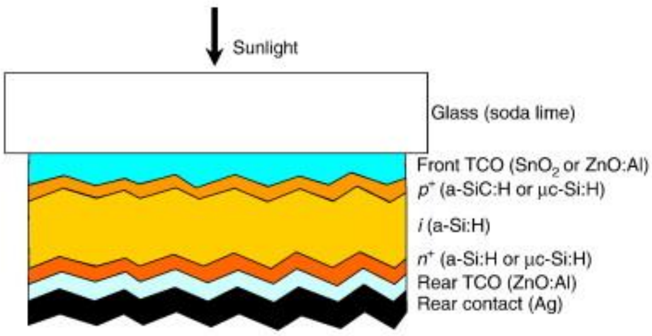


Figure 2.11 Architecture of an a-Si thin film solar cell [23].

Since a-Si thin film can be deposited at “a wide range of temperatures”, a variety of substrates can be used, such as glass, metal and plastics (as plastic polyethylene terphthalate (PET)). Once the substrate is chosen, a transparent conducting oxide (TCO) window material is deposited, with the purpose of not only acting as an electrical contact, but also as an efficient light trapper.

After that, the deposition of a very thin n-type a-Si layer, an intrinsic intermediate layer and a thin p-layer occurs. The thickness of all layers is chosen so that nearly all the incident light can be absorbed. Following that, another TCO and a metallic black-reflector layers are deposited [23].

Figure 2.12 shows a-Si disordered lattice with random oriented broken Si–Si bonds, which are called "dangling bonds" and have localised tetrahedral bonding schemes. Due to these dangling bonds, a-Si material has an absorption coefficient (α) of about two orders of magnitude higher than c-Si and pc-Si. Consequently, a thickness of just a couple microns is enough for an efficient absorption and solar spectrum usage.

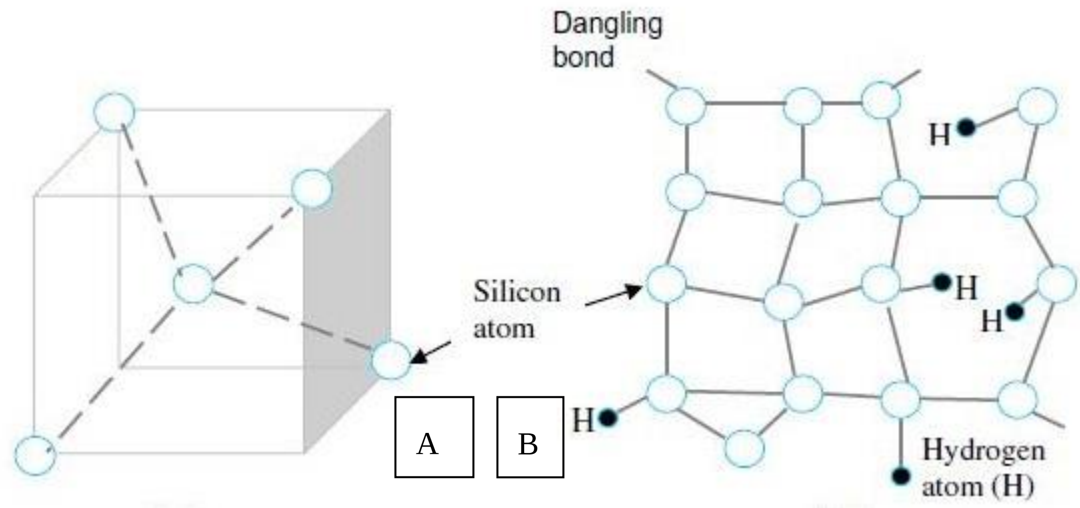


Figure 2.12 A) c-Si tetrahedral bonding scheme. B) a-Si:H network presenting dangling bonds passivated by hydrogen [11].

On the other hand, the a-Si disordered structure is responsible for the greatly dense "localized defect states within the energy gap", which trap generated free carriers. To solve this problem, a-Si thin film is passivated with hydrogen (5-10%), as Figure 2.12 shows, so its unsaturated bonds get attached to them and thus the density of defects is reduced, from $\approx 10^{19}$ to $\approx 10^{15}$ cm^{-3}. Once a-Si thin film is passivated with hydrogen, it can be doped with boron and phosphorous, and so making p- and n-type a-Si materials, which unfortunately increases the already high concentration of defect states. Consequently, a-Si:H cells are unsuitable for p-n configuration. To overcome this problem, a very thin intermediate layer is used to absorb practically all the incident light, thus providing a p-i-n structure or n-i-p structure [11]. Figure 2.13 shows a scheme of thin film a-Si cells with n-i-p structure connected in series. In this case, when a photon with energy higher than first ionization energy strikes the PV cell, it "creates an electron hole pair" on i-layer, generating electric current [23].

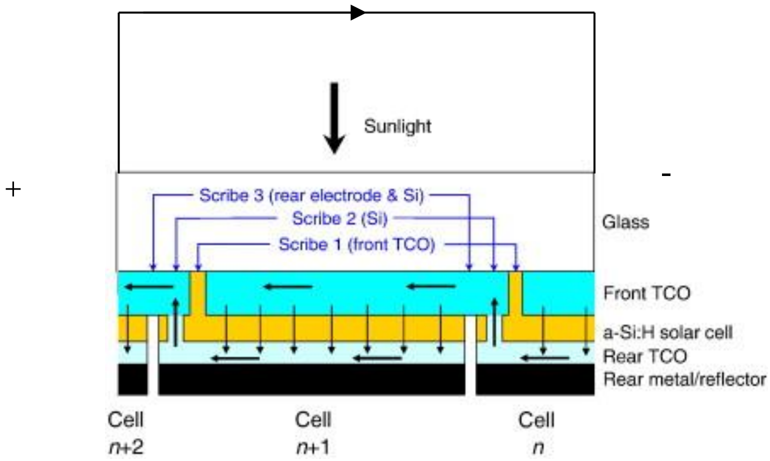


Figure 2.13 Scheme of a-Si:H solar cells connected in series on a glass superstrate [23].

Fabrication Technology

The fabrication of a-Si solar modules begins with the deposition of TCO layer on the substrate and then the definition of individual cells, by doing parallel scribes as “scribe 1”, shown in Figure 2.13. After that, the p-i-n junction is deposited, followed by a second set of parallel scribes, “scribe 2”, shown in Figure 2.13, so that individual layers are connected. Finally, the conducting back-electrodes are isolated by the third set of parallels scribes, “scribe 3”, to obtain the series interconnection. Figure 2.13 shows all these different scribes. Plasma chemical vapor deposition (CVD) is widely used for the deposition of all layers [11, 23].

2.1.1.3 Tandem cell of a-Si and microcrystalline (μc-Si) silicon

This double junction solar cell technology is part of the second generation of PV technologies, having currently commercial solutions an efficiency of 10% [24]. Since a-Si and μc-Si have different band gaps, these tandem cells can enhance the use of solar radiation, as Figure 2.14 shows [25]. In total, around 80% of solar spectrum between 500 and 800 nm is covered [11].

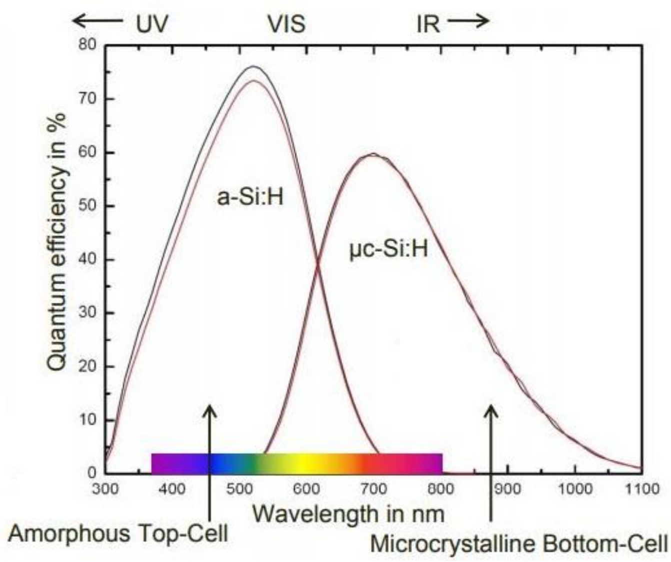


Figure 2.14 Band gap of a-Si and μc-Si [26].

Moreover, in a tandem solar cell there is a significantly reduction of “light dependent degradation”, which is only observed in the thinner a-Si thin film layer (0.2-0.3 µm) [11].

Architecture of the Solar Cell

Figure 2.15 shows a scheme of the tandem structure. There is the deposition on a substrate (such as glass, metal or polymer) of a front contact of TCO, an a-Si:H p-i-n junction layer, a µc-Si:H layer and a back contact.

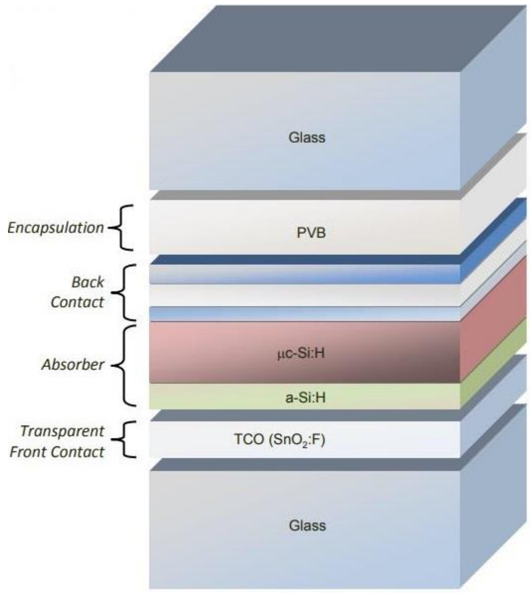


Figure 2.15 Structure of tandem a-Si and µ-Si solar cell [26].

Fabrication Technology

The TCO film is deposited on a substrate by low pressure chemical vapor deposition (LPCVD). After that, the a-Si and µc-Si films are usually deposited by plasma-enhanced chemical vapor deposition (PECVD). Lastly, the back contact is applied [25]. After, a scribing process is done, which is very similar to the one applied to a-Si cells.

2.1.1.4 Cadmium telluride thin film (CdTe) Solar Cell

CdTe PV technology is suitable for BIPV solutions, since PV modules can be made with different transparency degrees, colour and patterns [27].

CdTe solar cells are part of the second generation of PV technologies. As Figure 2.10 shows, the world production of CdTe at 2016 represented 3.1% of the total PV production [21], being the most used thin film technology. This can be explained by its high efficiency on commercial modules, which achieve 18% [28], and its low fabrication costs, which are expected to be as low as 0.25$/Wp at the end of 2018 [29]. The main drawback of this technology is the use of Cadmium, which is a rare material and has a considerable level of toxicity. However, according to researchers, “CdTe PV technology and modules are safe and do not pose significant risks” [11].

Architecture of the Solar Cell

Both "substrate" and "superstrate" configurations can be used in CdTe solar cells, although the highest efficiency is achieved with the second one. Figure 2.16 shows a superstrate configuration, which comprises a layer of TCO, a n-type CdS window layer, a p-type CdTe absorber layer (2-6 µm), a Te-rich CdTe surface, a buffer layer and a metal back contact.

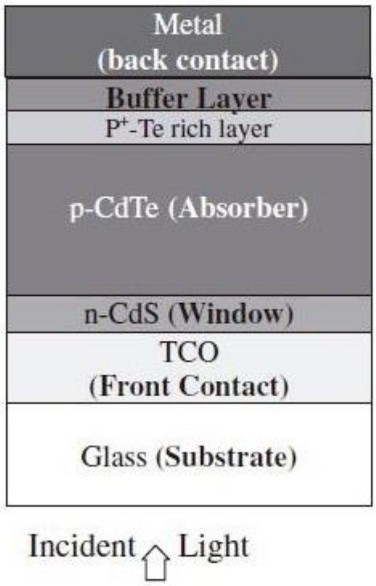


Figure 2.16 CdTe solar cell superstrate configuration [11].

Fabrication Technology

The fabrication process of the superstrate configuration starts with the deposition of a TCO layer on a glass substrate and definition of the first set of scribes. After that, a layer of CdS and a layer of CdTe are deposited. Many deposition technologies can be used [11], being the close-spaced sublimation the most commonly used.

These semiconductor materials are easily deposited at temperatures around 400–600 °C. Once the deposition is done, the heterojunction is exposed to an atmosphere containing chlorine monoxide (Cl-O) and is thermal annealed at 400-500 °C. This process "activates" the diode, conferring it better PV properties. After that, the second set of scribes is done, patterning the CdS/CdTe layers. Last, the back contact is deposited and scribed, making the third set of scribes [11, 23].

2.1.1.5 Copper Indium Gallium Selenide thin film (CIGS) Solar Cell

CIGS modules are lightweight (such as 3.3 kg/m^2 with adhesive) and flexible, as Figure 2.17 shows, which make them suitable for BIPV integration, such as roofs that cannot support glass module installations or curved roof and surfaces [30].

CIGS solar cells are part of the second generation of PV technologies, representing in 2016 1.3% of the total PV production. Known to be a cheap and highly efficient technology, current commercial solutions have an efficiency of around 14% and a production cost of 0.56$/W$_{DC}$ [31].

Figure 2.17 Lightweight and flexible modules [30].

As drawbacks, this technology uses rare materials such as indium and gallium and, until now, there is no semi-transparent commercial solution, even though there has been some successful research results: 5, 94% of efficiency in a CIGS module with 20% of transparency [32].

Architecture of the Solar Cell

Figure 2.18 shows the basic configuration of CIGS solar cells. Both substrate and superstrate configurations are possible, though the highest efficiency is obtained with the first configuration. In that case, solar cells have a first layer of Molybdenum (Mo) that is deposited on the substrate (can be glass, metal or polymer foils), which acts as a back electrode, an absorber layer of p-CIGS (≈2 μm), a buffer layer of n-CdS, a window layer of i-ZnO and another of n-Zno:Al.

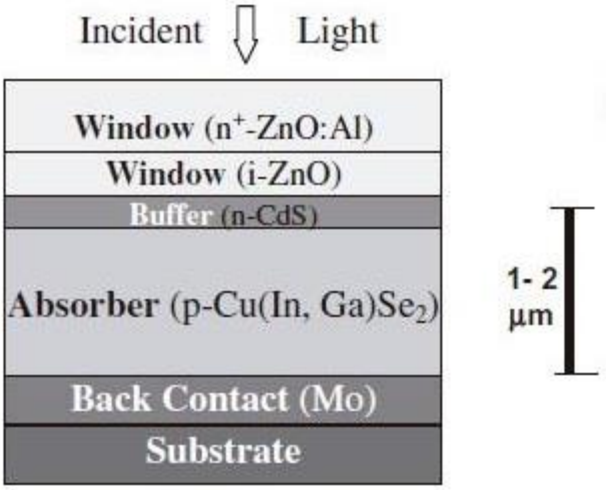


Figure 2.18 CIGS cell configuration [11].

Fabrication Technology

To fabricate CIGS solar cells, Mo is deposited by sputtering or e-beam evaporation and then scribed. For the deposition of CIGS, a variety of deposition methods can be used. After that, CdS is usually deposited by chemical bath deposition (CBD) and the semiconductor layers are scribed. Finally, the two layers of TCO are deposited by CVD methods, with temperatures lower than 150 ºC, so that an interdiffusion across the CdS/GICGS interface does not happen. At the end, the front TCO is scribed [11, 23].

2.2 BIPV products

The basic composition of BIPV glass for BIPV solutions is a laminated glass with PV cells and encapsulants, as Figure 2.19 shows. Encapsulants are used to bound the different glazing layers and to protect from humidity and dust. Apart from that, encapsulants ensure that, in case of breakage, the pieces of glass remain in place, at least up to a certain load level or for a certain period [33].

In the following sections, a detailed description of each component, glazing surface treatments as well as the explanation of the lamination process is given.

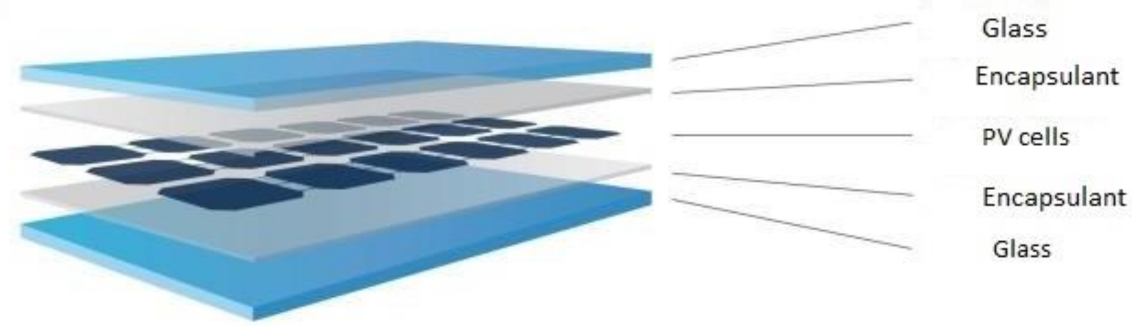


Figure 2.19 Typical structure of PV laminated glass [34].

2.2.1 Most used glazing solutions on BIPV products and alternatives

2.2.1.1 Float Glass

Mechanical properties

The float glass is a soda lime silicate glass product. It can be “flat, transparent, clear, and coloured” [33]. Table 2.1 shows the mechanical properties of float glass.

Table 2.1 Mechanical properties of float glass [35, 36]

Mechanical Property	Value
Density [kg/m^3]	2500
Young Modulus [GPa]	72
Characteristic bending strength [N/mm^2]	45
Mohs Hardness	6

Fabrication process

As Figure 2.20 shows, the fabrication process of glass starts with melting and refining the raw material at a temperature around 1600ºC [33]. During this step, the mixture is homogenised, and gas bubbles are eliminated. After that, the molten glass goes to a tin bath, where it is floated, and the sheets of glass are formed. The thickness of the sheets is defined in this step, by regulating the flow rate. Following that, the glass is cooled under controlled conditions, so that internal stresses are eliminated, and annealed glass is obtained. Finally, and after control steps, the glass "is cut into smaller sizes" [33].

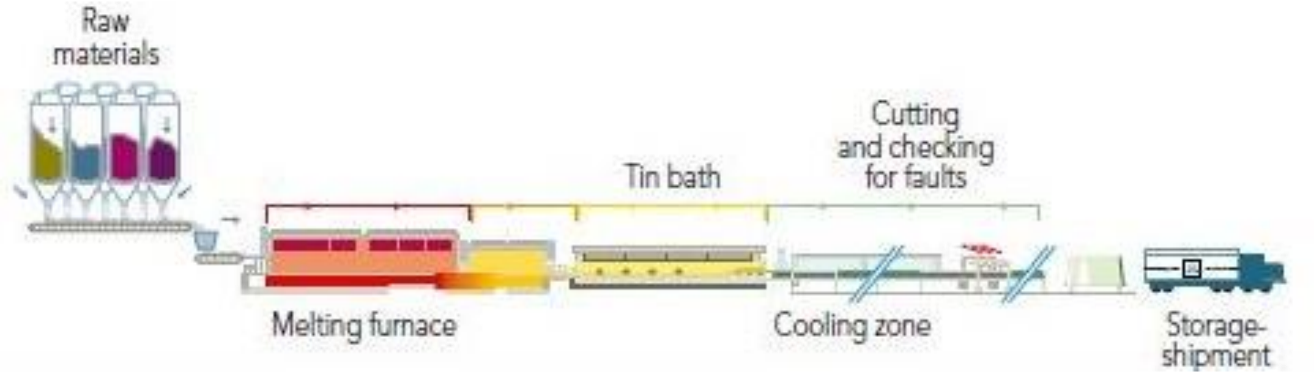


Figure 2.20 Fabrication process of floated glass [33].

Breakage pattern

Floated glass brakes into big pieces, as Figure 2.21 shows, and for that reason it is not considered a safety glass. However, when in a laminated glazing structure, it is considered a safety one. Depending on its final application, the sheets of glass should be in conformity with specific standards [33].

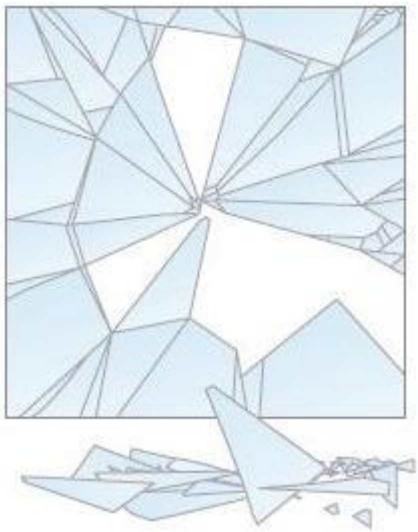


Figure 2.21 Breakage pattern of floated glass [33].

2.2.1.2 Tempered Glass

Tempered glass is a float glass that undergoes a heat treatment that induces surface compression, enhancing its mechanical and thermal resistance, as Figure 2.22 shows.

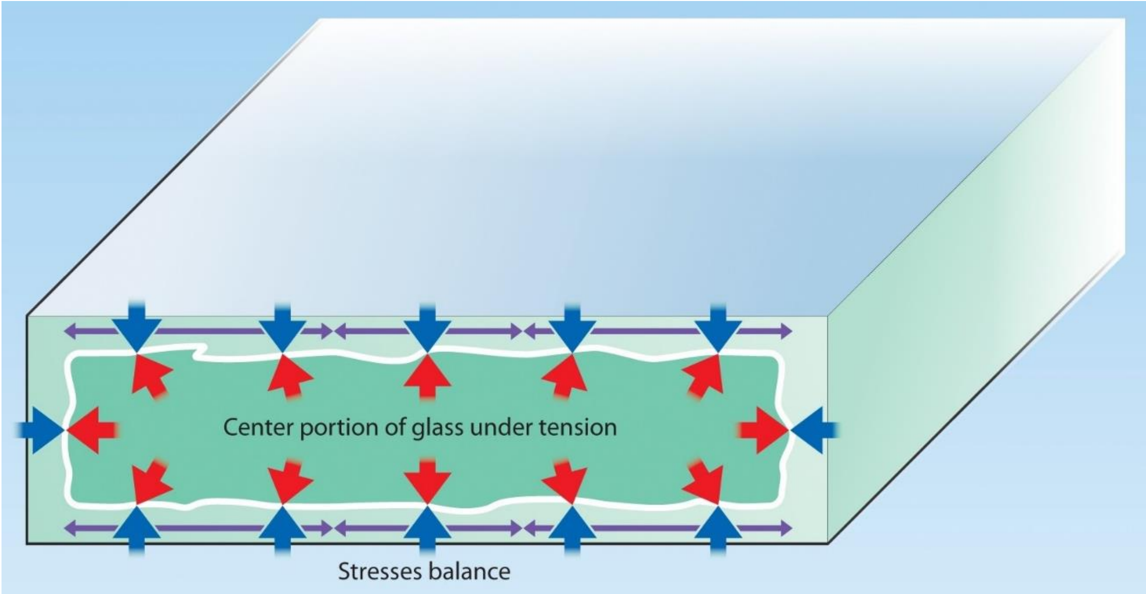


Figure 2.22 Compression of the inner part of the glass due to tempering [37].

Fabrication process

Figure 2.23 shows a scheme of the process. To obtain tempered glass, a floated one is heated at an approximate temperature of 600˚C and then quickly cooled using jets of air.

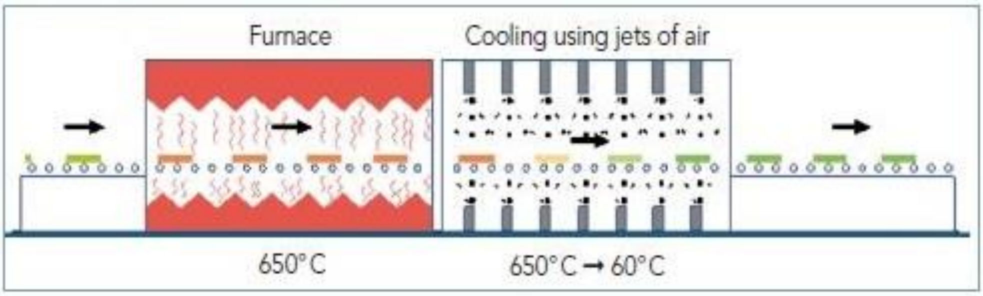


Figure 2.23 Fabrication process of tempered glass [33].

Breakage pattern

In contrast to floated glass, tempered one breaks into small pieces due to surface compression and so it is considered a safety glass. Figure 2.24 shows tempered glass breaking pattern.

Figure 2.24 Tempered glass breaking pattern [33].

2.2.1.3 Backsheet

A backsheet can be used to substitute the rear layer of glass. It protects PV cells and electrical components from external stresses and acts as an electrical insulator. Apart from that, it protects the PV cells from ultraviolet (UV) radiation, weather and moisture [38].

Backsheets are commonly polymer laminates, having three main layers: "weather-resistant outer layer, an electrically insulating core layer and an inner layer that promotes adhesion to the solar cell encapsulation". These polymeric materials tend to deteriorate and lose their properties due to outdoor exposure. Consequently, it is very important to select carefully the adequate backsheet for each PV module. Presently, the backsheet market is dominated by fluoropolymer-based outer layer materials, like polyvinyl fluoride (PVF) and polyvinylidene fluoride (PVDF), since they are capable of being weather resistant and maintain their properties during more than 20 years [39].

The backsheet that has proven to be the most adequate for Onyx Solar BIPV solutions is DuPont™ Tedlar®, which is a PVF. It has a durability of over 30 years and has both "weatherability, robust adhesion, mechanical strength as well as ultraviolet and chemical resistance" [40].

2.2.2 Most used Encapsulants on BIPV products

In order to bond the sheets of glass and equivalents together, encapsulants are placed between them. Apart from that, in case of breakage, encapsulants retain glass fragments and give residual resistance [41]. The most important encapsulants are described in the following sections.

2.2.2.1 Ethylene vinyl acetate (EVA)

EVA is a copolymer encapsulant which provides "structural support, electrical isolation, physical isolation/protection and thermal conduction for the solar cell circuit" [42]. As advantages, EVA has high transmittance, good adhesion to glass as well as good electrical isolation. As a disadvantage, EVA deteriorates and decolorates under UV light, humidity and heat [43], causing a loss of the efficiency of the PV module and cannot be coloured. This encapsulant is one of the most used in the c-Si PV modules because of its enhanced electrical insulation properties.

2.2.2.2 Polyvinyl Butyral (PVB)

PVB is classified as an amorphous thermoplastic [44] with excellent mechanical properties and very good optical clarity [45]. In addition, in contrast to EVA, it is possible to add coloured pigments to PVB and so have coloured PV modules. This encapsulant is one of the most used in the thin film a-Si PV modules [46].

2.2.2.3 Ionomer

This encapsulant has a better electrical resistivity compared to the above mentioned. In fact, EVA's is two orders of magnitude lower and PVB's is three to four times lower. Onyx Solar uses ionomer foils for large dimensions BIPV modules (4000 mm x 2000 mm).

2.2.3 Most used Surface Treatments on BIPV solutions

Surface treatments are used with the objective of enhancing glazing materials' visual, insulating and acoustic properties. The following subchapters present a brief description of the most common surface treatments used on BIPV solutions.

2.2.3.1 Silk-Screening

This treatment consists in applying a coloured ceramic layer to the glazing material and then submitting it to high temperatures, such as tempering. Figure 2.25 shows different possible designs with silk-screening surface treatment [47].

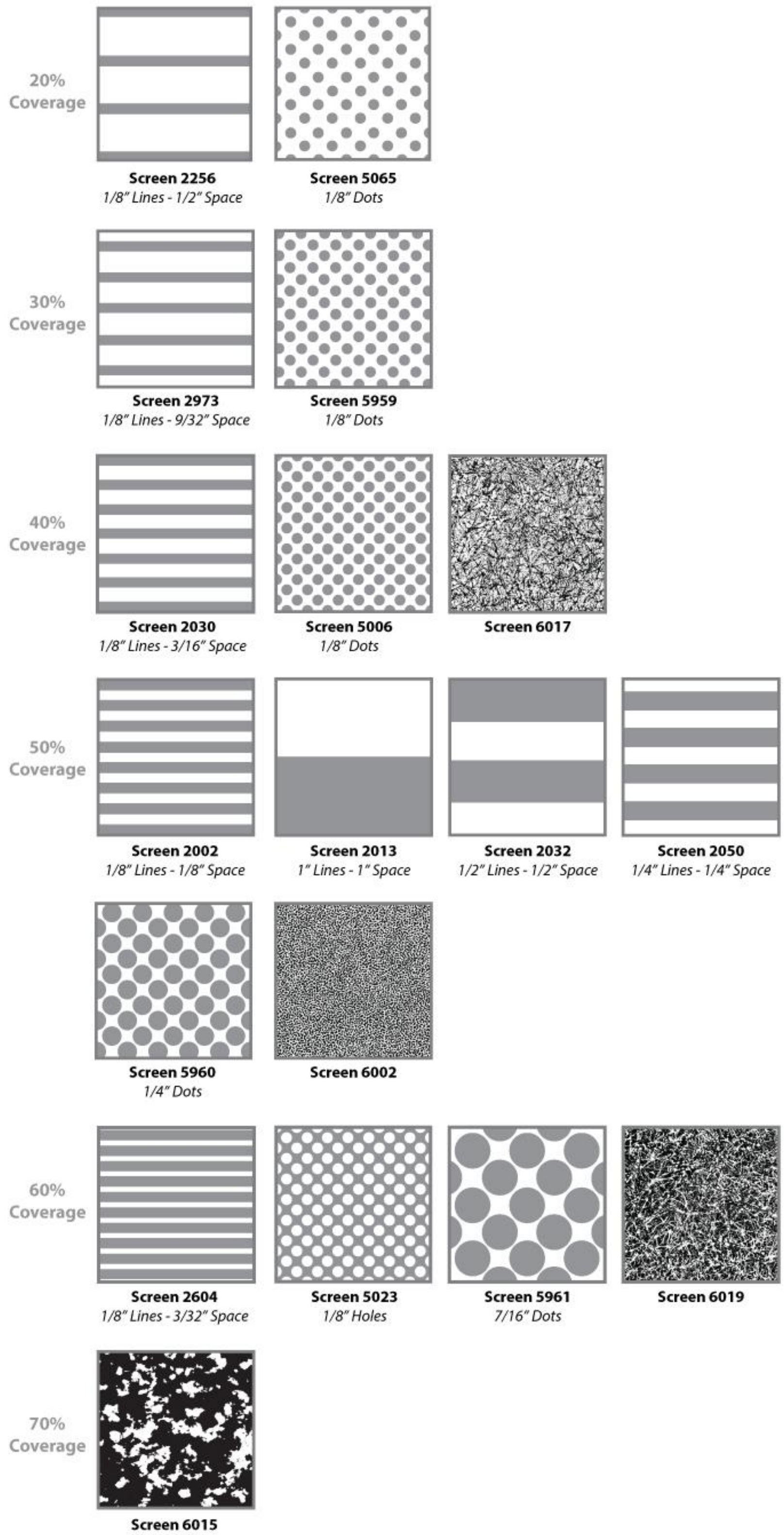


Figure 2.25 Viraspan^{TM} silk-screening glazing designs [47].

2.2.3.2 Acid Etching

In this surface treatment the glass surface is bombarded with hydrofluoric acid or a hydrofluoric acid gas using a blaster gun powered by an air compressor. At the end of the process, the treated surface has a frosted effect. This surface is particularly interesting, since it admits light and provides "softening and vision control". The glass can be fully etched or only partially, which is possible by using shaped resistant material during the abrasion process [48]. Figure 2.26 shows different commercial solutions of BENDHEIM® acid-etched glass.

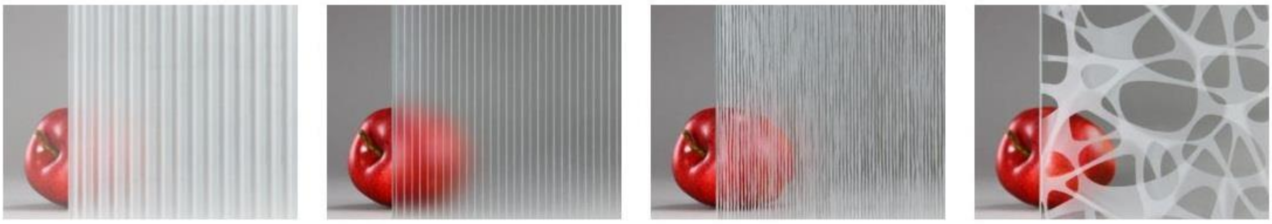


Figure 2.26 Different commercial solutions of acid-etched glass of BENDHEIM® [49].

2.2.3.3 Sand-blasting

The sand-blasting process is done by violently throwing sand to glass surface, "by means of a current of air or steam". The corroding level is obtained by controlling the amount of sand, the volume, velocity of current and the diameter of the jet [50]. Figure 2.27 shows a sand blasted glass from Glazette®.

Figure 2.27 Sand blasted glass by Glazette® [50].

2.2.3.4 Self-Cleaning

There are two categories of self-cleaning material surfaces: hydrophilic and hydrophobic. In hydrophilic surfaces, the water drops spread over the surface and wash away the contaminants on the surface, forming a film of water. On the other hand, in hydrophobic surfaces, the water repellence as well as poor adhesive properties make the water drops roll off the surface quickly, removing the contaminants on the surface [51]. Figure 2.28 illustrates how both processes work.

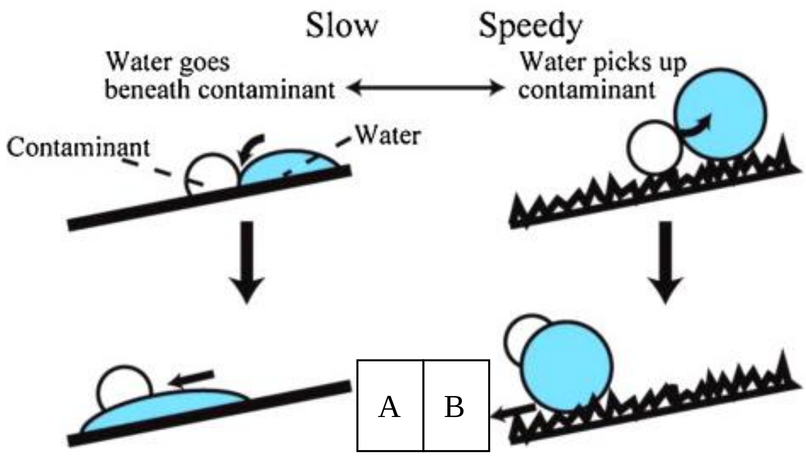


Figure 2.28 Self-cleaning surfaces. A) Superhydrophilic surface. B) Superhydrophobic surface [51].

2.2.3.5 Absorbent (tinted) glass

Absorbent (tinted) glass generally is a float glass that has colorants and iron mixed at the beginning of the fabrication process. Different colorants absorb different parts of the light spectrum. Figure 2.29 shows how tinted glass absorbs solar spectrum [33].

Figure 2.29 Energy absorption effect of tinted glass [33].

2.2.3.6 Reflective coatings

It is common to call reflective coatings to the ones that are applied on the external surface and act like a mirror, reducing substantially the fraction of solar radiation admitted through the glazing material. These coatings are made of thin metallic or metal oxide layers. Depending on the composition of the coating, it reflects either the short radiation (from the sun) or long (from heat outside the building) wave radiation, or even both. Figure 2.30 shows the effect of reflective coatings. This solution is available in various colours, commonly silver, gold and bronze [33].

Figure 2.30 Energy reflection effect of reflective coating [29].

2.2.3.7 Low Emissivity (Low-E) coatings

Low-E coatings are clear coatings applied with the purpose of increasing the reflection of the heat absorbed by the glass to the inside of the buildings. Consequently, they are deposited on the internal surfaces of the glazing material and consist of a metallic coating which can be a sputter or a pyrolytic one. The first is applied inside a double-glazing unit in a vacuum chamber. The second one is incorporated during the manufacturing process of the float glass. Figure 2.31 shows the effect of low-E coatings on the reduction of emissivity levels. Recent Low-E coatings reflect both short and long wave radiation, preventing also harmful UV radiation from reaching the inside of the building [29].

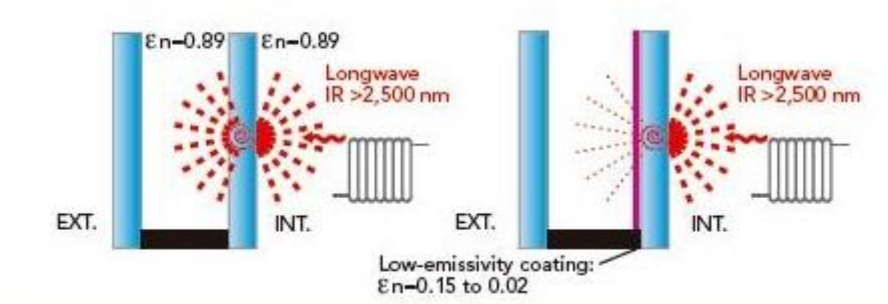


Figure 2.31 Low-E coating effect and the diminution of emissivity [33]

2.2.4 Lamination Process

In the case of c-Si/pc-Si cells, before starting the lamination process, the rear layers of the laminated glass are put in the right order and, above them, the solar cells. In the case of thin film technologies, cells are already deposited on the front/rear glass. After that, copper or aluminium wires (ribbons) are applied to assembly the different solar cells, in the case of c-Si and pc-Si, or to connect electrically upper and lower parts of the modules or sub-modules on the other PV technologies. These wires are called interconnections and they are attached to the PV cell/module using conventional or laser soldering processes [52]. Figure 2.32 shows both tabbing ribbons and bus ribbons that connect the different cells and the different strings/modules, respectively.

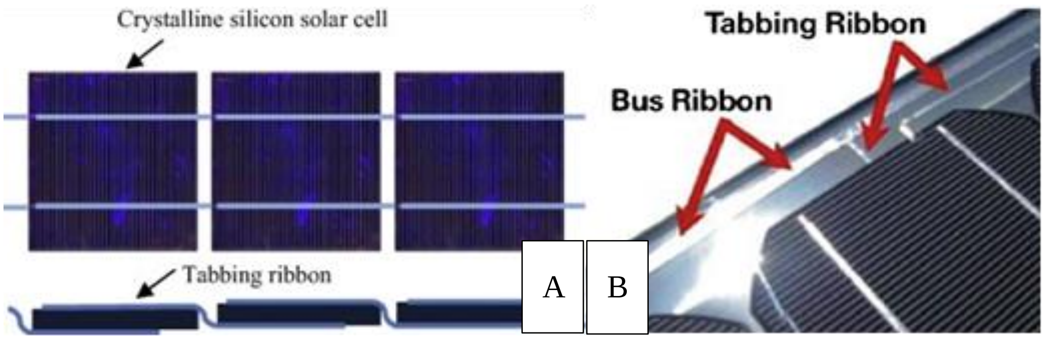


Figure 2.32 Interconnections used in c-Si and pc-Si modules. A) Front and cross section of a pc-Si module with visible tabbing ribbon. B) c-Si module with visible bus and tabbing ribbons [52].

After that, the lay-up is finished by putting the encapsulant and the front glass, and everything is put in a metallic framework. the flat-bed laminator has some pins that lift the PV module lay-up about 5 mm above the heating plate, in order to avoid glass curving and obtain a homogenous heating profile. On the first part of the lamination process, vacuum is created on the lower chamber, removing air and other volatiles as well as avoiding bubble formation. After achieving encapsulant softening point, the pins are released so that PV modules get heated faster and with higher temperatures. At last, the upper chamber is vented and so the different layers are pressed with a highly flexible elastomer membrane. In fact, solar cells are embedded in the encapsulant and adhere to the front and back layers. The metallic framework plays an important role in this step to prevent cells from moving and enable a homogenous pressure profile. The lamination cycle ends with a controlled cooling step, in order to stop chemical reactions [53]. Figure 2.33 shows the basic components and steps of the lamination process.

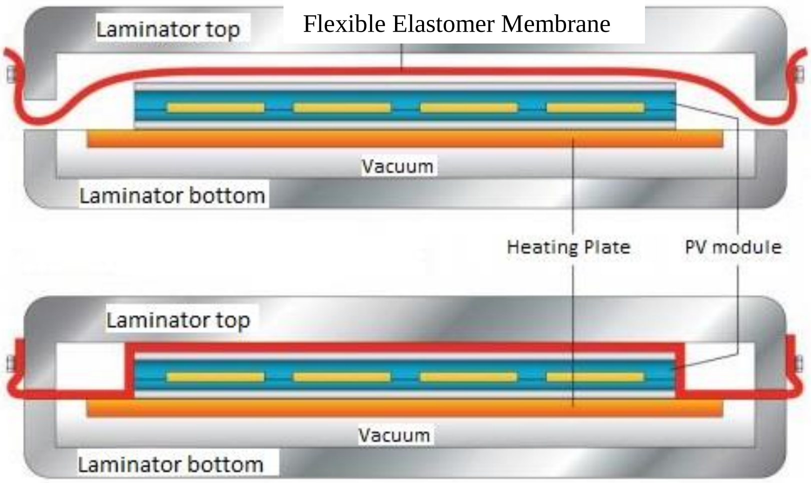


Figure 2.33 Encapsulation process [53].

2.2.5 Standards applicable to BIPV products

Depending on the type of BIPV products, they should be according to the following standards:

- IEC 61646: Thin-film terrestrial PV modules - Design qualification and type approval;
- IEC 61215: c-Si/pc-Si terrestrial PV modules – Design qualification and type approval;
- IEC 61730-1: Safety qualification for PV modules of crystalline silicon for construction use;
- UL 1703: Flat-Plate PV modules and panels;
- ISO 12543-4:2011: Glass in building - Laminated glass and laminated safety glass;
- EN 13501:2007: Fire classification of construction products and building elements;
- EN 356:2001: Resistance against hand broke;
- EN 410:2011: Glass in building – Determination of luminous and solar characteristics of glazing;
- EN 12150:2005: Glass in building – Thermally toughened soda lime silicate safety glass;
- EN 12600:2003: Glass in building – Pendulum test – Impact test method and classification for flat glass [54].

2.2.6 Onyx Solar standard BIPV glass

Onyx Solar currently works with c-Si, pc-Si and thin film a-Si PV technologies. Final products consist of a laminated glass, with at least two sheets of glass or glass and a backsheet. The sheets of glass can also be separated by a spacer that provides a space filled with dry air or Argon, which enhance thermal and acoustic insolation properties. In what respects to encapsulants and surface treatment, Onyx Solar provides solutions with all the above-mentioned possibilities. This company offers customized solutions to best fit clients' needs, in terms of dimensions, colours and shapes. Also, there are some standard products. Figure 2.34 and Figure 2.35 show the standard dimensions of commercial products for both a-Si, c-Si/pc-Si laminated glass [55].

Currently, the minimum standard dimensions of the Onyx Solar's a-Si thin film PV modules are 1245 mm x 300 mm with a thickness of 3,2 + 4 mm and of c-Si PV modules are 1475 mm x 480 mm with a thickness of 4 mm + backsheet. These dimensions are the starting point for the design of lightweight BIPV modules.

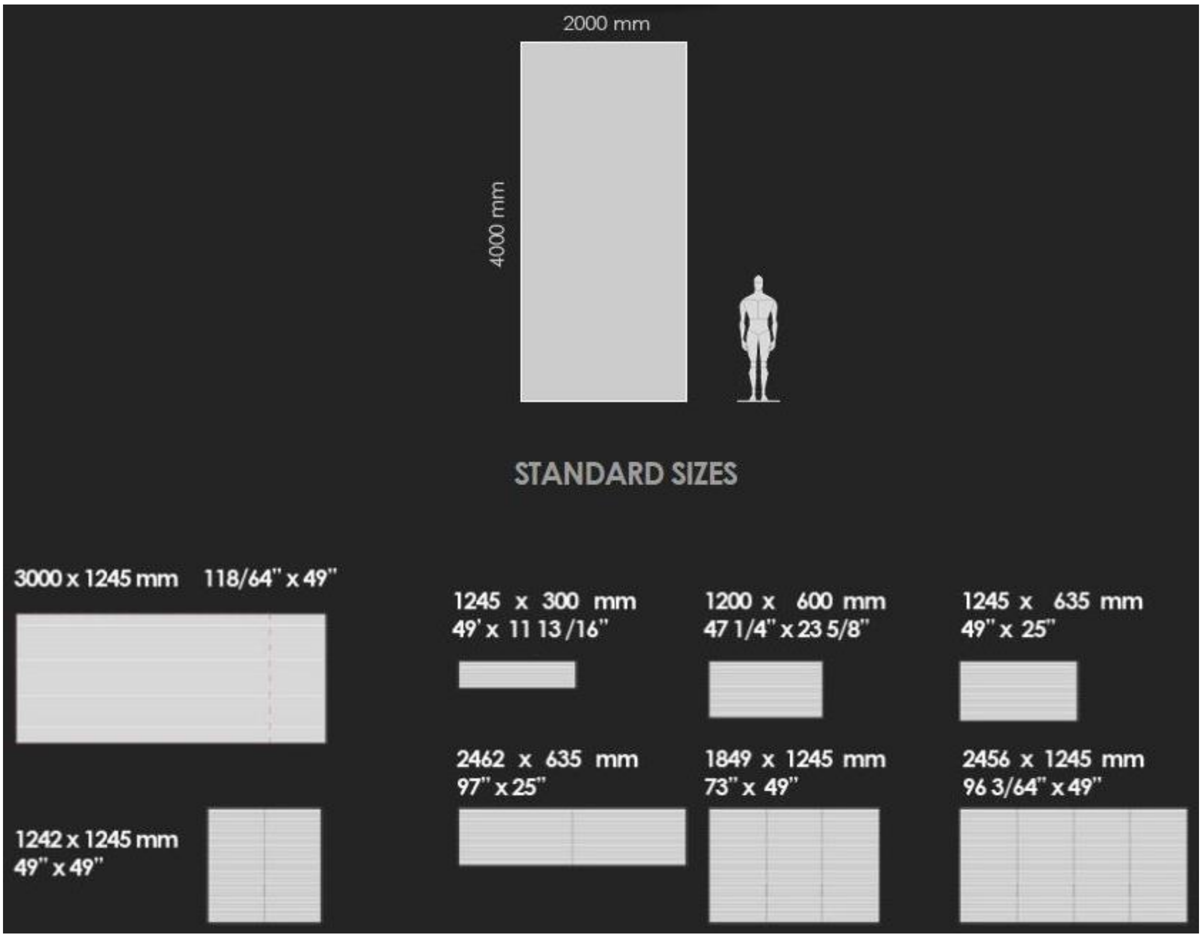


Figure 2.34 Standard dimensions of a-Si laminated glass Onyx Solar commercial products [55].

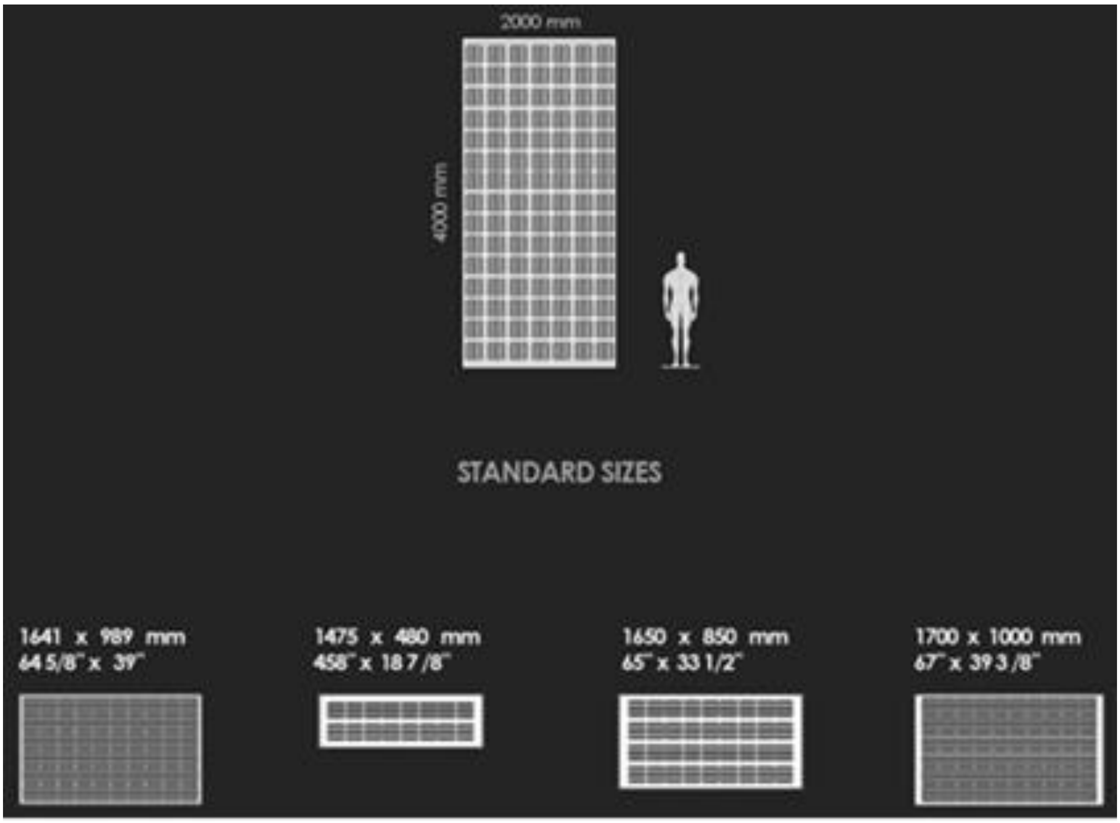


Figure 2.35 Standard dimensions of c-Si/pc-Si laminated glass Onyx Solar commercial products [55].

2.3 BIPV solutions

There are many BIPV solutions presently in the market, such as curtain walls, ventilated façades, skylights, rooftops, parking lots and canopies, as Figure 2.36 shows.

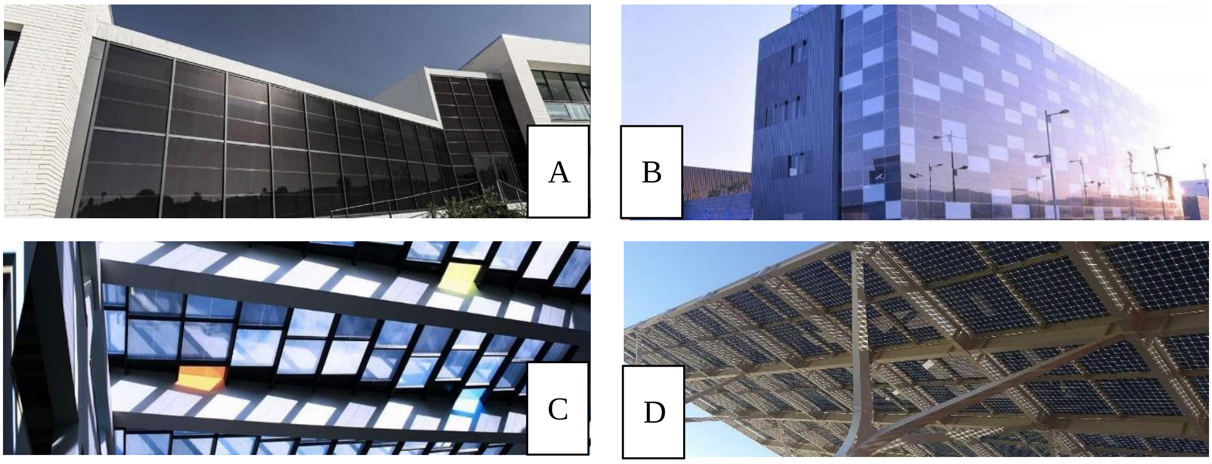


Figure 2.36 Onyx Solar different BIPV solutions A) Curtain wall. B) Ventilated façade. C) Skylight. D) Canopy [56-59].

2.3.1 Basic Components of a PV solar system

2.3.1.1 Junction Box

The junction box on a solar panel houses the electric bits and safeguards them from the environment. Inside the junction box, diodes are connected, linking PV modules together.

2.3.1.2 Balance of System (BOS)

BOS refers to every electrical component of the PV solar system rather than PV modules. This system is responsible to convert the direct flow electric charge (DC) produced by the solar panels and convert it to the alternating current (AC) electric power. BOS components include:

- Inverters;
- Charge controllers;
- Cables/Wires;
- Switches;
- Enclosures;
- Fuses;
- Ground fault connectors;
- Others [46].

2.3.2 Energy Management alternatives

There are two main energy management alternatives: off-grid and grid-connected PV systems. Moreover, both alternatives can have or not a battery to store surplus electricity. Figure 2.37 and Figure 2.38 show off-grid and grid connected PV systems, correspondently, and Figure 2.39 shows two grid-connected systems, with and without battery [46]. Batteries enable the storage of the electrical energy throughout daylight hours and so provide continuous power to the load under variable environmental conditions. However, the materials used in batteries have high environmental and energy impacts as well as expensive prices, increasing significantly PV systems environmental impact and payback time.

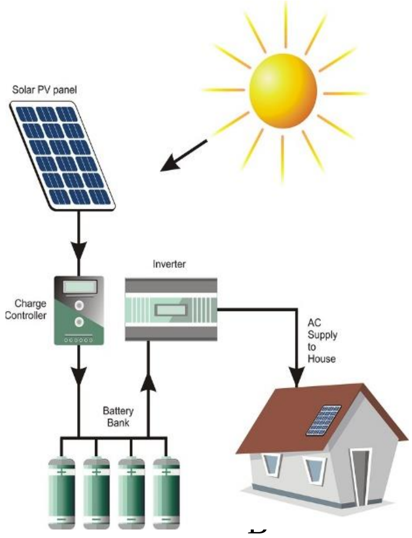


Figure 2.37 Off-grid connected PV system [53].

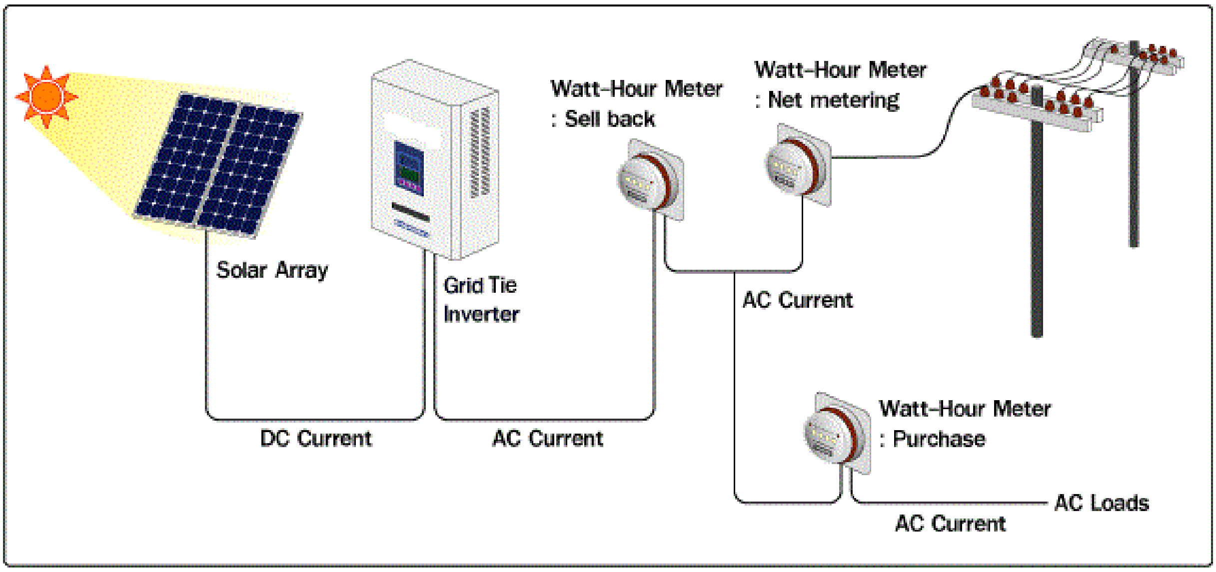


Figure 2.38 Grid-connected PV system [60].

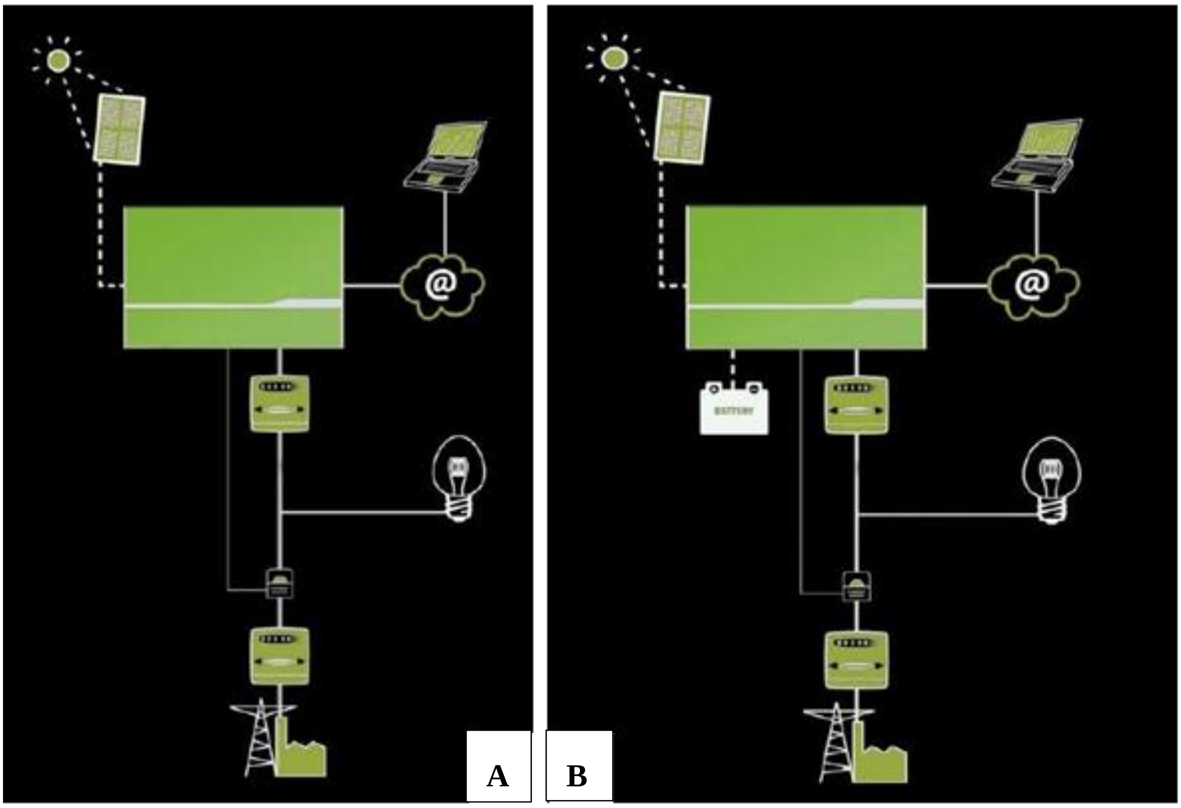


Figure 2.39 Grid connect PV system. A) Without battery. B) With battery [46].

2.3.3 Greenhouse

2.3.3.1 Key factors to be considered

Greenhouse Structure

The following text focuses on the different parameters that should be taken into account when designing greenhouse structures.

Levels of technology

There are three main levels of greenhouse technology: high, medium and low.

High technology greenhouses, which can be covered with polycarbonate, polyethylene as well as glass, using steel or aluminium as framing materials. Soilless culture is used for crop production as well as a fully controlled computerized automated drip irrigation system, monitoring EC, pH, irrigation duration and frequency. This type of greenhouses uses active cooling and heating systems. Maximum yields of 90 kg/m^2 per year (tomatoes production) could be achieved “with an investment over US$110/m^2”.

Medium technology greenhouses, which can be covered with rigid plastic or polyethylene, using steel as framing material. Soil or soilless culture is used for crop production as well as a computerized drip irrigation system, monitoring irrigation duration and frequency. This type of greenhouses can or not use active cooling or heating systems and can have maximum yields of 45 kg/m^2 per year (tomatoes production) “with an investment below US$110/m^2”.

Low technology greenhouses, which are covered with a single polyethylene film, using steel or wood as framing materials. Crops grow in the soil floor and it is used a manually controlled drip irrigation system. This type of greenhouses does not use neither active cooling nor heating systems and can have maximum yields of 20 kg/m^2 per year (tomatoes production) “with an investment below US$35/m^2”.

Load considerations

Some factors need to be considered when designing a greenhouse, depending on climate and location, such as dead, live, wind and snow load.

Dead load is the weight of the permanent construction. It includes “structure, covering, equipment attached to the structural members” and any “plants or equipment attached to the structure for more than a month”.

Live load is the extra weight added by use. It includes “vegetable plants attached to a high wire, hanging baskets, shelves, and any equipment attached to the structure for less than one month”.

Wind load is caused by winds from any direction. For designing purposes, the maximum wind speed over the last 100 years should be considered.

Snow load must be considered per square meter and should include “the heating system to melt the snow and the roof design”.

Type of greenhouse

Greenhouses can be either single-pan or multi-pan, i.e. a single or a multiple gutter connected greenhouse structure. Figure 2.40 shows the most used single span and Figure 2.41 the most used multi-span greenhouses.

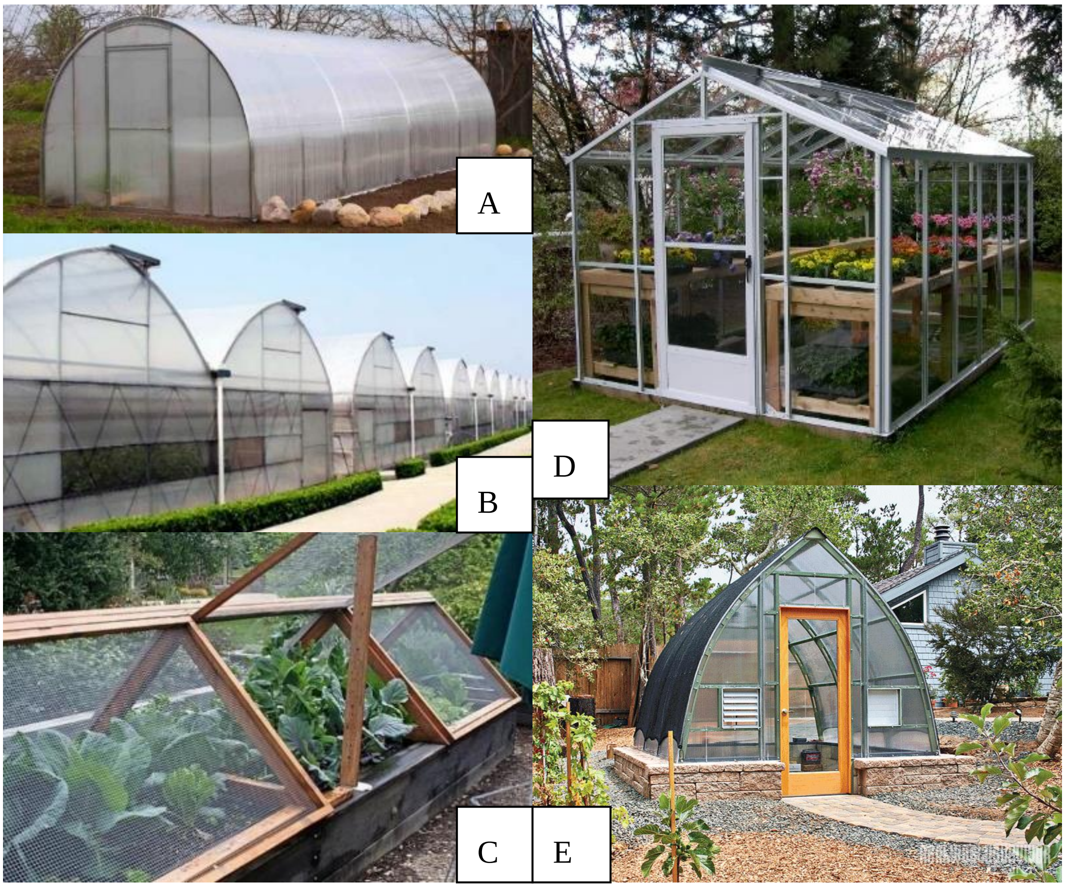


Figure 2.40 Single pan greenhouses. A) Hoop. B) Arch roof. C) Cold frame. D) Gable roof. E) Gothic [61-65].

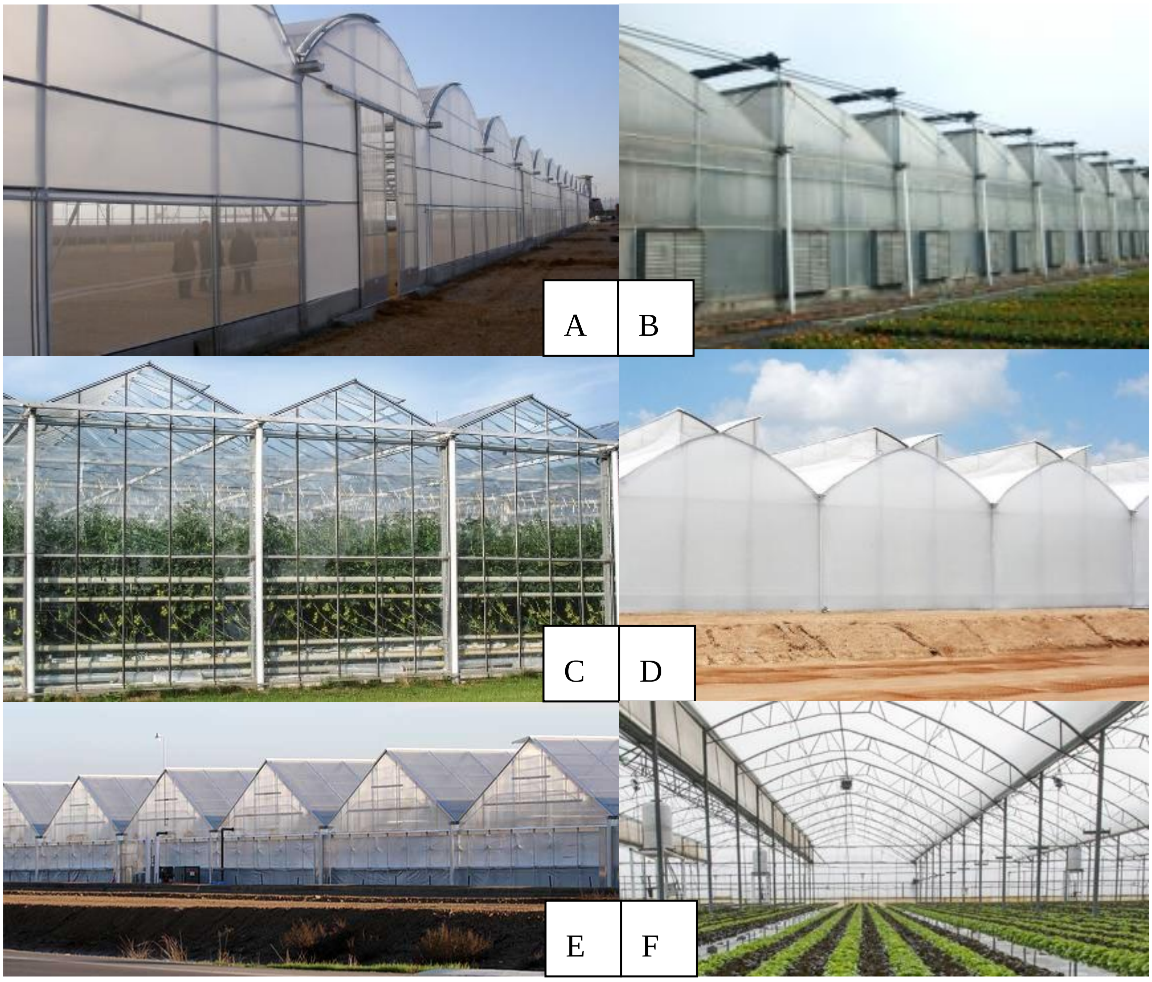


Figure 2.41 Multi-span greenhouses. A) Arch roof. B) Sawtooth. C) Venlo. D) Gothic. E) Gable roof F) High tunnel. [66-71].

Height of greenhouse

The type of crop production defines the ideal height of a greenhouse. The taller they are the greater is their air "buffer" capacity (air volume) to face quick changes from the outside environment. Moreover, in taller greenhouses cooling is improved since "the warm air rises above the plant canopy". In addition, in taller greenhouses there is more space "for the installation of supplemental light, overhead irrigation, shade and thermal cloth, benches and hanging baskets". As an example, in tomatoes production the height of the support cable should be from 2.4 – 6.7 m and consequently greenhouses should be in this range of heights.

Orientation

In order to have a more uniform sunlight reception across the width during the day, especially in the winter, tall plants like tomatoes should grow on north-south oriented multi-span greenhouses and in north-south oriented rows. This is even more important in latitudes over 30˚ north or south. On the contrary, if oriented east-west both greenhouse and row of plants, less light would reach the north end of the greenhouse, because of shadows from the plants on south.

In the case of short plants such as lettuce, there is not much difference if both greenhouse and row of plants are east-west oriented. Finally, the more amount of framing the greenhouse has, the less light it receives [72].

Greenhouse Environment

This section focuses on the ideal greenhouse environment and the important factors that should be taken into account when designing a greenhouse, as it is going to be done in chapter five.

Spacing between rows and plants

It is extremely important since it compromises other “parameters, such as light, air circulation and performing day to day tasks”. In the greenhouse, it has to be balanced plant needs for optimum growth and development and at the same time maximization of resources. As an example, tomatoes are grown in rows that are 1.8 m apart.

Light

“Latitude, orientation of the greenhouse, covering material, shadows from the structure and plants, dust and environment” are some of the factors that affect light. Flower abortion is a common problem of low light conditions. To avoid that, it can be used complementary artificial light, particularly during the winter. The excess of light is as well damaging, causing sunburn. Installing shade cloth can be a solution to this problem.

In order to have a minimum production, plants need to receive the adequate photoactive radiation (PAR) light, which is within the wavelength range of 400–700 nm and is only 45% of the global solar radiation. The required amount of PAR radiation is measured either by instantaneous photosynthetic photon flux density (PPFD) [$\mu mol\ m^{-2}\ s^{-1}$] or daily light integral (DLI) [$mol\ m^{-2}\ d^{-1}$]. Table 2.3 shows average daily light integral need of different species [73].

Table 2.2 Average daily light integral needs of different species [74]

Minimum aceptable quality
Good quality
High quality

1=Requires ample water to perform well at high-light levels.
2=Requires cool or moderate temperatures to perform well at high-light levels.
3=Stock plants perform well under higher light levels than finished plants.

Species	Average Daily Light Integral (Moles/Day)														
	Greenhouse														
	2	4	6	8	10	12	14	16	18	20	22	24	26	28	30
Ferns (Pteris Adiantum)															
Maranta															
Phalaenopsis (orchid)															
Saintpaulia															
Spathiphyllum															
Forced hyacinth															
Forced narcissus															
Forced tulip															
Aglaonema															
Bromeliads															
Caladium													1	1	1
Dieffenbachia															
Dracaena															
Nephrolepsis															
Streptocarpus															
Hosta													1	1	1
Hedera (English ivy)															
Begonia (heimalis)															
Sinningia															
Schlumbergera									2	2	2	2	2	2	2
Cyclamen															
Exacum															
Heuchera															
Coleus (shade)															
Impatiens, New Guinea															
Iris, Dutch (cut flowers)															
Kalanchoe															
Lobelia												2	2	2	2
Primula															
Impatiens															
Pelargonium peltatum (Ivy geranium)															
Begonia (fibrous)															
Senecia (dusty miller)															
Fuchsia												2	2	2	2
Euphorbia (poinsettia)													3	3	3
Hydrangea															

Table 2.3 Average daily light integral needs of different species [73]

Species	Average Daily Light Integral (Moles/Day)														
	Greenhouse														
	2	4	6	8	10	12	14	16	18	20	22	24	26	28	30
Lilium (asiatic and oriental)															
Lilium longiflorum (easter lily)															
Ageratum															
Antirrhinum															
Chrysanthemum (potted)															
Dianthus															
Gazania															
Gerbera															
Hibiscus rosa-siniensis															
Lobularia															
Pelargonium hororum (zonal geranium)															
Rose (miniature potted)															
Salvia splendens															
Schefflera															
Angelonia															
Aster															
Salvia farinacea															
Iberis															
Catharanthus (vinca)															
Celosia															
Chrysanthemum (garden)															
Coleus (sun)															
Coreopsis															
Cosmos															
Croton															
Dahlia															
Echinacea															
Ficus bejaminia															
Gaura															
Gomphrena															
Hemerocallis															
Lantana															
Lavendula (lavender)															
Tagetes (marigold)															
Petunia															
Phlox (creeping)															
Rudbeckia															
Scaevola															
Sedum															
Thymus															
Verbena															
Viola (pansy)														2	2
Zinnia															
Alstroemeria (cut flower)															
Capsicum (pepper)															
Chrysanthemum (cut flower)															
Dianthus (carnation)															
Gladiolus (cut flower)															
Lycopersicon (tomato)															
Rose (cut flower)															

Temperature

Plant growth and development depend on greenhouse temperatures. However, temperature increases pest pressure. The greenhouse may be compared with a solar energy collector, where solar radiation is absorbed, reflected and transferred. The heat transfer coefficient and colour of the physical components are responsible for the way light is distributed when it reaches each physical component. Shade cloths reduce heat load and air temperature, especially during the summer, although it reduces irradiance (or light levels) of crops.

Relative humidity

It has major effects on plant diseases. Desirable daytime relative humidity levels are between 60-80%.

Cooling

It can be achieved by two methods: passive ventilation and active cooling. For passive ventilation side vents are used, where “fresh air enters and hot air leaves the greenhouse thru roof openings”. Vents’ surface area “should be 25% of the greenhouse ground surface area”.

Exhaust fans are used for active ventilation, forcing “old air out of the greenhouse by pulling in outdoor air through vents located on the opposite walls”. Lots of energy are required for working this system.

Heating

Several types of heating systems can be used such as hot water that runs through pipes throughout the greenhouse or forced air heaters. Air heaters have some drawbacks, such as consumption of oxygen that plants require at night for respiration and the production of ethylene and CO, which are “toxic elements for plants and they can cause poor growth especially in new growth, flower abortion and early maturation of fruits”. It is more efficient to mixture both air heating and ground heating.

CO_2

Since it is essential for the photosynthesis, a detrimental plant growth can be caused by an inadequate concentration of this element. CO_2 should be injected in greenhouse plant production to achieve 1000 ppm (ambient concentration is 350 ppm) [73].

3 Design of Lightweight BIPV modules

This chapter and the following present research work that was developed in the framework of two European H2020 R&D projects in which Onyx Solar is an active partner: EnergyMatching and Rezbuild.

EnergyMatching aims at optimizing building integrated NZEBs on residential buildings and drive its market. This objective will be accomplished by developing highly aesthetical and flexible active envelope solutions to suit different architectural concepts. In this project, Onyx Solar is developing coloured and size diversified glass+glass and glass+backsheet c-Si and a-Si thin film BIPV plug & play envelope solutions, using a pre-defined fixation system provided by one of the partners.

Rezbuilt aims at developing and diversifying cost-effective residential renovation typologies and technologies of NZEBs and so enhance residential buildings refurbishment activity. In this project Onyx Solar is developing and optimizing dimensions and the use of colour in glass+glass, glass+backsheet and monolithic composite-based c-Si, a-Si and CIGS (flexible) thin film BIPV plug & play envelope solutions, using 3D prefabricated fixation systems provided by one of the partners as well as other commercial plug & play fixation systems. Moreover, Onyx Solar is developing and parameterising a real time PV production monitoring tool.

The design of coloured and variable size glass+glass and glass+backsheet BIPV plug & play solutions comes as a response to the important demand from the market in what respects to sizes and colour customizations as well as the diminishment of BIPV systems' payback times. This is possible since plug & play solutions make installation process easier and faster, and consequently lower installation costs, as well as make possible to easily remove individual modules. For economic and practical reasons, it is important to use lightweight PV modules on these plug & play envelope solutions and so these two components, lightweight BIPV modules and plug & play fixation systems are the scope of the present and next chapters.

The third chapter focuses on the design of prototypes of lightweight glass+glass and glass+backsheet BIPV modules, considering mechanical and feasibility aspects. The following presents plug & play commercial fixation systems and approximations to the concept, where the laminated BIPV modules could be integrated to obtain plug & play ventilated façades solutions.

3.1 Identification of the Requirements of the Lightweight BIPV c-Si and a-Si Thin Film Solutions

The solutions should be conforming the following requirements:

- Be Lightweight BIPV solutions;
- Apt to be integrated in ventilated façades of residential buildings;
- Use c-Si and a-Si thin film PV technologies.

3.2 Considerations on lightweight BIPV solutions

The Lightweight Structures Association of Australasia defines a lightweight structure as one of any material, regardless of its shape, which undergoes an “optimisation process to efficiently carry the loads from a critical loading case" [75]. Apart from that, the BIPV solutions must have a safety glass, which is either laminated glass (at least two panes of float/tempered glass) or at least a tempered one.

The minimum thickness of the PV modules used by Onyx Solar is 3.2+4 mm float glass, with standard dimensions of 1245 mm x 635 mm and a weight of 14.60 kg. Taking that into account, it is considered a lightweight laminated glass one that has less than 10 kg. To achieve such weight, glasses with lower thicknesses than the above mentioned are considered, which means using panes of glass without more than 4 mm of thickness. Since it is very difficult to find float glass with a thickness lower than that, only c-Si lightweight BIPV solutions with laminated tempered glass are considered. In the case of a-Si thin film lightweight BIPV solutions, the a-Si thin film is always deposited on a float front glass with a thickness of 3.2 mm. Consequently, solutions with a front float glass and a rear tempered glass are considered.

In what respects to commercial products, the minimum thickness of tempered glass widely available is 2.5 mm, and the following are 3 and 4 mm. For that reason, only tempered glasses with these characteristics are considered.

It is important to say that Onyx Solar’s PV module 4 mm+backsheet is certified according to IEC 61730’s impact test, and so the proposed modules with a thickness equal or higher than this should be apt according to IEC 61730.

3.3 Analysis and characterization of the solution

Glass+glass lightweight BIPV solutions with c-Si solar cells consist of a front layer of tempered glass, c-Si solar cells and a rear layer of tempered glass, using EVA as encapsulant. c-Si lightweight BIPV solutions with 2.5 mm + 2.5 mm, and 3 mm + 3 mm tempered glass (2.5/3+2.5/3 mm) are considered.

Glass+backsheet lightweight BIPV solutions with c-Si solar cells consist of a front layer of tempered glass, c-Si solar cells and a backsheet as a rear layer, using EVA as encapsulant c-Si lightweight BIPV solutions with 2.5/3/4 mm tempered glass+backsheet (2.5T/3T/4T mm) are considered.

Glass+glass lightweight BIPV solutions with a-Si thin film solar cells consist of a front layer of float glass (where a-Si is deposited) and a rear layer of tempered glass, using PVB as encapsulant. 3.2 mm + 2.5 mm, and 3.2 mm + 3 mm float+tempered glass (3.2+2.5/3 mm) are considered.

3.4 Accounting Standards for BIPV solutions

The most important standard for designing ventilated facades' BIPV solutions is EN 1991 – Eurocode 1: Actions on structures. It was used the Spanish standard Structural security – Actions on structures, which is based on the first one. Concerning PV modules configuration, two main standards define minimum acceptable spacing at wiring terminals, elsewhere than at wiring terminals and for creepage (the shortest distance along the surface of a solid insulating material between two conductive parts): IEC 61730: Photovoltaic (PV) module safety qualification, which is the European standard, and UL 1703-Standard for Flat-Plate Photovoltaic Modules and Panels, which is the American standard. Since the American standard is more restrictive, Table 3.1, Table 3.2 and Table 3.3 show minimum acceptable spacings at wiring terminals, elsewhere than at wiring terminals and for creepage, respectively, depending on the potential involved.

Table 3.1 Minimum acceptable spacing at wiring terminals [76]

Potential involved, V	Through air and over surface	
	in	(mm)
0 – 50	1/4	(6.4)
51 – 300	3/8	(9.5)
301 – 600	1/2	(12.7)
601 – 1000	5/8	(15.9)
1001 – 1500	15/16	(24)

Table 3.2 Minimum acceptable spacing elsewhere than at wiring terminals [76]

Potential involved, V	Through air		Over surface	
	in	(mm)	in	(mm)
0 – 50	1/16	(1.6)	1/16	(1.6)
51 – 300	1/8	(3.2)	1/4	(6.4)
301 – 600	1/4	(6.4)	3/8	(9.5)
601 – 1000	3/8	(9.5)	1/2	(12.7)
1001 – 1500 [a]	9/16	(14)	19/32	(15)

[a] For edge spacings (live parts to the accessible edge of the module) the values in Table 12.2 are for metallic framed modules. Double the over-surface and through-air distances for edge spacings of modules without metallic frames.

Table 3.3 Minimum acceptable spacing for creepage distances using Pollution Degree 1 [76]

Potential involved, V	Over surface	
	in	(mm)
600	0.066	(1.68)
1000	0.126	(3.20)
1500	0.205	(5.20)

Note: Distances for 600 V and 1500 V are based on linear interpolation of the Standard for Insulation Coordination Including Clearances and Creepage Distances for Electrical Equipment, UL 840, Table 9.1, using Pollution Degree 1.

3.5 Specific considerations when configuring modules of each PV technology

3.5.1 c-Si PV technologies

When considering the incorporation of both c-Si solar cells, it should not only be taken into account the dimensions of the cells, but also the space needed between cells and on the edges of the laminated glass to guarantee electrical insulation.

3.5.1.1 Dimensions of c-Si solar cells

Every solar panel is made up of individual solar PV cells. PV cells have a standard size of 156 mm x 156 mm.

3.5.1.2 Minimum space required between c-Si solar cells and on edges

Minimum space required between c-Si solar cells and on edges is the same on both solutions, either tempered glass + glass or tempered glass + backsheet. The following values were obtained by considering standard UL 1703 and consulting Onyx Solar's experts:

- Between solar cells of the same string: 3 mm;
- Between solar cells of different strings: 4 mm;
- Distance between cells and bus ribbons: 5 mm;
- Distance between the active part of the module and edges: 15 mm.

3.5.2 a-Si thin film PV technology

Designing a-Si PV modules has fewer restrictions than the above-mentioned technology. The space between the active part of the module and edges must be higher than 10 mm, according to Onyx Solar's experts.

It is important to mention that a-Si thin film is always deposited in a float glass with dimensions of 1245 mm x 635 mm and a thickness of 3.2 mm. To obtain other dimensions, the glass has to be cut and then laser etched on the edges.

3.6 Considering Wind Load Actions on Ventilated Façades

The following text is based on the Spanish Standard Structural security – Actions on structures and explains how the maximum suction and pressure that the lightweight BIPV solutions undergo when integrated on residential buildings' ventilated façades is calculated. As no place is specified for this project, it will be considered that the ventilated façades are going to be implemented in Spain.

The action of the wind is usually a load perpendicular to the surface, which can be expressed by Equation 3.1.

$$q_e = q_b * c_e * c_p \tag{3.1}$$

Where:

q_b is the dynamic pressure of the wind, which can be generally considered equal to 0.5 kN/m^2 for every place of the Spanish territory;

c_e is the exposition coefficient, which varies with height of the considered point. It can be approximated to 2.0 for buildings with the maximum of eight floors, which is considered;

c_p is the eolic or pressure coefficient, which depends of the shape and orientation of the surface with respect to the wind and of the localization of the point in analysis with respect to the edges of the surface. A negative value of this coefficient means suction (c_s).

For generic buildings, c_p and c_s have the values shown on Table 3.4.

Table 3.4 c_p and c_s depending on the slenderness ratio of the plane parallel to the wind [77]

	Slenderness ratio of the plane parallel to the wind					
	< 0,25	0,50	0,75	1,00	1,25	≥ 5,00
Eolic pressure coefficient , c_p	0,7	0,7	0,8	0,8	0,8	0,8
Eolic suction coefficient , c_s	-0,3	-0,4	-0,4	-0,5	-0,6	-0,7

Since the slenderness ratio is unknown, it is considered the worst-case scenario, which is more than 5. Finally the pressure and suction load is obtained on Equation 3.1 [77].

$$\mathrm{q}_s = 0.5 * 2 * (-0.7) = -0.7\,\mathrm{kN/m^2} \tag{3.2}$$

$$\mathrm{q}_p = 0.5 * 2 * (0.8) = 0.8\,\mathrm{kN/m^2} \tag{3.3}$$

For design purposes, it is considered the highest value, which is 0.8 kN/m^2.

3.7 Maximum length of the sides without supporting material for a given thickness

Since lightweight solutions are supposed to be applied on ventilated façades, the design method has to be adapted to its fixation system. As in these applications only two opposite sides have some kind of support, the maximum length of the sides without supporting material for a given thickness has to be obtained. To design that, a laminated tempered symmetric glass with two sheets of tempered glass with the same thickness is considered to be equivalent to one sheet of tempered glass with the same thickness of the laminated one. In the case of laminated a-Si thin film glass+glass with one sheet of float glass of 3.2 mm (where a-Si thin film is deposited) and another of tempered glass with different thicknesses, for design purposes, it is considered to be equivalent to the values obtained for one sheet of float glass with a thickness inferior to the sum of the laminated one. The following simplifications are done:

- 3.2 mm + 2.5 mm ≈ 2.5 mm + 2.5 mm
- 3.2 mm + 3 mm ≈ 3 mm + 3 mm

Finally, tempered glass is considered to be four times more resistant to wind pressure than float glass [78]. In the following sections, a commercial table from FLOAT® is used to obtain the maximum length of the sides without supporting material, which is the working tool currently used by Onyx Solar's experts.

3.8 c-Si BIPV solutions

As it was mentioned before, the maximum length of the sides without supporting material for solutions with the following thicknesses and respective approximations are going to be obtained (T meaning tempered glass + backsheet):

- 2.5 mm + 2.5 mm → 5 mm
- 3 mm + 3 mm → 6 mm
- 2.5T mm → 2.5 mm
- 3T mm → 3 mm
- 4T mm → 4 mm

Figure 3.1 shows a graph that relates wind pressure, thickness of the laminated tempered glass and maximum length of the sides without supporting material.

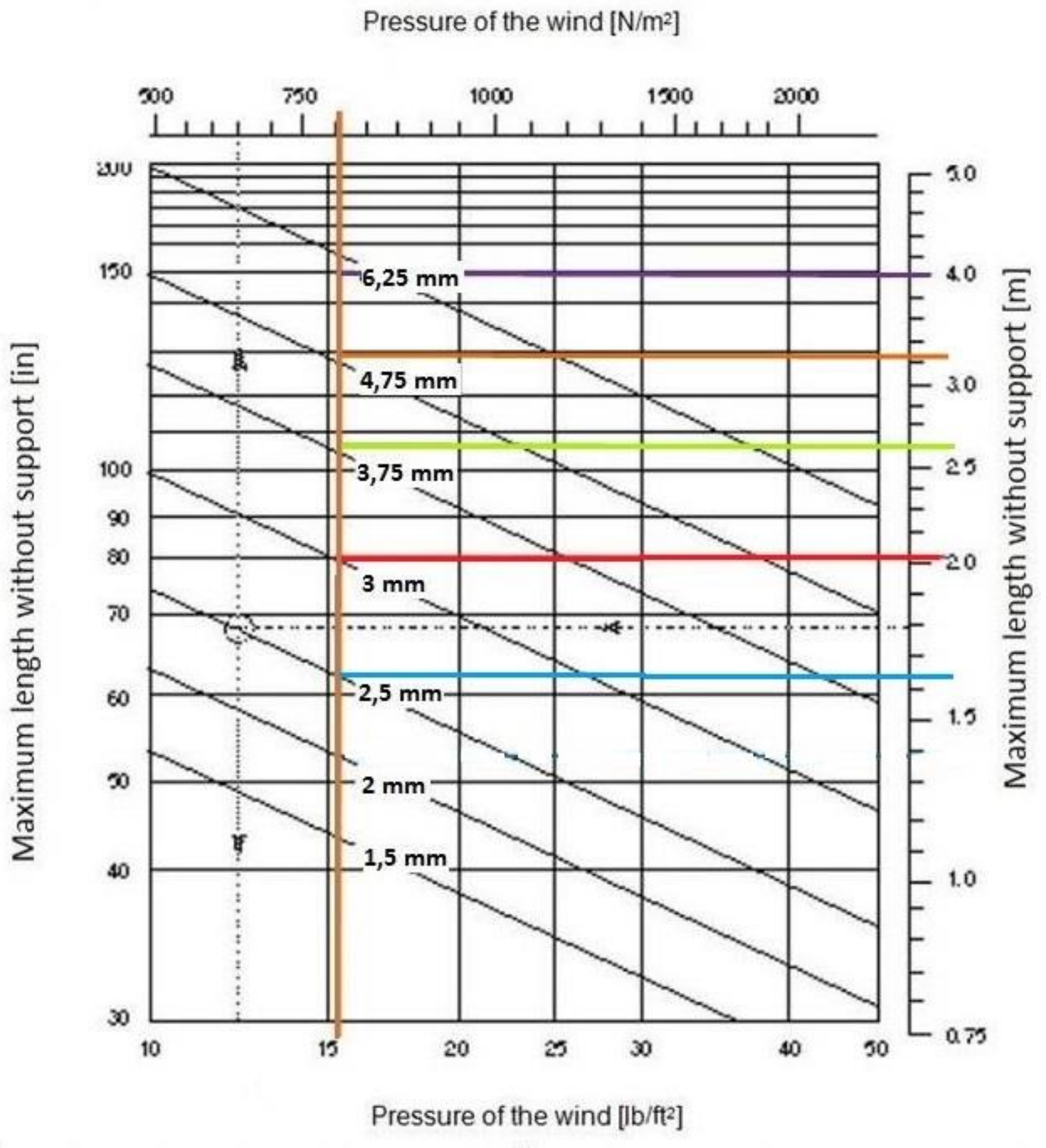


Figure 3.1 Graph that relates wind pressure, thickness of the tempered glass and maximum length of the sides without supporting material [78].

As it is possible to see in Figure 3.1, the maximum length of the sides without a supporting material is:

- 2.5 mm → 1640 mm
- 3 mm → 2000 mm
- 4 mm → 2625 mm
- 5 mm → 3220 mm
- 6 mm → 4000 mm

Since glass's deflection should not be greater than 1/250 of the length of the edge of the glass without a supporting material, the deflection correspondent to each maximum length of the sides without a supporting material is:

- 2.5 mm → 1640 mm → 6.6 mm = 0.26 in
- 3 mm → 2000 mm → 8.0 mm = 0.32 in
- 4 mm → 2625 mm → 10.5 mm = 0.41 in
- 5 mm →3220 mm → 12.9 mm = 0.51 in
- 6 mm → 4000 mm → 16.0 mm = 0.63 in

Taking into account the values of deflection and expected wind pressure, the final maximum length of the sides without a supporting material are obtained, in an iterative process [78]. Figure 3.2 shows a graph that relates the pressure of the wind, thickness, maximum deflection and maximum length without a supporting material of tempered glass.

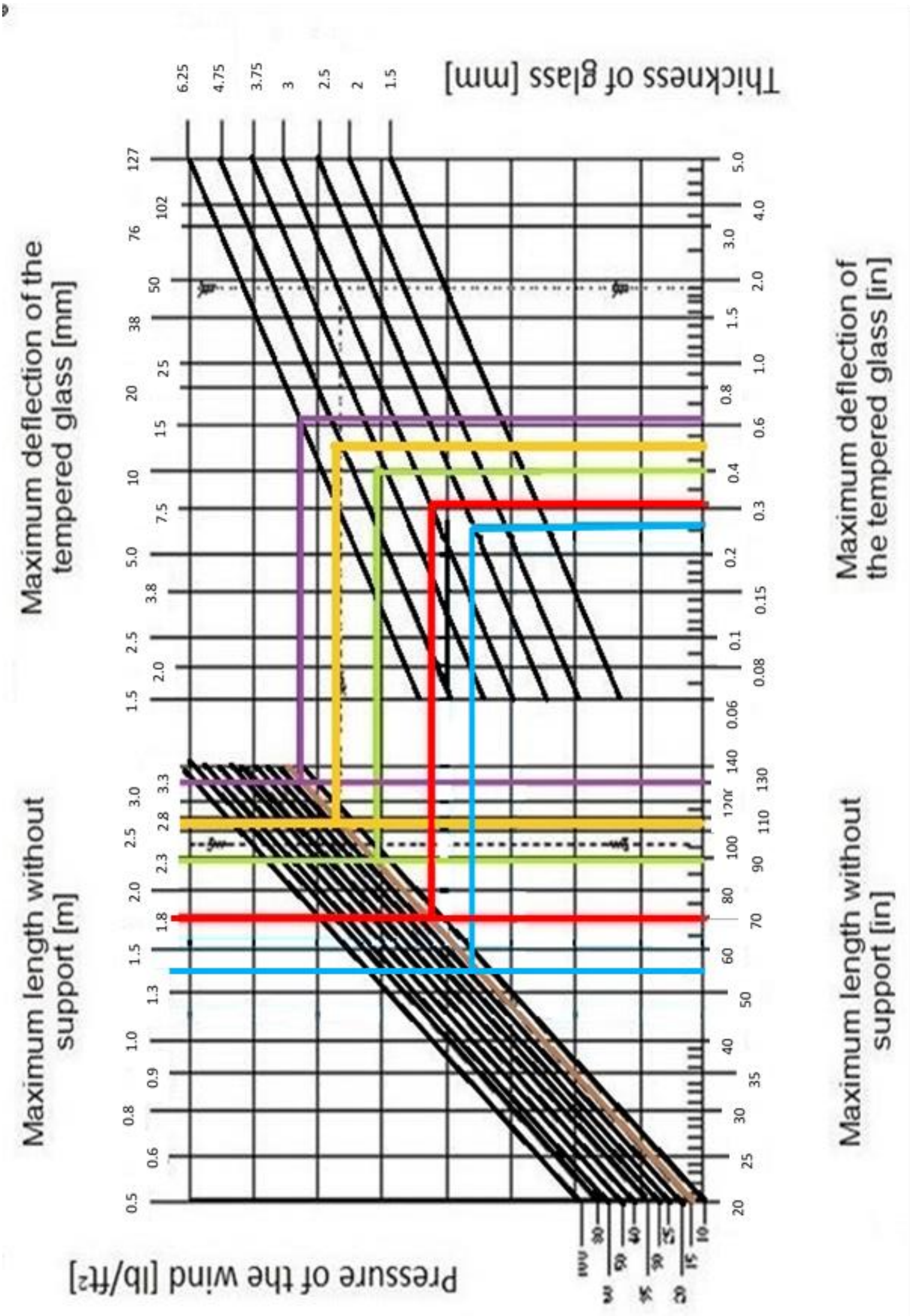


Figure 3.2 Graph that relates the pressure of the wind, thickness, maximum deflection and maximum length without a supporting material of the tempered glass. The blue line respects to 2.5 mm, the red line to 3 mm, the green line to 4 mm tempered, the yellow line to 5 mm and the purple line to 6 mm tempered glass [41].

As a result of the iteration process, the maximum length of the sides without a supporting material is:

- 2.5 mm → ≈ 1375 mm
- 3 mm → ≈ 1750 mm
- 4 mm → ≈ 2300 mm
- 5 mm → ≈ 2600 mm
- 6 mm → ≈ 3300 mm

For safety reasons, the values obtained with the graph are multiplied per 0.8. Consequently, the final maximum length of the edges without a supporting material for each solution is:

- 2.5T mm → ≈ 1100 mm
- 3T mm → ≈ 1400 mm
- 4T mm → ≈ 1840 mm
- 2.5 mm + 2.5 mm → ≈ 2080 mm
- 3 mm + 3 mm → ≈ 2640 mm

3.9 a-Si thin film BIPV solutions

As it was mentioned before, the maximum length of the sides without supporting material for solutions with the following thicknesses and respective approximations are going to be obtained:

- 3.2 mm + 2.5 mm → ≈ 2.5 mm + 2.5 mm
- 3.2 mm + 3 mm → ≈ 3 mm +3 mm

Figure 3.3 shows a graph that relates wind pressure, thickness of the laminated tempered glass and maximum length of the sides without a supporting material.

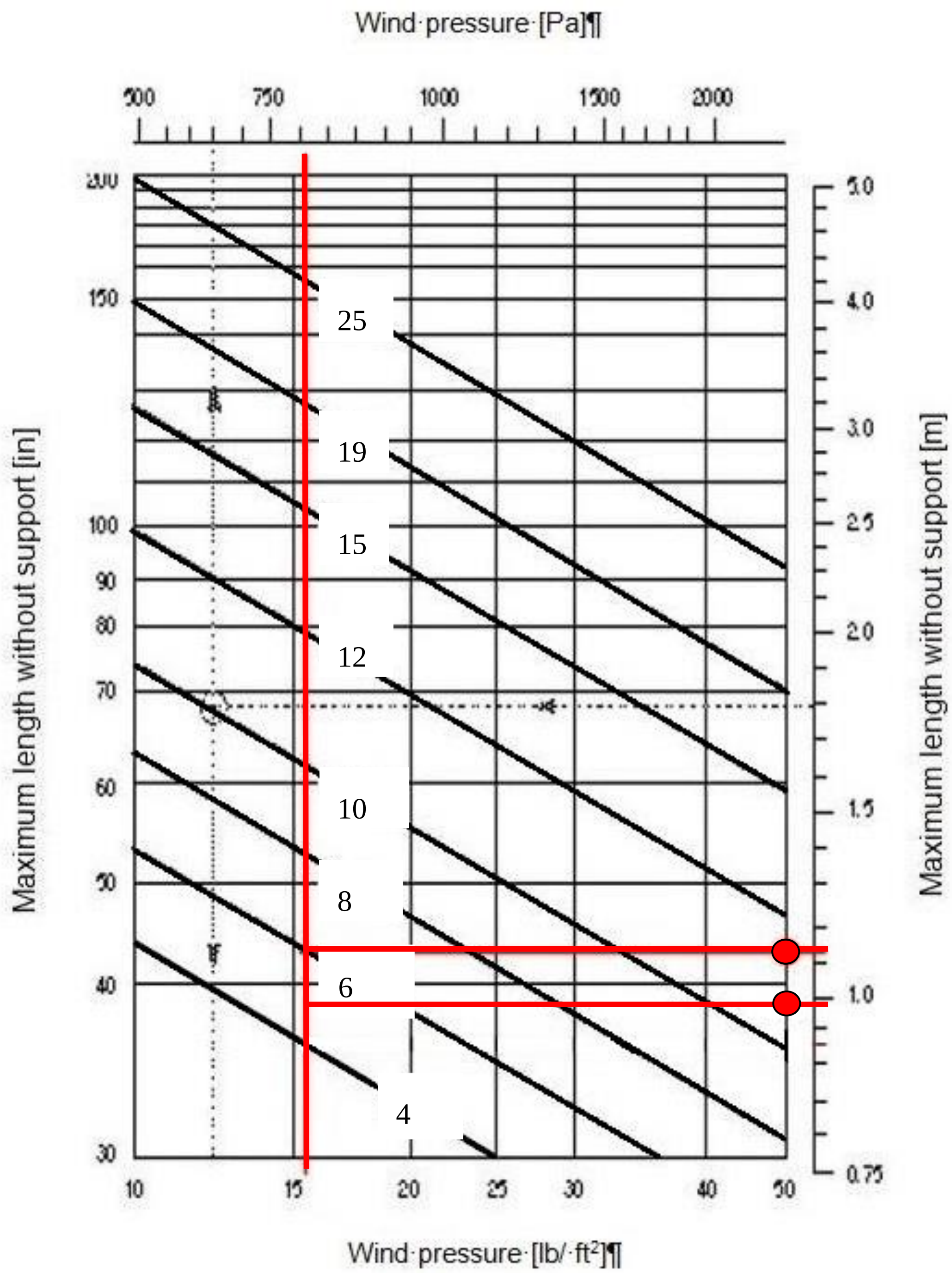


Figure 3.3 Graph that relates wind pressure, thickness of the laminated floated glass and maximum length of the sides without supporting material [78].

As it was possible to obtain with the graph, the maximum length of the sides without a supporting material is:

- 2.5 mm + 2.5 mm → ≈ 1000 mm
- 3 mm + 3 mm → ≈ 1150 mm

The deflection of the laminated glass should not be greater than 1/250 of the length of the sides of the glass without a supporting material. Consequently, the maximum value of deflection for each solution is:

- 2.5 mm + 2.5 mm → 1000 mm → 4 mm → 0.16 in
- 3 mm + 3 mm → 1150 mm → 4.6 mm → 0.18 in

Considering the values of deflection and wind pressure, it is done an iterative process, and so the final maximum length of the sides without a supporting material is obtained. Figure 3.4 shows a graph that relates the pressure of the wind, thickness, maximum deflection and maximum length without a supporting material of the float glass.

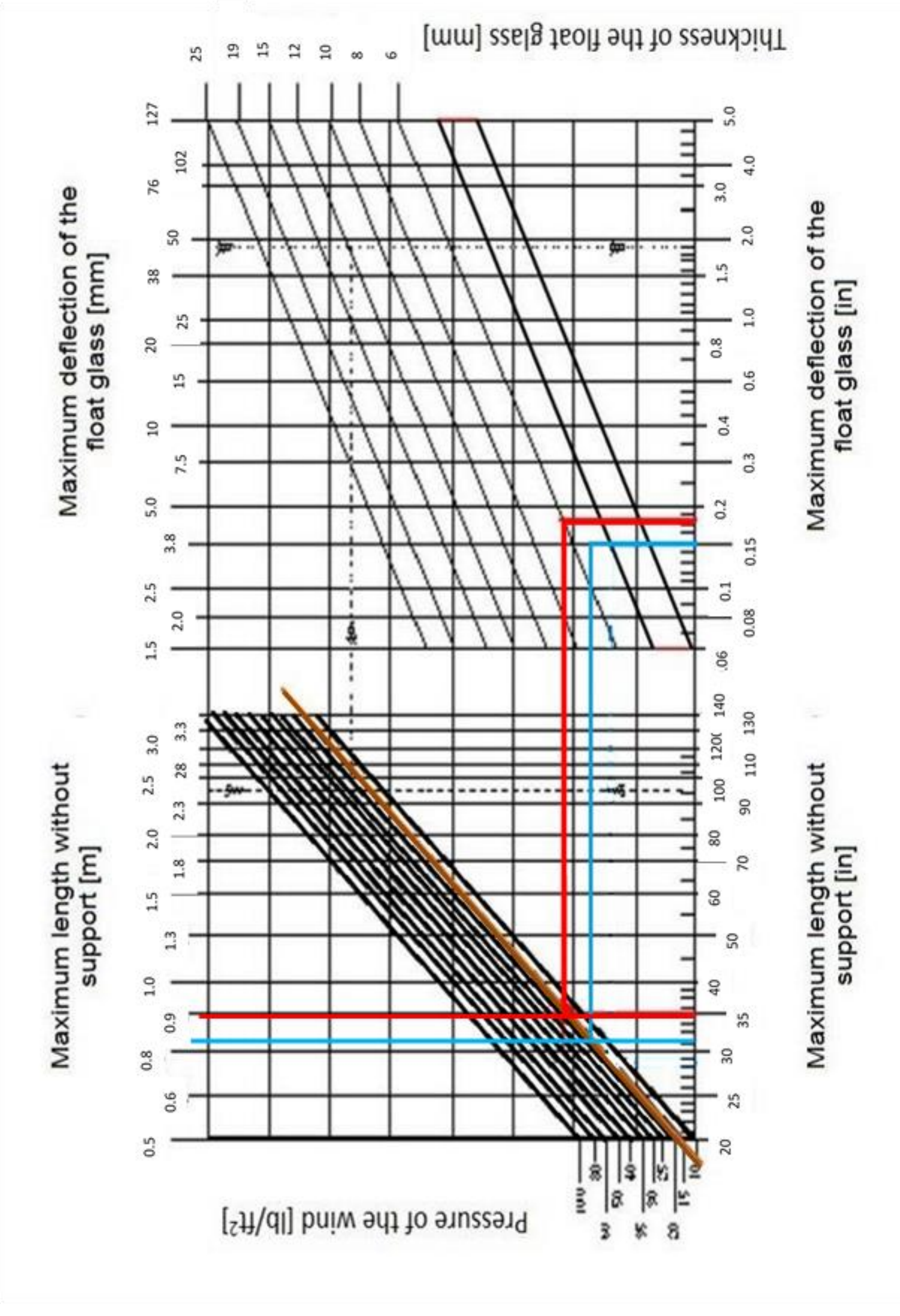


Figure 3.4 Graph which relates pressure of the wind, thickness, maximum deflection and maximum length without a supporting material of the float glass. The blue line respects to 2.5+2.5 float glass and the red line to 3+3 float glass [78].

As a result of the iteration process, the maximum length of the sides without a supporting material is:

- 3.2 mm + 2.5 mm → 813 mm
- 3.2 mm + 3 mm → 900 mm

For safety reasons, the values obtained with the graph are multiplied per 0.8:

- 3.2 mm + 2.5 mm → ≈ 650 mm
- 3.2 mm + 3 mm → ≈ 720 mm

3.10 Minimum possible dimensions of c-Si modules

As it was mentioned before, for this calculations, a maximum weight of BIPV solutions of 10 kg, the obtained maximum length of the sides without a supporting material, the defined minimum required distance between the active part of cells and edges and dimensions of c-Si PV cells have been taken into consideration. Table A.1 to Table A.15 show the minimum possible dimensions of c-Si modules.

3.11 Minimum possible dimensions of a-Si modules

For these calculations, a maximum weight of BIPV solutions of 10 kg, the obtained maximum length of the sides without a supporting material, the defined minimum required distance between the active part of cells and edges have been taken into consideration. As a-Si thin film modules have less constraints when compared to c-Si modules, the dimensions of the 3 mm + 3 mm c-Si modules are going to be adapted to a-Si thin film requirements. Table B.1 to Table B.3 show the minimum possible dimensions of a-Si thin film modules.

3.12 Analysis and evaluation of the existing solutions

In order to find the most competitive solutions, the products of three companies (TRESPA®, Butech® and Euronit®) that have presently on the market products for ventilated facades are analysed. Annex C shows, from Table C.1 to Table C.15, the referred solutions.

Even though the analysed products have a significant variety of aspect ratios (AR), the average of AR is around 2, as it is possible to see in Annex C. The most extreme aspects ratios are not considered in this analysis, since they are not representative.

3.13 Selection of the most competitive lightweight BIPV modules

Taking into consideration the analysis of the existing market products for ventilated façades, configurations with AR around from 1.5 to 2.5 are adopted. From Table D.1 to Table D.15 and from Table E.1 to Table E.3 the most competitive dimensions of c-Si modules and the most competitive dimensions of a-Si thin film modules, respectively, are presented. The dimensions were selected according to the following criteria:

- Selection of the minimum dimensions of the PV glasses with a weight less than 10 kg and an AR between 1.5 and 2.5;
- Approximation of the minimum dimensions of the selected glasses to the closest higher number ending in *50 or *100;
- Sum +0, +50 or +100 to length and/or width to obtain an AR of 1.5, 2 or 2.5.

3.14 Final drawings

After the design process, some samples were prepared with configurations based on the previous calculations. Some dimensions were adapted according Onyx Solar's best interest. Figure 3.5 to Figure 3.8 show the drawings of the desired samples. In this case, float glass was used.

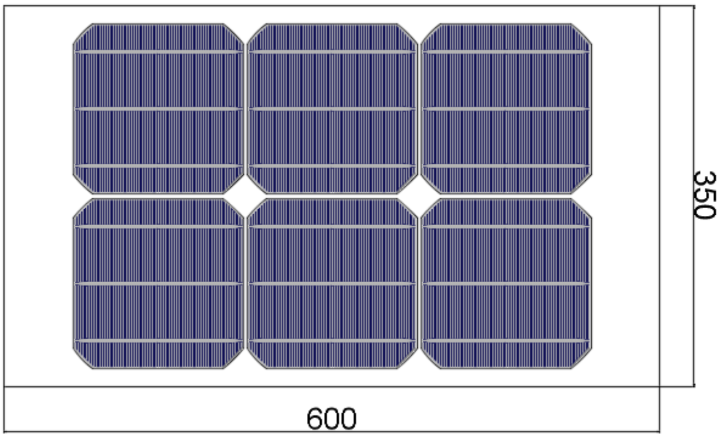


Figure 3.5 Front view of BIPV module with 2x3 c-Si cells (units: mm).

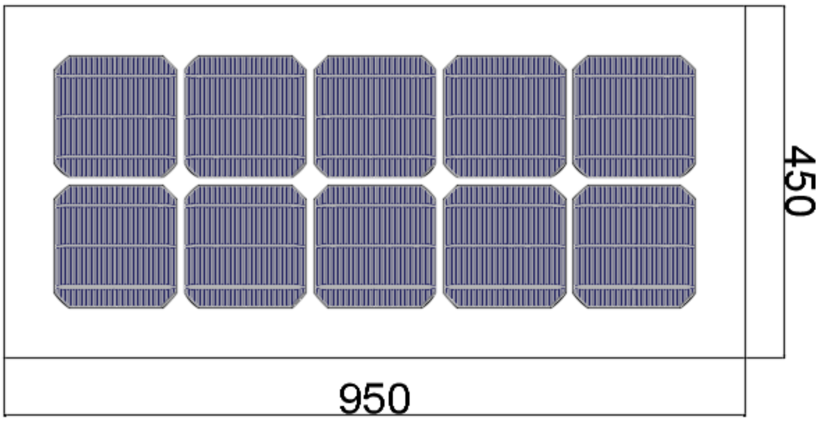


Figure 3.6 Front view of BIPV module with 2x5 c-Si cells (units: mm).

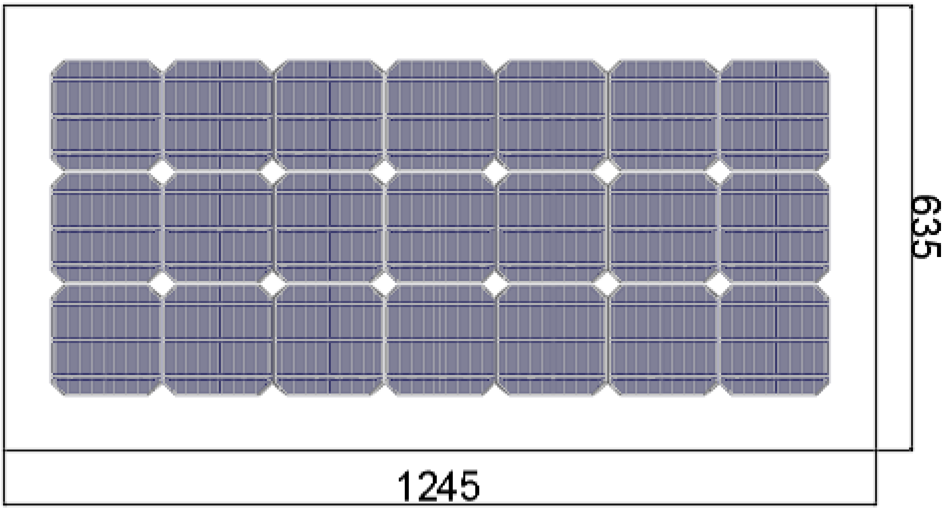


Figure 3.7 Front view of t BIPV module with 2x7 c-Si cells (units: mm).

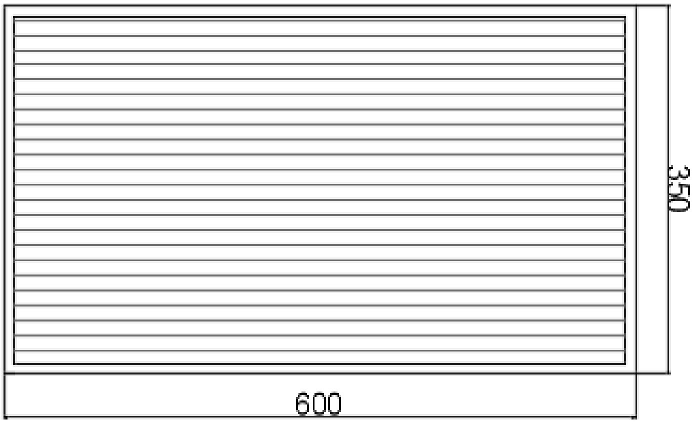


Figure 3.8 Front view of BIPV module with 2x3 thin film a-Si cells (units: mm).

3.15 Experimental samples

The following text presents laminated lightweight BIPV glass+glass and glass+backsheet samples, of c-Si and a-Si thin film PV technologies.

Regarding the c-Si modules, the following nomenclature code has been used for their description and references on the text:

Module X.Y.W.Z., where X is the number of c-Si cells/module used in its manufacturing, with front glass of Y mm and rear glass of W mm thicknesses and Z is the number of the module with the X c-Si cells/module fabricated with front glass of Y mm and rear glass of W mm. For instance, the first module fabricated with ten c-Si cells, front glass of 2 mm and rear glass of 2 mm is referred as Module 10.2.2.1. In the case of a-Si, X will assume letter A.

3.15.1 c-Si PV glass

Figure 3.9 shows Module 6.2.2.1. and Module 6.2.2.2 of 600 mm x 350 mm.

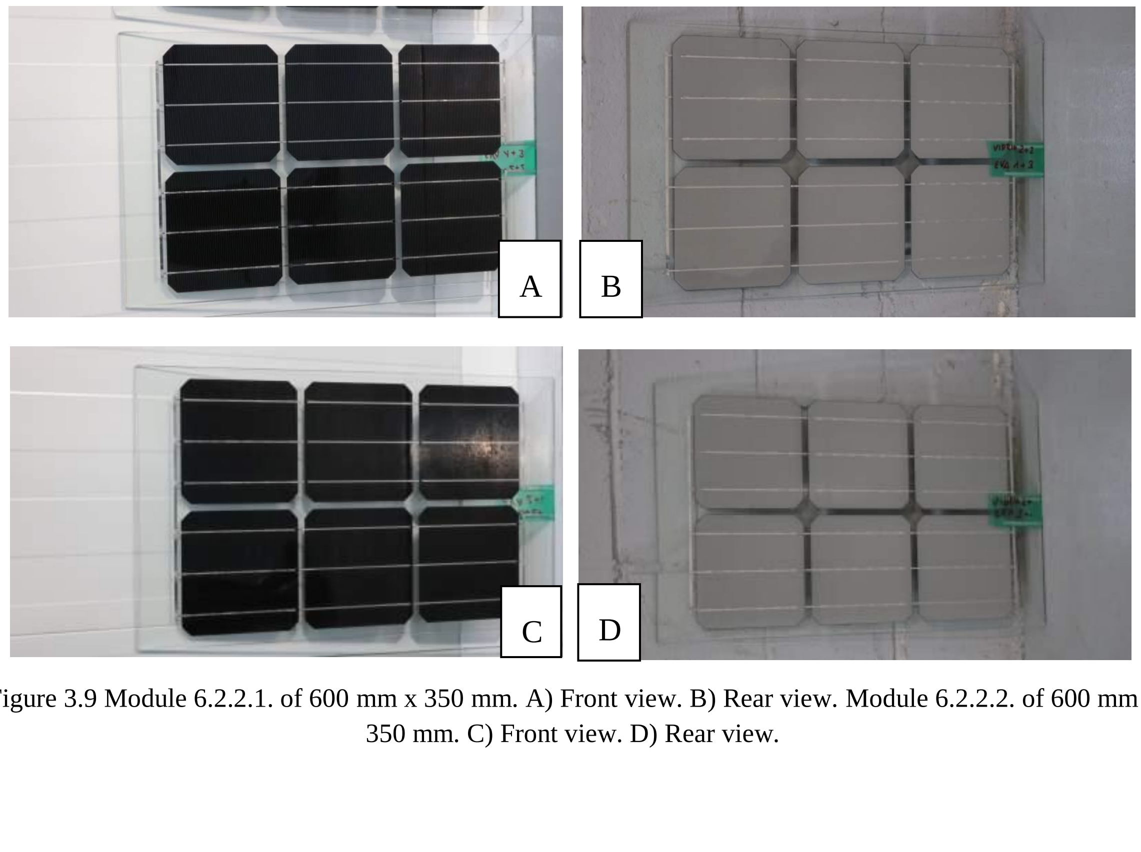


Figure 3.9 Module 6.2.2.1. of 600 mm x 350 mm. A) Front view. B) Rear view. Module 6.2.2.2. of 600 mm x 350 mm. C) Front view. D) Rear view.

No imperfection was detected on these samples.

Figure 3.10 shows Module 6.3.3.1. of 600 mm x 350 mm.

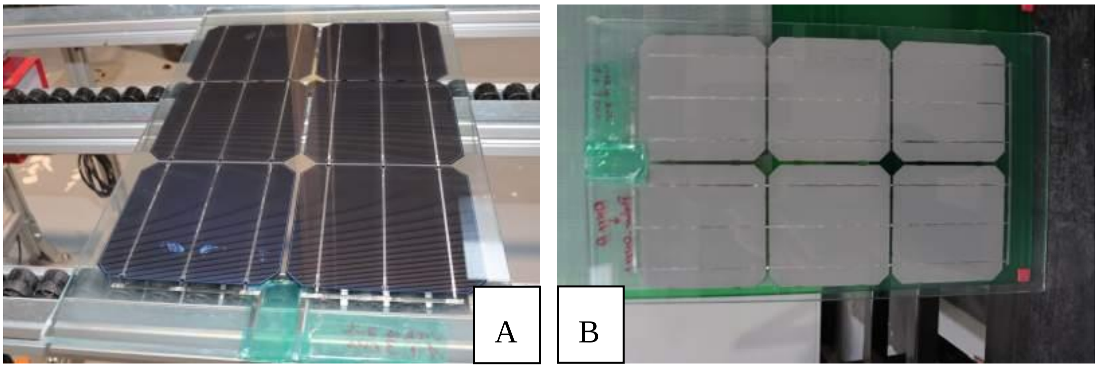


Figure 3.10 Module 6.3.3.1. of 600 mm x 350 mm. A) Front View. B) Rear View.

Figure 3.11 shows a detailed view of the front part of Module 6.3.3.1. of 600 mm x 350 mm.

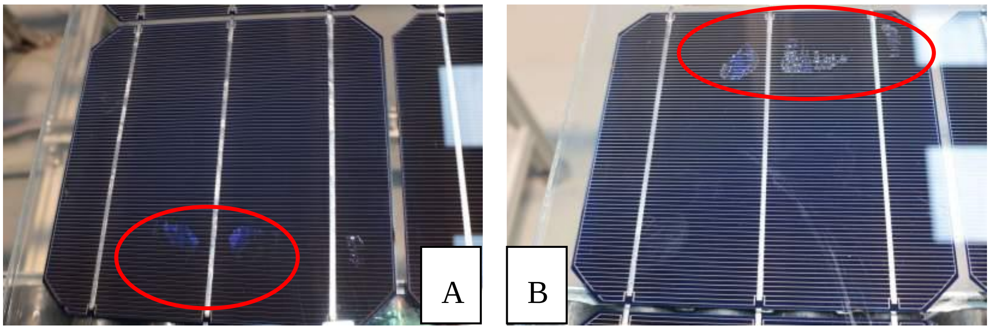


Figure 3.11 Detailed view of the Module 6.3.3.1. A) B) Red circles show defects (bubbles) found in the front of the sample.

Figure 3.12 shows a detailed view of Module 6.3.3.1. of 600 mm x 350 mm.

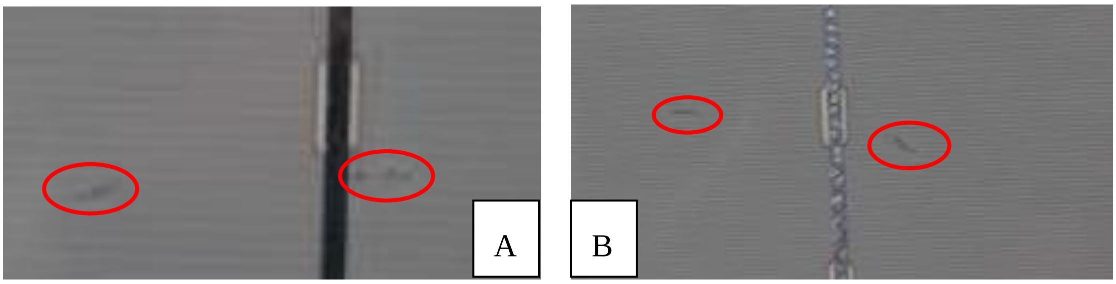


Figure 3.12 Detailed view of the Module 6.3.3.1. Red circles show defects (bubbles) found in the rear side of the sample.

In this case, small defects of the lamination process (bubbles) can be appreciated on some cells of the module (red mark in Figure 3.11 and Figure 3.12).

Figure 3.13 shows Module 10.2.2.1. of 950 mm x 450 mm. For stock reasons, the module presents a black ribbon.

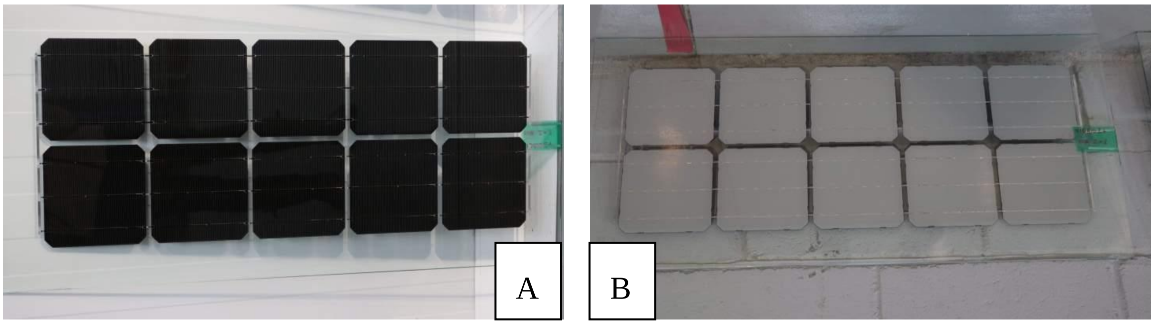


Figure 3.13 Module 10.2.2.1. of 950 mm x 450 mm. A) Front view. B) Rear view.

Figure 3.14 shows a detailed view of Module 10.2.2.1.

Figure 3.14 Detailed view of Module 10.2.2.1.

No imperfection was detected on this sample.

Figure 3.15 shows Module 21.4.backsheet.1. of 1245 mm x 635 mm. The front glass of this sample was tempered glass with Kromatix Blue.

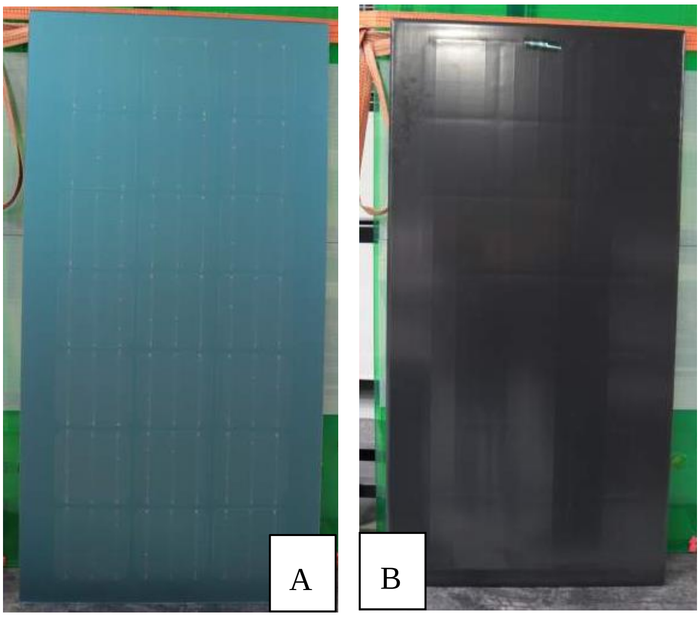


Figure 3.15 Module 21.4.Backsheet.1. of 1245 mm x 635 mm. A) Front view. B) Rear view.

No imperfection was detected on this sample.

3.15.2 a-Si PV glass

Figure 3.16 shows a triple laminated a-Si Module A.3.3,2.3.1. of 600 mm x 350 mm.

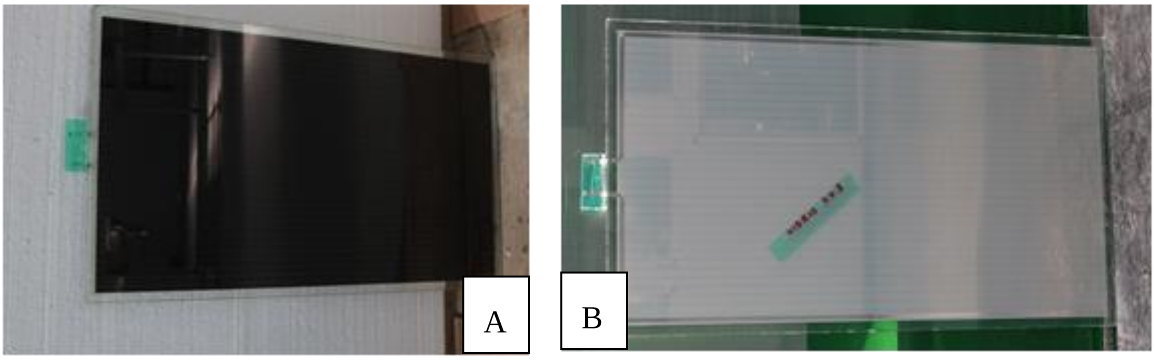


Figure 3.16 Module A.3.3,2.3.1. of 600 mm x 350 mm. A) Front view. B) Rear view.

No imperfection was detected on this sample.

Figure 3.17 shows a triple laminated a-Si Module A.2.3,2.2.1. of 600 mm x 350 mm.

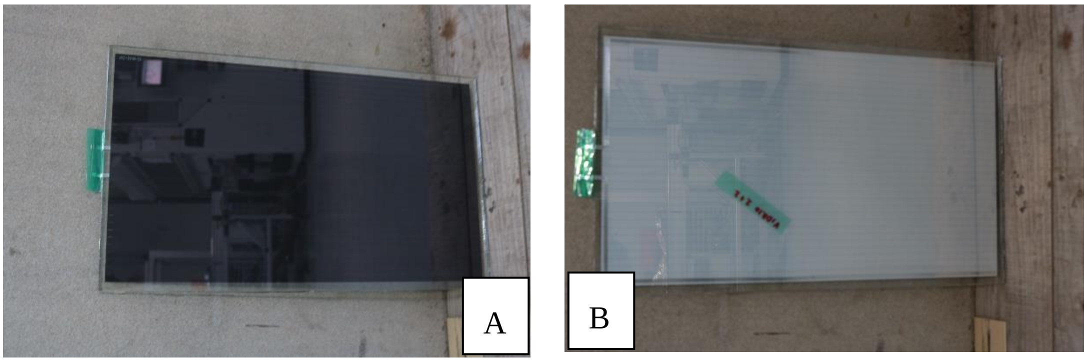


Figure 3.17 Module A.2.3,2.2.1. of 600 mm x 350 mm. A) Front view. B) Rear view.

Figure 3.18 shows a detailed view of Module A.2.3,2.2.1. of 600mm x 350 mm.

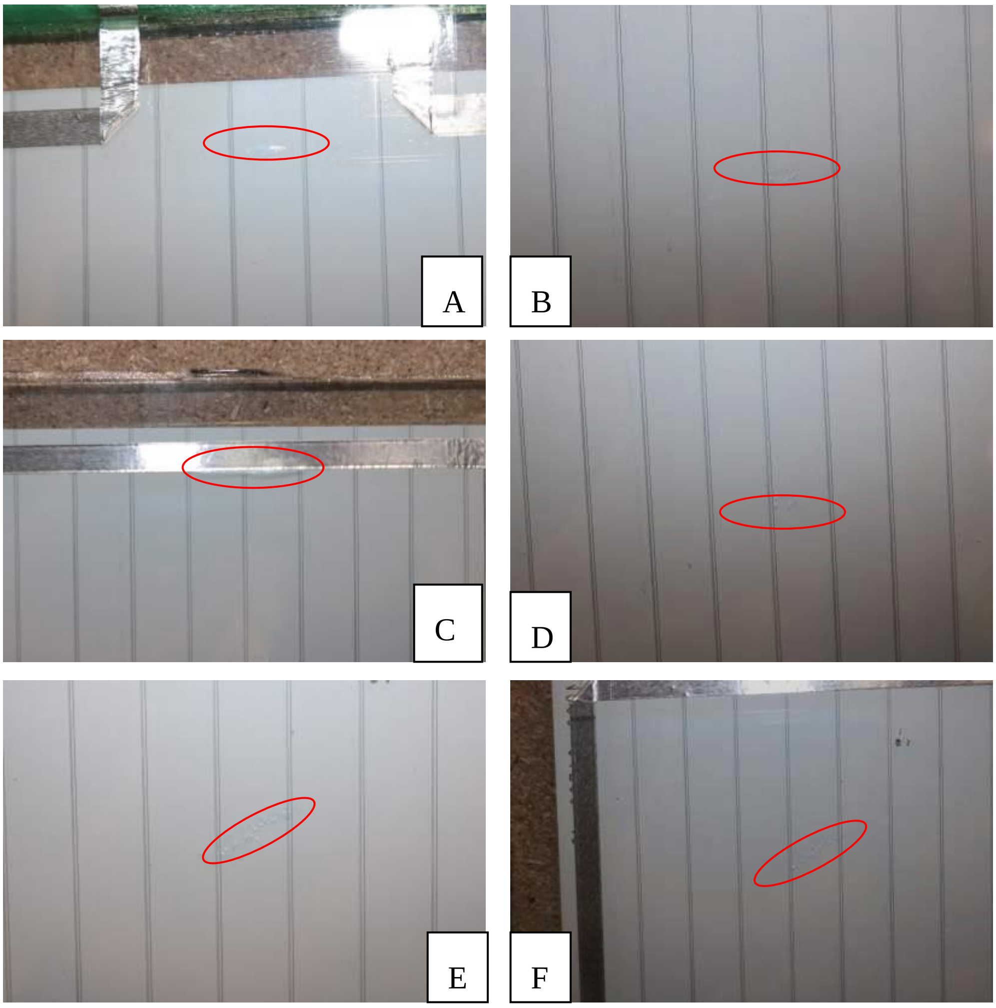


Figure 3.18 Detailed view of the Module A.2.3.2.2.1. A) B) C) D) E) F) Red circles show defects (bubbles) found in the rear of the sample.

Figure 3.19 shows a detailed view of Module A.2.3.2.1. of 600 mm x 350 mm, which has an orange PVB encapsulant.

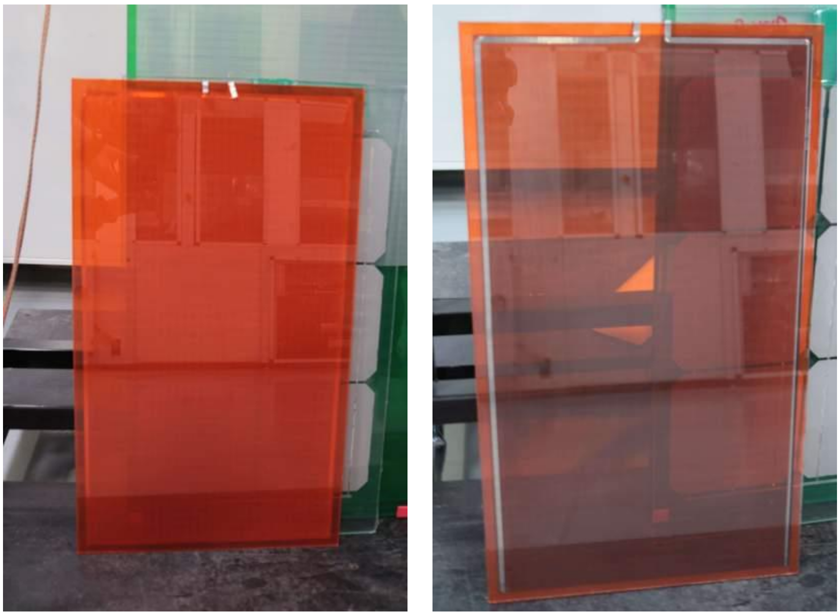


Figure 3.19 Module A.2.3.2.1. of 600 mm x 350 mm. A) Front view. B) Rear view.

No imperfection was detected on this sample.

3.16 Results analysis

The samples' results were very positive. The bubbles that appeared in some samples can be explained by the existence of problems during the optimization of lamination process's recipe. It happened as there were applied lamination receipts used with modules that had distinct configurations. The bubbles were caused by an insufficient vacuum level.

4 Plug & play framing solutions for BIPV ventilated façades

4.1 Concept of Plug & Play

The idea behind plug & play ventilated façades' framing solutions is having a quick and easy installation, using prefabricated modular solutions, for example, and also easily replace individual modules. These solutions are particularly interesting since they make installation time much shorter as well as enable the replacement of individual PV modules without moving the surrounding ones or easily changing the entire façade for aesthetic purposes. Moreover, installation costs would be reduced and so payback time. These solutions also require the use of lightweight materials, so that they are easily transported, placed and removed. This explains the importance of designing lightweight BIPV solutions, presented on the previous chapter.

Figure 4.1 shows the plug & play concept applied to electronic devices and curtain wall solutions. Although many commercial solutions of plug & play curtain walls are already available, that is not the case of ventilated facades, which usually need a structural framing as well as highly complex structures, and consequently have a long installation time [79].

Figure 4.1 The plug & play concept. A) On portable music player. B) On curtain walls.

The following subchapters present framing solutions for ventilated façades that approximate to the plug & play concept. The solutions found could be used as the framing of the lightweight BIPV solutions obtained in the previous chapter.

4.2 Possible solutions

4.2.1 TRIMO® Qbiss One Wall System

This solution has both prefabricated modules and the ability of easily removing individual modules in case of damage, without practically affecting the surrounding ones. Figure 4.2 shows this ventilated façade solution and Figure 4.3 presents two different options for the replacement of individual modules. Figure 4.4 shows some technical data of the mentioned solution. It is important to mention that the BIPV laminated glass would have to be fixed to the modules by a sealant glazing system.

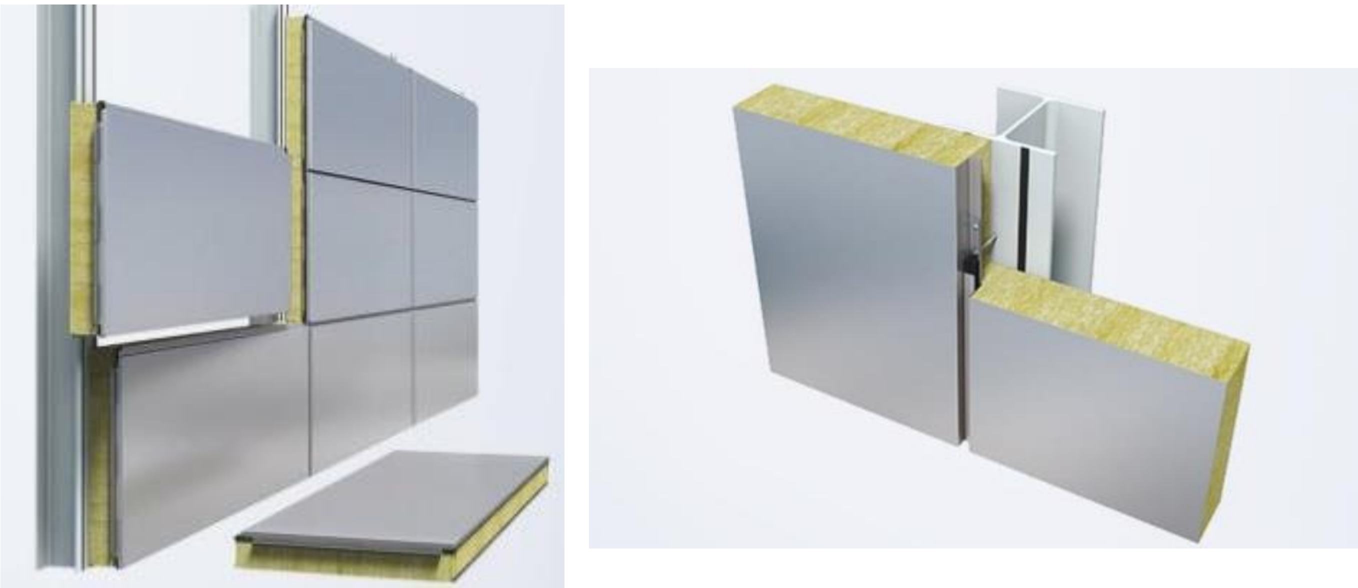


Figure 4.2 TRIMO® Qbiss one wall system [80].

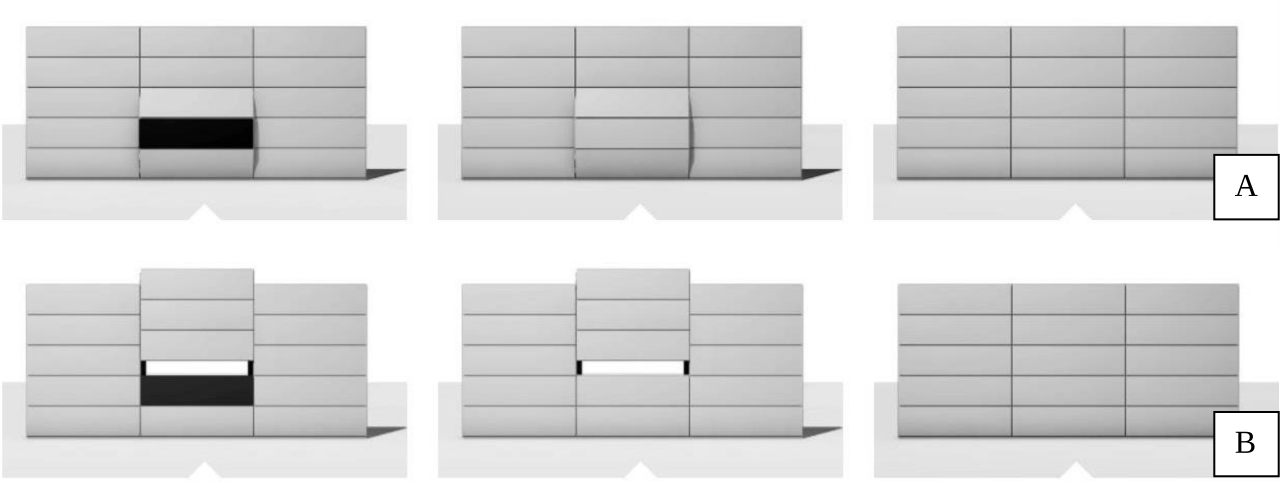


Figure 4.3 Different options for the replacement of individual modules. A) By "tilting upper and lower neighbouring elements outwards". B) By taking out the modules "placed above the damaged one". C) By painting the element [80].

Thickness (S)	**80, 100, 120, 133, 150, 172, 200, 240 mm**
Element width (M)	standard 1000 mm non-standardized widths available between 600 -1200 mm
Element length (R):	530 - 6500 mm
External surface (side A)	smooth
Core	mineral wool

Figure 4.4 Technical data of Qbiss one wall system [81].

4.2.2 Corian® pre-fabricated ventilated façade

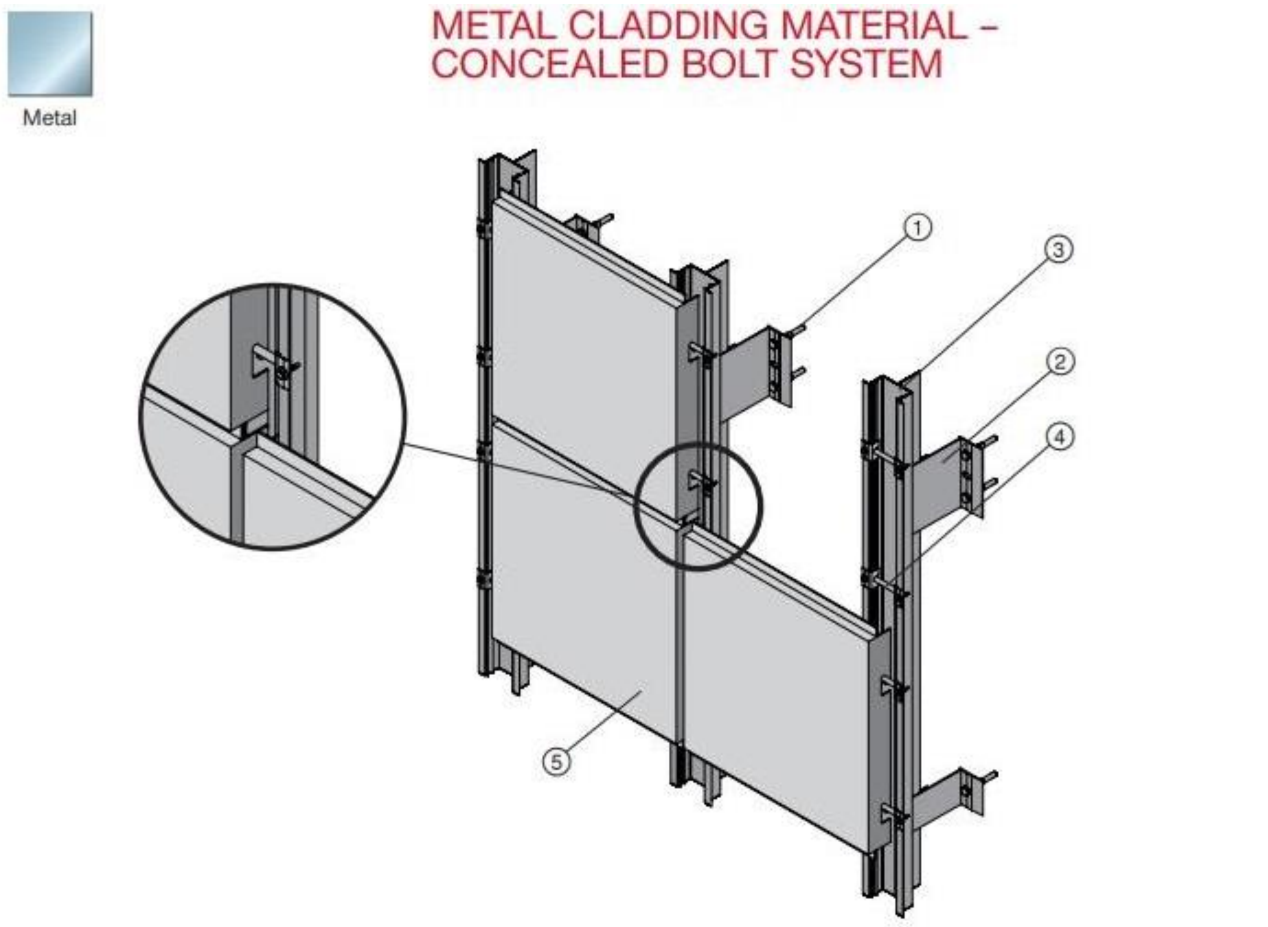
Figure 4.5 shows a prefabricated modular ventilated façade BIPV solution that was done for the project "Solar Decathlon Europe 2010". This solution satisfies the plug & play concept, since the prefabricated modules make installation times much shorter. Each module (1.85 m x 7.80 m) needed three bearing points, which were on a "sub-structure of four light steel adjustable columns fixed onto a steel plate". Moreover, the modules are fixed to the framing system by an elastomeric and waterproof band. The same happens with the PV glass, which is fixed to the module by a sealant glazing system [82].

Figure 4.5 Corian® pre-fabricated ventilated façade with Onyx Solar PV glass [83].

4.2.3 HILTI® - Metal Cladding Material – Concealed Bolt System + ETEM® - Aluminium ventilated facade / composite / sheet BRAVO W

This solution combines a very simple framing structure and plug & play aluminium/composite ventilated façade modules, where the lightweight BIPV should be applied using a sealant glazing system. Figure 4.6 shows HILTI® framing structure with a metal sheet and Figure 4.7 shows the different components provided by HILTI® in this system.

Figure 4.6 Framing structure of HILTI® metal cladding material – concealed bolt system [84].



Bill of materials

Reference	Description	Supplier
①	**Bracket fastening**	**Hilti**
②	**Bracket**	**Hilti**
③	**Profile**	**Hilti**
④	**Bolt system**	**Hilti**
⑤	**Metal sheet**	**Others**

Figure 4.7 Framing components of HILTI® metal cladding material – concealed bolt system [47].

The metal/composite sheets would be provided by ETEM®, specifically the BRAVO W product, which is shown on Figure 4.8. It is important to mention that the BIPV laminated glass would have to be fixed to the modules by a sealant glazing system. It should be discussed with ETEM® if the modules can be cut in the middle and so be suitable for ventilated façades where some transparency degree is required.

Figure 4.8 ETEM® Aluminum ventilated facade / composite / sheet BRAVO W.

4.2.4 Sto – StoVentec® ARTline Invisible

This solution of StoVentec® can be considered a plug & play product, because although it needs a framing structure, it seems it can be easily put and removed. It also has a quick and weather independent installation [85]. Figure 4.9 shows a picture of the referred product.

Figure 4.9 StoVentec® ARTline Invisible product [85].

4.2.5 BENDHEIM® - Wall-F Compression Fitting for Glass Cladding & Rainscreen Systems

The BENDHEIM® solution demands a framing structure, as it is possible to see in Figure 4.10. It makes possible the replacement of individual BIPV modules in less than one minute and “without deglazing surrounding panels” [86, 87].

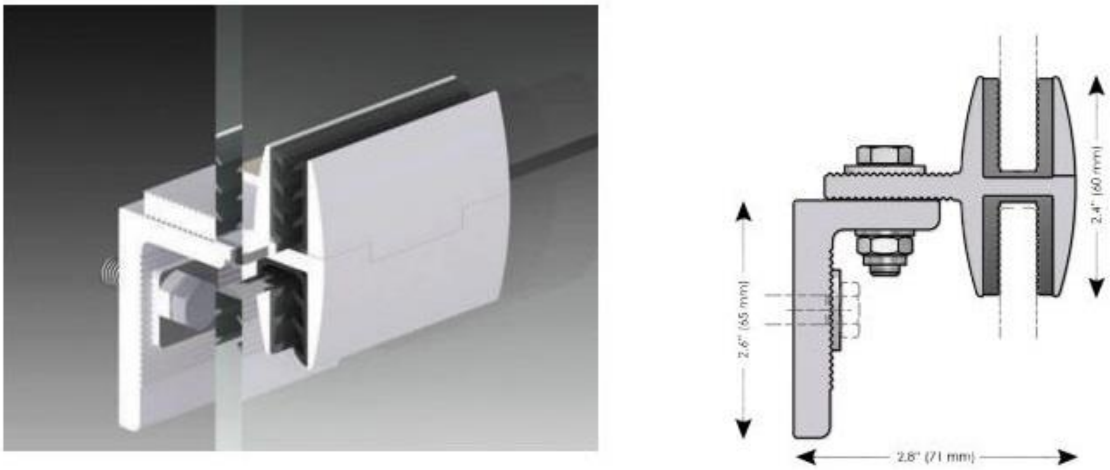


Figure 4.10 BENDHEIM® - Wall-F Compression Fitting for Glass Cladding & Rainscreen Systems [88].

4.2.6 Sierragres® Ceramic Block with Ventilated Facade Supports

As Figure 4.11 shows, this system is composed by two basic components: clinker blocks and an exterior façade cladding, which can be PV modules. The main advantages of this system are the fact that it does not need any metallic framing and that individual modules can be easily put and removed [89].

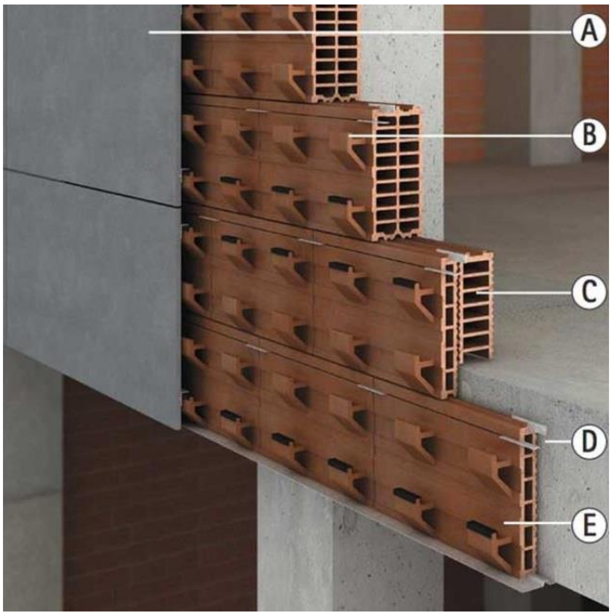


Figure 4.11 Ventilated façade system of Sierragres®. A - Exterior façade cladding. "B – Base element with integral ceramic support. C – Infill element for the tile slip. D – Plastic strap. E – Hollow clay tile slip with integral support" [89].

4.2.7 SAP ventilated façade solution

This ventilated façade's framing is in aluminium. The width of the modules can be from 250 mm to 500 mm and length from 350 mm to 10 m. Figure 4.12 shows how the modules can be installed both upwards and downwards and Figure 4.13 shows how individual modules can be demounted. It is important to mention that the PV glass would have to be fixed to the modules by a sealant glazing system.

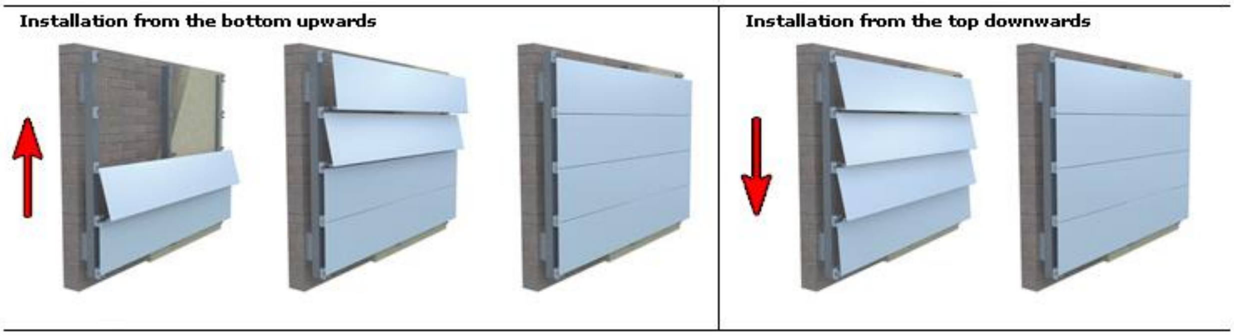


Figure 4.12 SAP ventilated façade solution installation from upwards and downwards [90].

Figure 4.13 Demounting of individual modules of SAP® ventilated façade [91].

5 Design Of a GIPV

The main objective of this chapter is to design a GIPV capable of producing enough energy for self-consumption operation. It also aims to demonstrate the technical, economic, environmental and energetic viability of GIPV solutions. This work is part of a R&D regional project *Invernadero Fotovoltaico-es* and so it has many specific requirements [92].

For comparison purposes, the GIPV addressed throughout this project is divided in two parts by a transparent wall. Each area has an access door and an area of approximately 15 m^2. In one part of the GIPV, all the walls and roof have semi-transparent modular PV glasses. On the other one, the building envelope has conventional clear glasses.

For aesthetic and light homogeneity purposes, PV glass based on a-Si thin film technology is going to be used, with some transparency degree. Onyx Solar provides commercially a-Si PV glass, from 10% to 30% transparency degree.

One of the objectives of the project is to find the most economical solution, to be competitive in the global market. For that reason, the most affordable PV glass of Onyx Solar is used, which is a double laminated (3.2 mm + 4 mm) a-Si PV glass, 1245 mm x 635 mm. For the same reason, the BIPV system should be grid connected and preferably with no batteries.

The GIPV is going to be placed in Soria (Latitude: º41.8, Longitude: º-2.6), which is located in the northeast of Spain, and so the greenhouse crop production should be adapted to the climate of Soria. Figure 5.1 shows the map of Spain.

Figure 5.1 Map of Spain.

5.1 Soria's climate, type of crop production and PV modules

5.1.1 Soria's climate

As it was mentioned before, the GIPV is going to be located in Soria and so it is necessary to consider the climate of this city. Soria has an Oceanic Climate (Cfb), according to Köppen climate classification, which means mild temperate, fully humid and warm summer [93]. Figure 5.2 shows other European countries with the same climate classification.

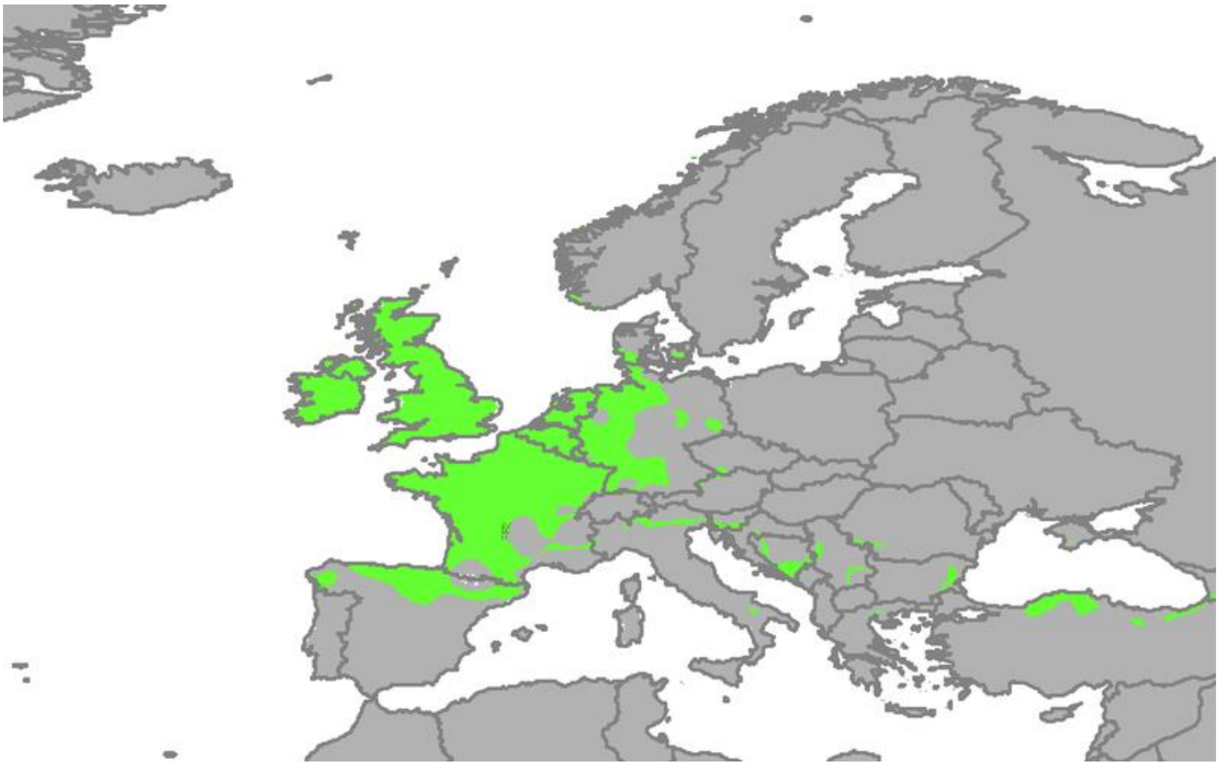


Figure 5.2 European countries with ocean climate Cfb in green [94].

5.1.1.1 Climate data of Soria

Table 5.1 shows average climatic data of Soria, from 1981 to 2010.

Table 5.1 Average annual climate data of Soria, from 1981 to 2010 [95]

Month	T	TM	Tm	R	H	DR	DN	DT	DF	DH	DD	I
January	3.2	7.7	-1.3	37	77	7.1	5.0	0.0	4.0	19.7	4.8	138
February	4.3	9.6	-1.0	36	71	6.4	5.1	0.1	1.9	17.1	4.6	158
March	7.1	13.2	1.0	30	63	5.8	3.0	0.3	1.0	12.0	5.1	202
April	8.7	14.6	2.8	55	64	8.6	2.5	1.3	1.0	5.9	2.8	208
May	12.5	18.7	6.2	67	63	9.6	0.4	4.4	1.1	0.8	2.0	244
June	17.2	24.6	9.9	40	56	5.6	0.1	4.4	0.6	0.1	4.7	293
July	20.5	28.7	12.4	30	50	3.7	0.0	4.1	0.1	0.0	9.0	339
August	20.3	28.3	12.2	30	52	3.8	0.0	4.4	0.2	0.0	7.4	313
September	16.4	23.6	9.3	33	60	5.2	0.0	2.9	0.9	0.1	5.4	233
October	11.6	17.4	5.8	55	70	7.7	0.1	0.7	2.1	1.5	3.6	180
November	6.7	11.5	1.9	50	75	7.6	2.1	0.1	2.7	9.2	4.9	143
December	4.0	8.4	-0.4	50	78	7.7	3.9	0.1	4.7	17.4	5.3	126
Year	11.0	17.2	4.9	512	65	78.8	21.4	23.2	20.3	83.3	60.6	2571

Key

T Monthly/Annual average temperatures (°C)
TM Monthly/Annual average of maximum daily temperatures (°C)
Tm Monthly/Annual average of minimum daily temperatures (°C)
R Monthly/Annual average rainfall (mm)
H Average relative humidity (%)
DR Monthly/Annual average number of rainfall days equal or greater to 1mm
DN Monthly/Annual average number of snow days
DT Monthly/Annual average number of stormy days
DF Monthly/Annual average number of foggy days
DH Monthly/Annual average number of frosty days
DD Monthly/Annual average number of cloudless days
I Monthly/Annual average number of hours of sunshine

5.1.1.2 Sunshine hours

Table 5.2 and Table 5.3 show the number of daylight hours on the 15th of each month in Soria and monthly average sunshine hours per day.

Table 5.2 Average daylight hours per month in Soria [94]

Date	Duration of daylight
Monday, 15 de January	9h 30min 8s
Thursday, 15 de February	10h 38min 42s
Thursday, 15 de March	11h 55min 51s
Monday, 16 de April	13h 24min 33s
Tuesday, 15 de May	14h 33min 35s
Friday, 15 de June	15h 12min 0s
Sunday, 15 de July	14h 54min 26s
Wednesday, 15 de August	13h 51min 16s
Saturday, 15 de September	12h 28min 56s
Monday, 15 de October	11h 6min 3s
Thursday, 15 de November	9h 49min 42s
Saturday, 15 de December	9h 9min 50s

Table 5.3 Monthly average sunshine hours per day in Soria [95]

Month	Average sunshine hours per day
January	4
February	6
March	7
April	7
May	8
June	10
July	11
August	10
September	8
October	6
November	5
December	4

5.1.1.3 Photosynthetically active radiation (PAR)

As previously mentioned, plants need minimum levels of PAR to grow. Consequently, it is important to know Soria monthly average daily global irradiation and, even more important, the radiation that would reach the GIPV, depending on the transparency degree of the chosen PV glasses. In that way, it is possible to select both the type of crop production and the type of PV glass that best fit the GIPV located in Soria. Table 5.4 shows Soria monthly average daily global irradiation as well as PAR, which represents 45% of the sunlight irradiation [96]. Table 5.4 also presents the values of PAR that would reach the inside of the GIPV depending on the transparency degree of the selected PV glasses.

Table 5.4 Monthly average daily global radiation, PAR radiation with PV glasses with 30%, 20% and 10% of transparency degree [97]

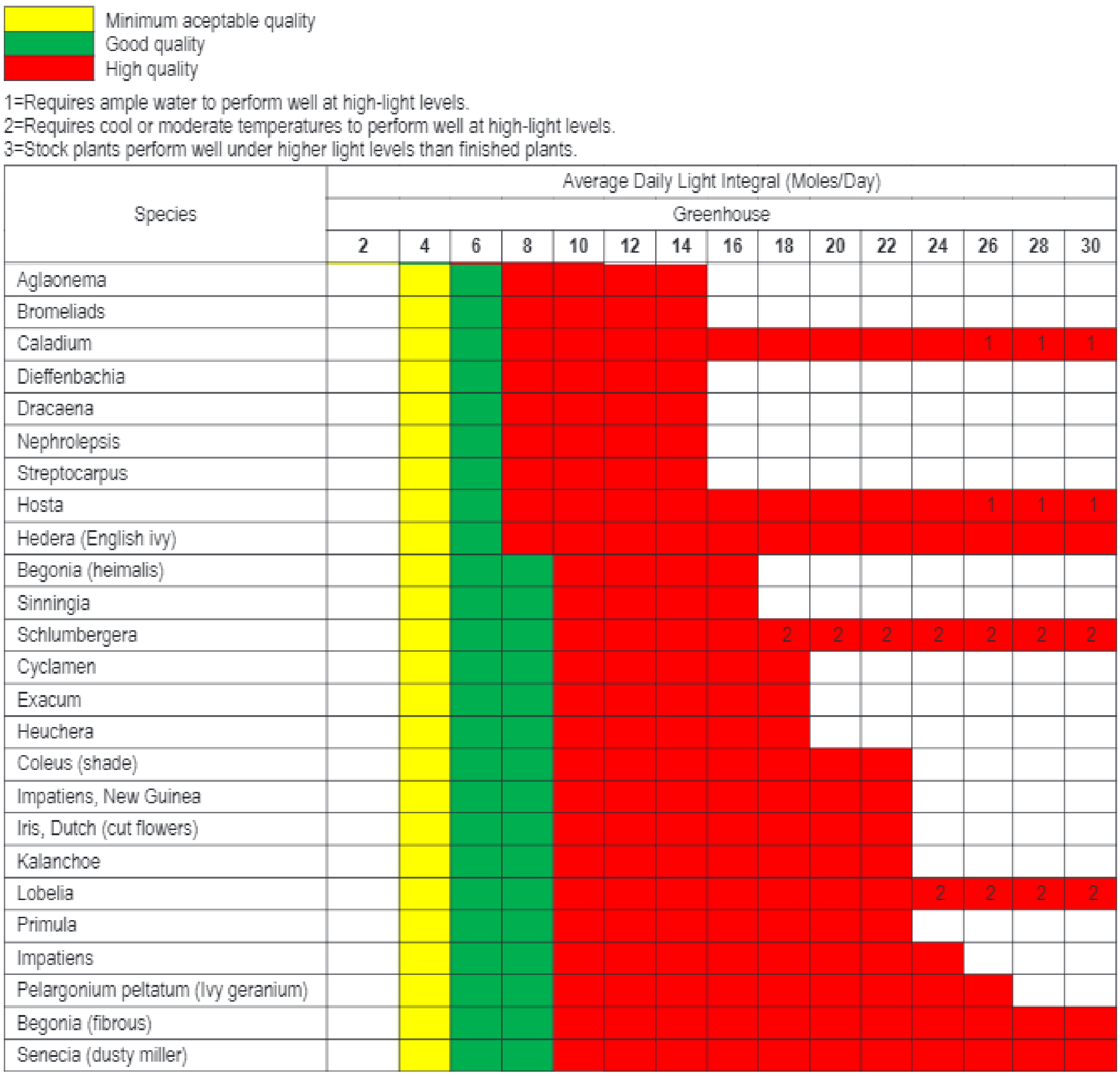
Month	**Monthly average daily global irradiation [mol/day/m^2]**	**Monthly average PAR [mol/day/m^2]**
January	26.0	11.7
February	40.2	18.1
March	60.0	27.0
April	75.8	34.1
May	88.4	39.8
June	104.9	47.2
July	108.9	49.0
August	93.1	41.9
September	64.7	29.1
October	41.1	18.5
November	29.2	13.1
December	22.9	10.3

Month	**30 % Transparency [mol/day/m^2]**	**20 % Transparency [mol/day/m^2]**	**10 % Transparency [mol/day/m^2]**
January	3.51	2.3	1.2
February	5.43	3.6	1.8
March	8.09	5.4	2.7
April	10.23	6.8	3.4
May	11.93	8.0	4.0
June	14.17	9.4	4.7
July	14.70	9.8	4.9
August	12.57	8.4	4.2
September	8.74	5.8	2.9
October	5.54	3.7	1.8
November	3.94	2.6	1.3
December	3.09	2.1	1.0

5.1.1.4 Plants PAR needs vs Soria PAR irradiation

According to experts, fruit production requires much more PAR than ornamental flower crops. Furthermore, crops that do not receive 12 moles of light from November through February produce a minimal yield of fruit. With low levels of light and photosynthetic activity, the plants cannot produce significant amounts of fruit [98]. Consequently, comparing the above mentioned values with those shown in Table 5.4, it is possible to conclude that no fruit can be produced in a GIPV in Soria with PV glasses with 30%, 20% or 10% of transparency degree. As a result, plants that require minimum PAR daily radiation levels of around 4 [mol/day/m^2] should be selected to grow in the GIPV with PV glasses with 30% transparency degree. Another option would be picking up plants that require minimum PAR daily levels of around 2 to 3 [mol/day/m2] to grow in a GIPV with PV modules with a 20% transparency degree. Tables 5.5 and 5.6 show the type of plants adequate to each PV glass transparency degree.

Table 5.5 Types of plants adequate for a PV glass with 30% transparency degree [74]



Minimum aceptable quality
Good quality
High quality

1=Requires ample water to perform well at high-light levels.
2=Requires cool or moderate temperatures to perform well at high-light levels.
3=Stock plants perform well under higher light levels than finished plants.

Species	Average Daily Light Integral (Moles/Day)														
	Greenhouse														
	2	4	6	8	10	12	14	16	18	20	22	24	26	28	30
Aglaonema															
Bromeliads															
Caladium													1	1	1
Dieffenbachia															
Dracaena															
Nephrolepsis															
Streptocarpus															
Hosta													1	1	1
Hedera (English ivy)															
Begonia (heimalis)															
Sinningia															
Schlumbergera									2	2	2	2	2	2	2
Cyclamen															
Exacum															
Heuchera															
Coleus (shade)															
Impatiens, New Guinea															
Iris, Dutch (cut flowers)															
Kalanchoe															
Lobelia												2	2	2	2
Primula															
Impatiens															
Pelargonium peltatum (Ivy geranium)															
Begonia (fibrous)															
Senecia (dusty miller)															

Table 5.6 Types of plants adequate for a PV glass with 20% transparency degree [91]

Yellow: Minimum aceptable quality
Green: Good quality
Red: High quality

1=Requires ample water to perform well at high-light levels.
2=Requires cool or moderate temperatures to perform well at high-light levels.
3=Stock plants perform well under higher light levels than finished plants.

Species	Average Daily Light Integral (Moles/Day)														
	Greenhouse														
	2	4	6	8	10	12	14	16	18	20	22	24	26	28	30
Ferns (Pteris Adiantum)	Yellow	Green	Red	Red	Red										
Maranta	Yellow	Green	Red	Red	Red										
Phalaenopsis (orchid)	Yellow	Green	Red	Red	Red										
Saintpaulia	Yellow	Green	Red	Red	Red										
Spathiphyllum	Yellow	Green	Red	Red	Red										
Forced hyacinth	Yellow	Green	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red
Forced narcissus	Yellow	Green	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red
Forced tulip	Yellow	Green	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red

Choosing PV glass with 20% or less transparency degree would excessively limit the type of plants that could be produced. Consequently, PV glass with 30% transparency degree is selected.

5.2 Configuration and energy output

5.2.1 Predesign

5.2.1.1 <u>Configuration</u>

As previously mentioned, the orientation of the greenhouse to produce pot plants is indifferent, since it is a short type of crop production. Furthermore, the best orientation for PV glass power production is south, followed by west [99]. Consequently, the greenhouse is going to be south oriented.

Additionally, as already mentioned, at least 25% of the roof should have open areas and so the upper side of the roof should have a vent system. According to Onyx's experts, the vent system should not open more than 300 mm, which is half the length of the cables, corresponding to an opening angle of 14º. Since there are "no effects of the angle of aperture of the vents on the ventilation efficiency" [100], the upper half the roof area has a vent system.

For a correct comparison between the side of the greenhouse with PV glass and the side with conventional clear glass, and for a maximum electricity production, the GIPV is going to be designed with a mono-pitched roof, south oriented and divided in equal parts with approximately 15 m^2 each by plastic transparent wall, using materials such as polycarbonate. Each part should have an independent door.

In general, the tilt of the greenhouse's roof for maximum electricity production over the year is given by subtracting to the latitude 10º. Since Soria's latitude is 42°, the ideal tilt is 32º.

It is possible to conclude that the GIPV should have the following characteristics in terms of configuration:

- Total surface area of approximately 30 m^2;

- South oriented;
- Mono-pitched roof;
- Roof with a tilt of 32º.

Figure 5.3 shows the preliminary drawing of the GIPV, with the above mentioned characteristics and a total surface area of 32.2 m^2 with a roof tilt of 32º.

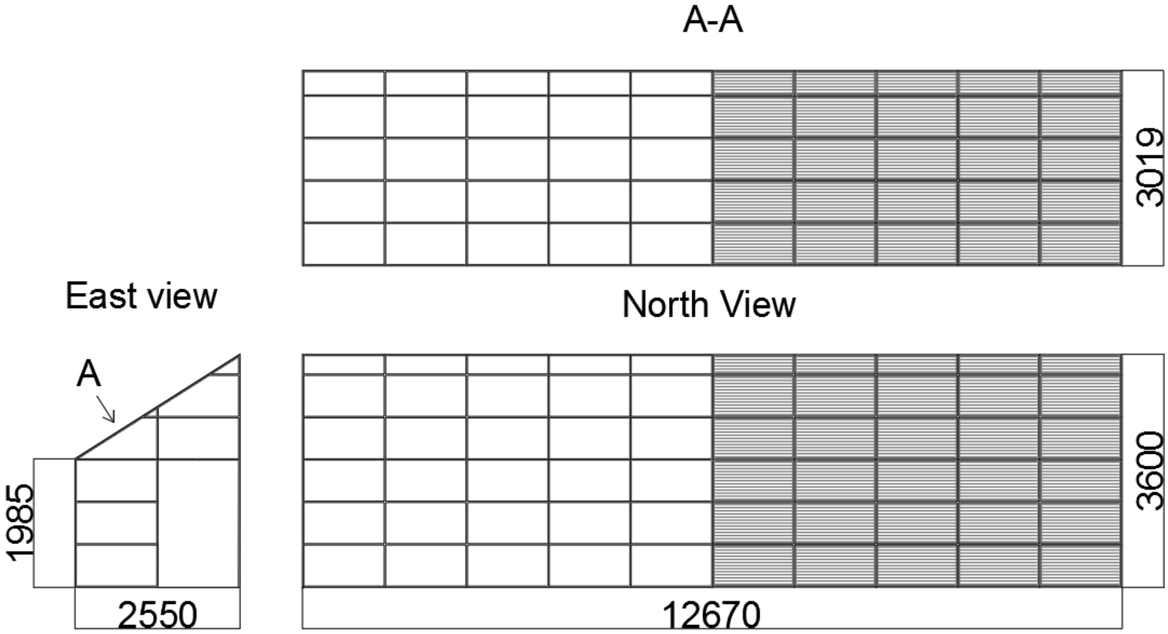


Figure 5.3 Preliminary drawing of the GIPV. The left part represents the area with conventional glass. The right part represents the area with PV modules.

Figure 5.4 shows the 3D drawing of the GIPV.

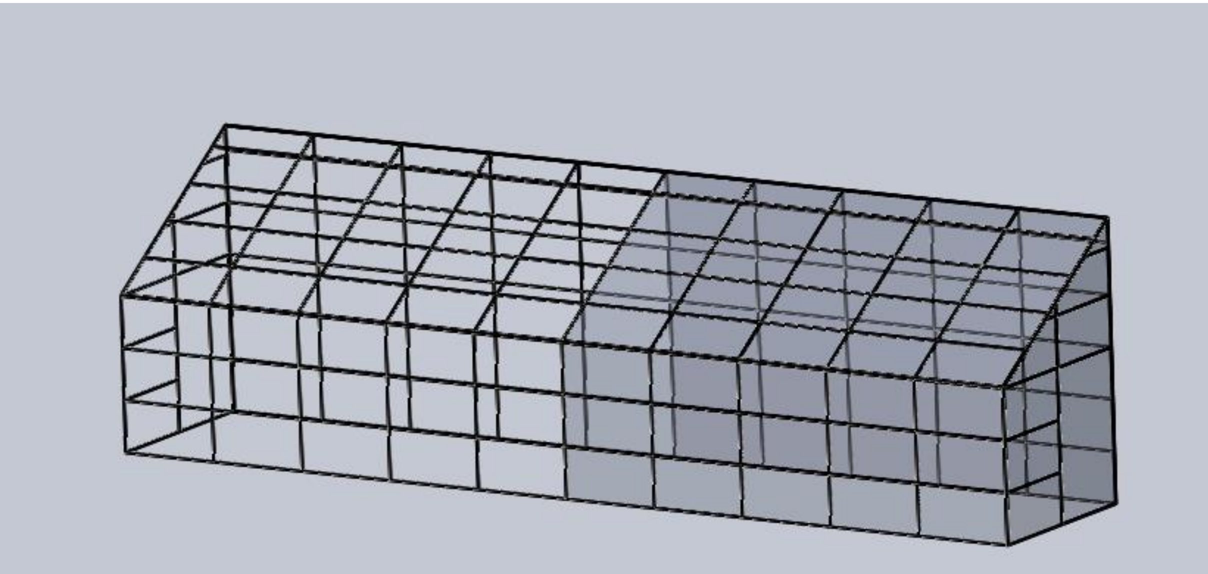


Figure 5.4 Preliminary 3D drawing of GIPV. The left part represents the area with conventional glass. The right part represents the area with PV modules.

Electricity output of the PV system

First, the electricity production is calculated, considering that only the south and north wall, as well as the roof, are connected to the PV system.

Table 5.8 shows the total nominal peak power per surface, according to the technical data of the PV glass shown in Table 5.7 and the dimensions of the GIPV given by Figure 5.3.

Table 5.7 Electrical data of the selected PV glass [55]

PHOTOVOLTAIC GLASS 1245 x 635 mm		034_N-12450635-_ _-_ ref. 00	ref. 10	ref. 20	ref. 30
Electrical data test conditions (STC)		DARK (0%)	M VISION (10%)	L VISION (20%)	XL VISION (30%)
Nominal peak power	P_{mpp}(Wp)	46	32	27	22
Open-circuit voltage	V_{oc}(V)	50	50	50	50
Short-circuit current	I_{sc}(A)	1,50	1,15	0,97	0,77
Voltage at nominal power	V_{mpp}(V)	34	34	34	34
Current at nominal power	I_{mpp}(A)	1,34	0,93	0,79	0,65
Power tolerance not to exceed	%	±5	±5	±5	±5

STC: 1000 w/m², AM 1.5 and a cell temperature of 25°C, stabilized module state.

Table 5.8 Nominal peak power generated per surface

North facing façade	South facing façade	Roof
550 Wp	330 Wp	440 Wp

For economic reasons, it was defined at the beginning that the PV system would be grid connected, if possible, without any storage. However, the inverters adequate to a-Si technology available on the market only work with levels of generated power higher than 0.5 kWp. In addition, only three surfaces generate power: South and North wall as well as roof. As it is very difficult to find inverters which can connect with three entrances, each façade should have its own inverter, making impossible to achieve the minimum power to have a grid connected PV system with the configuration shown in Figure 5.3.

There are two possible alternatives to solve this problem. One is to use a standalone PV system with battery, which significantly increases the cost of the PV system, due to the high cost of batteries. Another alternative would be to obtain the minimum dimensions of the GIPV so that it can be connected to the grid. The two alternatives are developed in the following sections.

Standalone PV system

As referred in the second chapter, the standalone PV system is composed by the PV glass, a charge controller, to adapt the tension given by the PV glasses to the working tension of the electrical devices that work with DC current, an inverter, to convert the DC current given by the PV glasses to the AC current needed by some of the electrical devices, and battery. Figure 5.5 shows a scheme of a common standalone PV system.

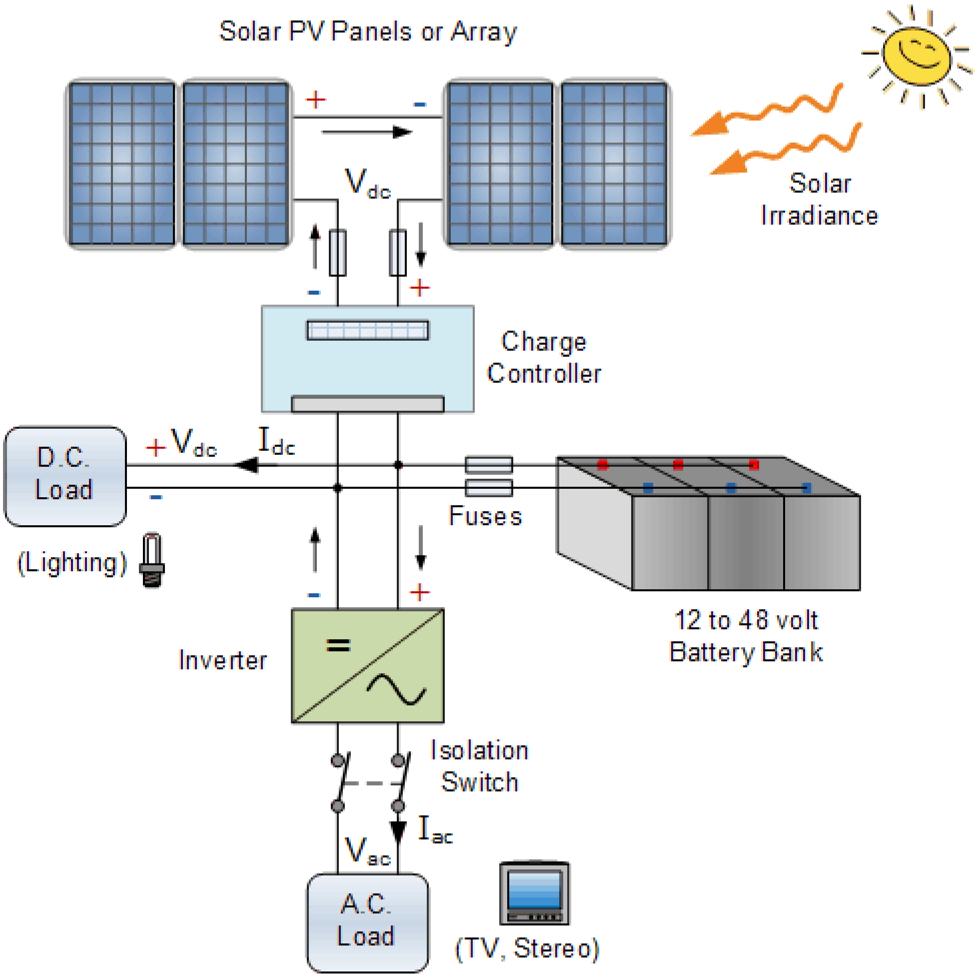


Figure 5.5 Common composition of a standalone PV system [101].

In order to design a standalone PV system, it is necessary to take into account the total electricity consumption of the GIPV. For a very profound analysis, it would have to be considered not only the monitoring system, but also a complete greenhouse heat transfer model. However, all the available research was done for commercial greenhouses with much larger dimensions than the case of study. In addition, a significant part of the consumption applicable to multi-span greenhouses is not economically viable for little greenhouses, neither the consumption varies in a proportional way. Consequently, it was decided to make a rough estimation of the electricity consumption of the greenhouse. For the heating system, an electrical one would represent a very significant power consumption and as the electric boilers are less efficient when compared to gas boilers, it was considered that a gas boiler would be used and, consequently, it was not necessary to take into account the heating system when selecting the most adequate battery for the PV system. Considering all the above mentioned, Table 5.9 shows a rough estimation of the daily consumption of the most significant electrical devices of the greenhouse, in terms of electric energy consumption. This estimation was done considering that glass greenhouses are highly technological, according to what was explained in chapter 2, and so the case study should have active heating and cooling as well as an automatic monitoring system.

Table 5.9 Estimation of the electric consumption of each electrical device, per day [102-108]

Electrical device	Energy per day [Wh]
3 LED lamps (2 hours per day)	180
1 PC (2 hours per day)	800
Ventilation (3 hours per day)	360
Water pump (1 hours per day)	800
Total (per day)	2140

Table 5.10 shows the output energy of the mono pitched GIPV, obtained using the software *PVsyst*.

Table 5.10 Output electricity of the PV system at the end of the array

Month	North wall [19.76 m^2]	South wall [11.86 m^2]	Roof [15.81 m^2]	Total	
	E_{Array} [kWh]	E_{Array} [kWh]	E_{Array} [kWh]	E_{Array} [kWh]	E_{Array} [kWh/day]
January	11.74	20.21	22.81	54.76	1.77
February	14.7	25.57	29.59	69.86	2.38
March	24.47	34.28	47.84	106.59	3.32
April	23	43.79	49.15	115.94	3.74
May	27.03	48.56	57.98	133.57	4.19
June	26.93	52.53	61.45	140.91	4.59
July	28.87	53.45	63.81	146.13	4.63
August	26.42	47.99	56.98	131.39	4.15
September	22.52	37.67	45.98	106.17	3.44
October	16.29	25.28	32.61	74.18	2.29
November	11.64	17.39	22.97	52	1.64
December	10	18.1	19.19	47.29	1.43
Year	243.6	424.82	510.36	1178.78	3.13

As Table 5.10 shows, the daily average output energy of the PV system at the end of the array is 3.13 kWh, which is higher than the total consumption of energy per day, 2.140 kWh. Consequently, the greenhouse's configuration shown in Figure 5.3 is considered to match the standalone PV system. The capacity of the battery, the adequate inverter and charge controller are now going to be calculated.

As Table 5.9 shows, the total electricity consumption per day is 2140 Wh. Considering a system with an efficiency of 80%, the electricity needed per day is 2675 Wh/day. To choose the most adequate batteries, this value is multiplied by the required number of days of autonomy, which is usually considered as 4, and per discharge (expressed as a percentage of maximum capacity), which is usually 50%. Consequently, the total capacity of the battery is given by Equation 5.1.

$$\frac{2675\ Wh * 4\ days}{0.5} = 21400\ Wh \tag{5.1}$$

The capacity of the batteries is usually given in Ah. As the tension of the batteries is usually 12 V, Equation 5.2 gives the capacity of the battery in Ah.

$$\frac{21400}{12} = 1783\ Ah \tag{5.2}$$

Having the necessary capacity of the battery, the number of a-Si modules needed for the electricity consumption may be estimated. In that way, and since the number of PV glasses is defined by the requirements of the project, it is possible to confirm if the PV glasses of the GIPV are enough to satisfy the daily consumption. For that, the needed energy is divided by the nominal peak power of a PV glass and a shadow factor of 23%

This value must be divided by the average number of sunshine hours per day during the month with less sunshine hours, which are December and January, according to Table 5.3, with 4 sunshine hours, by the peak power of each module (22 kW) and by the shine factor. It is then obtained the number of PV glasses needed to power the considered electrical devices, by Equation 5.3.

$$\frac{2675}{22 * 0.77 * 4} = 40\ PV\ glasses \tag{5.3}$$

Since most of the PV glasses are not in the most favourable orientation, in particular the North and South walls, it is considered that the 60 active PV glasses generate not much more than the needed energy. Moreover, comparing the results of Table 5.9 with Table 5.10, it is concluded that only during the months of January, February and December the total production per day is less than the total consumption per day. As in very rare occasions all the electronic devices are working simultaneously, it is considered that the total power production per day is enough to satisfy self-consumption operation.

It is now necessary to select the battery, inverter and charge controllers. As it was already mentioned, the battery needs to have a capacity of 1783 Ah. For that reason, the OS 33P of Rolls® battery [109] was selected, with a capacity of 1883 Ah and a 20 hour rate. With respect to the charge controller, it is necessary to find an inverter that has the range of tension needed for each configuration. Table 5.11 presents the range of voltage needed for each number of PV glasses per string.

Table 5.11 V_{min} and V_{max} for each number of glasses connected in series

Number of modules connected in series	V_{min} [V]	$V_{máx}$ [V]
1	29	55
2	58	110
3	88	165
4	117	220
5	146	275
6	175	329

For that reason, two charge controllers TAROM MPPT 6000-M from steca® are selected, with the characteristics described in Table 5.12.

Table 5.12 STECA TAROM MPPT 6000-M charge controller [110]

	MPPT 6000-S / MPPT 6000-M
Characterisation of the operating performance	
System voltage	12 / 24 / 48 V
Nominal power	900 W / 1800 W / 3600 W
Max. DC-DC efficiency	99.4 % (Ubatt=48 V; Uin=70 V; P=0.65*Pnom)
European efficiency	96.6 % (Ubatt=24 V; Uin=30 V) 98.9 % (Ubatt=48 V; Uin=70 V)
European efficiency (weighted across all Ubatt and Uin)	96.4 %
Static MPP efficiency	99.9 % (DIN EN 50530)
Dynamic MPP efficiency	99.8 % (DIN EN 50530)
Weighted REW (Realistic Equally Weighted efficiency)	94.8 %
Own consumption	< 1 W
DC input side	
Min. MPP voltage / input	17 V / 34 V / 68 V
Max. MPP voltage / input	180 V
Min. Open circuit voltage solar module / input (at minimum operating temperature)	20 V / 40 V / 80 V
Max. Open circuit voltage solar module / input (at minimum operating temperature)	200 V
Module current	2 x 30 A / 1 x 60 A
Battery side	
Charge current	60 A
End-of-charge voltage	14.1 V / 28.2 V / 56.4 V
Boost charge voltage	14.4 V / 28.8 V / 57.6 V
Equalisation charge	15 V / 30 V / 60 V
Set battery type	liquid (adjustable via menu)
Operating conditions	
Ambient temperature	-25 °C ... +50 °C

Each charge controller has two Maximum Power Point trackers, which are algorithms that convert DC to DC converter and work by "taking DC input from PV module, changing it to AC and converting it back to a different DC voltage and current to exactly match the PV module to the battery" [111]. As the MPPT trackers work independently, one of them is going to be connected to the roof and south façade and the other is going to be connected to the North façade. As Table 5.12 shows, with this charge controller it is possible to connect until 3 modules in series.

To find the most adequate inverter it is necessary to calculate the total power consumption, which is 1410 W. Since the starting power of electronic devices are significantly higher than the nominal power, an inverter with a significantly higher power that the one calculated will be selected: Phoenix Inverter C12/2000 from victron energy®. Table 5.13 shows the characteristics of the inverter, which has a maximum power of 2000 W.

Table 5.13 Phoenix Inverter C12/2000 [112]

Phoenix Inverter	C12/1200 C24/1200	C12/1600 C24/1600	C12/2000 C24/2000	12/3000 24/3000 48/3000
Parallel and 3-phase operation	Yes			
INVERTER				
Input voltage range (V DC)	9[illegible] – 17V 19 – 33V 38 – 6[illegible]V			
Output	Output voltag[illegible] 230 VAC ±2% Frequency: [illegible]0 Hz ± 0,1% (1)			
Cont. output power at 25ºC (VA) (2)	1200	1600	2000	3000
Cont. output power at 25ºC (W)	1000	1300	1600	2400
Cont. output power at 40ºC (W)	900	1200	1450	2200
Cont. output power at 65ºC (W)	600	800	1000	1700
Peak power (W)	2400	3000	4000	6000
Max. efficiency 12/ 24 /48 V (%)	92 / 94 / 94	92 / 94 / 94	92 / 92	93 / 94 / 95
Zero load power 12 / 24 / 48 V (W)	8 / 10 / 12	8 / 10 / 12	9 / 11	20 / 20 / 25
Zero load power in AES mode (W)	5 / 8 / 10	5 / 8 / 10	7 / 9	15 / 15 / 20
Zero load power in Search mode (W)	2 / 3 / 4	2 / 3 / 4	3 / 4	8 / 10 / 12
GENERAL				
Programmable relay (3)	Yes			
Protection (4)	a - g			
VE.Bus communication port	For parallel and three phas[illegible] operation, remote monit[illegible]ing and system integration			
Remote on-off	Yes			
Common Characteristics	Operating temper[illegible]ture range: -40 to +65ºC (f[illegible]n assisted cooling) Hum[illegible]dity (non-condensing): ma[illegible] 95%			
ENCLOSURE				
Common Characteristics	Material & Colour: alu[illegible]nium (blue RAL 5012) P[illegible]tection category: IP 21			
Battery-connection	battery cables of 1.5 meter included		M8 bolts	2+2 M8
230 V AC-connection	G-ST18i plug		Spring-clamp	Screw te
Weight (kg)	10		12	18
Dimensions (hxwhd in mm)	375x214x110		520x255x125	362x258x218
STANDARDS				
Safety	EN 60335-1			
Emission Immunity	EN 55014-1 / EN 55014-2			

1) Can be adjusted to 60 Hz and to 240 V
2) Non-linear load, crest factor 3:1
3) Programmable relay that can a.o. be set for general alarm, DC under voltage or genset start/stop function.
AC rating: 230 V / 4 A
DC rating: 4 A up to 35 VDC, 1A up to 60VDC

4) Protection key:
a) output short circuit
b) overload
c) battery voltage too high
d) battery voltage too low
e) temperature too high
f) 230 V AC on inverter output
g) input voltage ripple too high

Once all the components were selected, the most adequate connection configuration of PV modules can be defined. With the objective of maximizing the number of PV modules connected, it was decided to connect two modules per series. Therefore, one of the modules of the North façade will not be connected.

Table 5.14 shows the electricity production of the PV system, considering the efficiency of both charge controller and inverter, which are, according to Table 5.12 and Table 5.13, 94.8% and 92%, respectively.

Table 5.14 Output electricity of the PV system

Month	North wall [18.97 m²]	South wall [11.86 m²]	Roof [15.81 m²]	Total	
	E_{Av}[kWh]	E_{Av} [kWh]	E_{Av} [kWh]	E_{Av} [kWh]	E_{Av} per day [kWh/day]
January	10.24	16.92	19.89	47.05	1.52
February	12.82	21.41	25.81	60.04	2.08
March	21.34	28.70	41.72	91.77	2.90
April	20.06	36.69	42.87	99.62	3.26
May	23.57	40.73	50.57	114.87	3.65
June	23.49	44.26	53.59	121.34	4.00
July	25.18	45.23	55.65	126.06	4.04
August	23.04	40.67	49.70	113.41	3.62
September	19.64	31.63	40.10	91.38	3.00
October	14.21	21.18	28.44	63.83	2.00
November	10.15	14.57	20.03	44.75	1.43
December	8.72	15.15	16.74	40.61	1.25
Year	212.46	357.15	445.12	1014.72	2.73

Having designed and obtained all the components for a standalone PV system, due to the small dimensions of the initially predefined areas of the BIPV, the minimum dimensions of the GIPV will be identified, so that it is possible to have a grid-connected PV system.

5.3 Minimum dimensions for a grid-connected GIPV system

To have a grid-connected GIPV system, the smallest greenhouse active façades for which there are inverters available are going to be designed. Figure 5.6 shows the minimum configuration for a grid-connected GIPV, which has a surface area of 51.7 m^2.

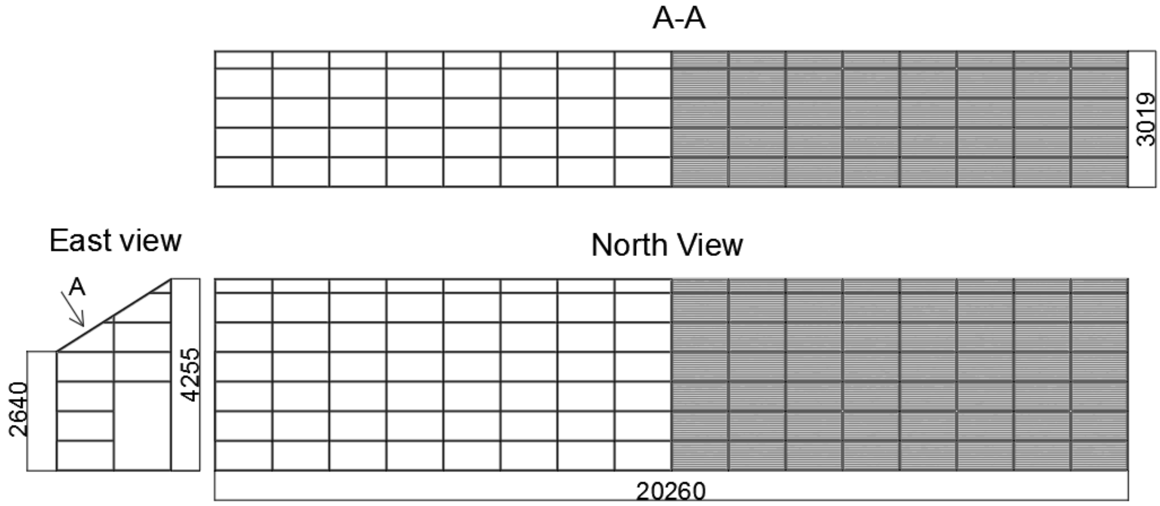


Figure 5.6 Drawing of the new configuration of the GIPV. The left part represents the area with conventional glass. The right part represents the area with PV modules.

Figure 5.7 shows the 3D drawing of the grid connected GIPV.

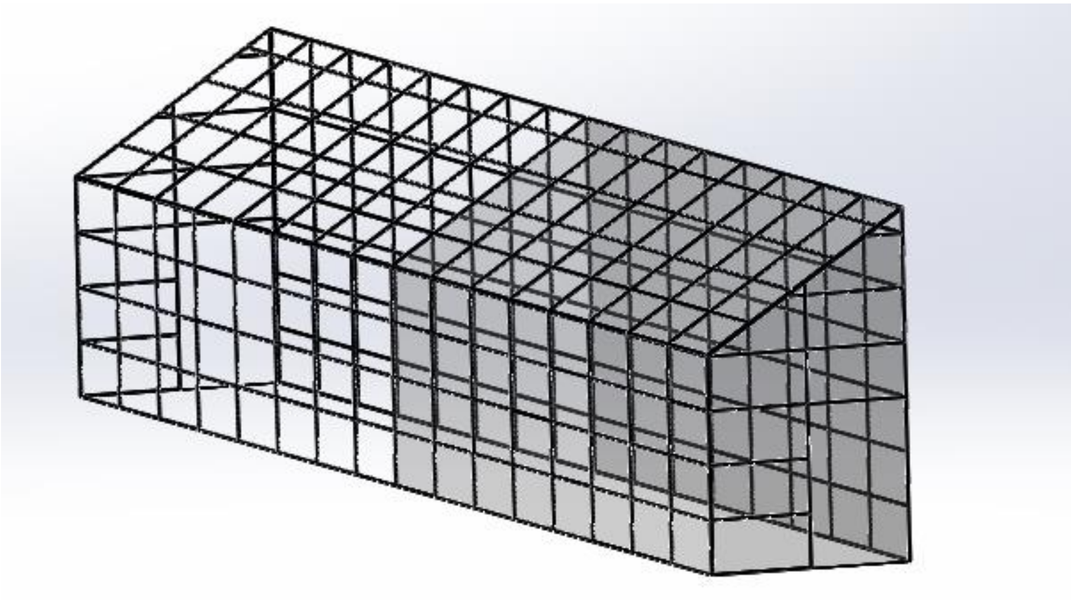


Figure 5.7 3D drawing of the grid connected GIPV. The left part represents the area with conventional glass. The right part represents the area with PV modules.

5.3.1.1 Output power of the GIPV system

To obtain the adequate inverter for each façade, the following method is used:

- Calculate the total nominal power generated per façade;
- Find inverters that work at the calculated nominal powers;
- Obtain the number of PV modules connected per string that generate a voltage and current that are in the range of the inverters.
- Verify if the minimum nominal voltage (at 70ºC) of the PV system of each façade is higher than the minimum acceptable voltage of the inverter;
- Verify if the maximum open circuit voltage (at -15ºC) of the PV system of each façade is lower than the maximum acceptable voltage of the inverter;
- Verify if the maximum short circuit current (at 70ºC) of the PV system of each façade is lower than the maximum acceptable current of the inverter.

Table 5.15 shows the characteristics of the façades and Table 5.16 the inverter selected for each façade and their characteristics.

Table 5.15 Characteristics of each façade PV system

Façade	Nº of modules	Nº of modules per string	Nominal Power [Wp]	Voltage range [V]	Maximum short circuit current [A]
Skylight	32	2	704	58-110	12.87
South façade	32	2	704	58-110	12.87
North façade	48	6	880	175-258	6.44

Table 5.16 Characteristics of the inverter selected for each façade

Façade	Inverter	PV power range [Wp]	Operating voltage [V]	Maximum short circuit current [A]
Roof	Soladin 700	500-900	50-200	17
South	Soladin 700	500-900	50-200	17
North	PS-1200i-MV	810-1100	100-350	10

Table 5.17 show the total output energy available. These data were obtained using the software “PVsyst”.

Table 5.17 Output energy of the PV system

Month	North wall [37.95 m²]	South wall [25.30 m²]	Roof [25.30 m²]	Total	
	E_{grid} [kWh]	E_{grid} [kWh]	E_{grid} [kWh]	E_{grid} [kWh]	E_{grid} [kWh/day]
January	23.42	33.77	34.73	91.92	2.96
February	29.59	43.55	45.33	118.47	2.38
March	49.64	58.61	73.51	181.76	3.32
April	46.43	75.96	75.36	197.75	3.74
May	54.67	84.24	88.89	227.8	4.19
June	54.4	92.2	94.24	240.84	4.59
July	58.41	94.06	97.83	250.3	4.63
August	53.49	84.42	87.46	225.37	4.15
September	45.48	65.1	70.47	181.05	3.44
October	32.76	42.6	49.84	125.2	2.29
November	23.24	28.43	34.93	86.6	1.64
December	19.82	29.97	29.1	78.89	1.43
Year	491.35	732.91	781.69	2005.95	3.23

5.3.2 Structure

For the roof, it is going to be used the metal structure Schüco FWS 60 [113] and for the walls Schüco AWS 60, as Figure 5.8 shows.

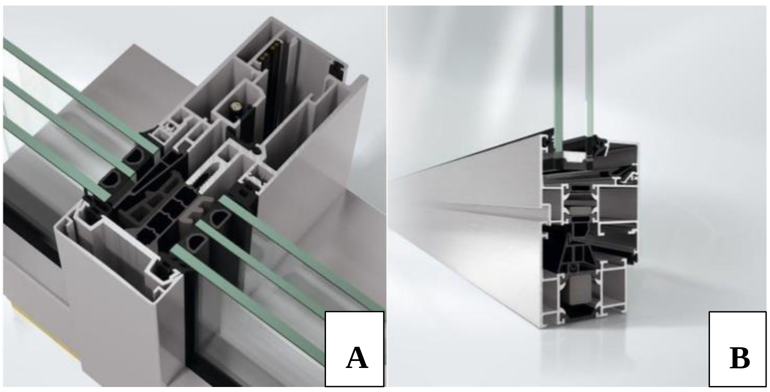


Figure 5.8 Framing solutions for the roof and walls of the GIPV, respectively. A) Schüco FWS 60. B) Schüco AWS 60 [114, 115].

It should be verified with a structural engineer if additional structural elements are necessary. Those should be designed according to Greenhouses: Design and construction - Part 1: Commercial production greenhouses [116].

5.3.3 Quotation

Table 5.18 shows the quotation of the greenhouse.

Table 5.18 Quotation of the grid-connected greenhouse

Elements	Price
Aluminium framing structure Foundation Installation	30.000€
PV modules	15.000€
Conventional clear glass 4+4 mm	3000€
BOS system	4000€
Hot water boiler Finned tube heating system Light system Field drip irrigation components Valve on-off + pressure regulator + filter Irrigation tank Controller Monitoring software Indoor Digital C02, light, Temperature and Humidity Sensor Contactor Panel Fan Power Vent system	8.000€
Total	60.000€

6 Conclusions and Future Work

The main objective of the research work conducted at Onyx Solar was studying, both at product and at solution level, innovative BIPV solutions based on a-Si thin film and c-Si technologies.

The current state of the use of energy resources for the global production of electricity was presented. It was concluded that there is a very positive forecast for the BIPV market, which must be combined with development and innovation, including the enhancement of aesthetics and diversity of BIPV products, as well as the development of new BIPV solutions.

The state of art of the BIPV field was also presented. The difference between BIPV and BAPV was clarified, and the working principle, architecture and fabrication process of the commercial PV technologies were described. Furthermore, the main components of BIPV products were mentioned, as well as the most important BIPV solutions and a brief introduction of greenhouse key factors.

Requirements of lightweight PV modules were defined and possible solutions were studied. Following that, standards related to actions on buildings and PV electrical insulation were evaluated to obtain the minimum dimensions of the lightweight PV modules. Furthermore, similar commercial solutions were analysed and so a group of promising dimensions for future commercial dimensions were identified. At the end, experimental samples were fabricated, taking account the previous analysis and Onyx Solar's best interest. It was possible to conclude that:

- Lightweight BIPV modules should have a maximum weight of 10 kg;
- The most interesting total thicknesses of glass+glass and glass+backsheet c-Si lightweight BIPV modules should be 2.5/3/4/5/6 mm and glass+glass and glass+backsheet a-Si thin film BIPV modules total thicknesses should be 5.7/6.2 mm;
- The most important actions on ventilated façades are wind actions and should be considered as 0.8 kN/m^2;
- The glass+glass and glass+backsheet c-Si BIPV modules with total thicknesses of 2.5/3/4/5/6 mm should have a maximum length without a supporting material of 1640/2000/2625/3220/4000 mm and glass+glass and glass+backsheet thin film a-Si BIPV modules with total thicknesses of 5.7/6.2 mm a maximum length without a supporting material of 1000/1050 mm;
- Commercial lightweight modules for ventilated façades have an AR around 2;
- The experimental samples were very aesthetic with almost no defects, which is a very positive commercial perspective.

The plug & play concept was explored and how it should be adapted to ventilated façade's framing solutions. Many commercial solutions were analysed, and advantages and disadvantages were discussed. It was possible to conclude that:

- Plug & play framing solutions should be made of prefabricated modules easy to install and remove, with the possibility of replacing individual modules;
- Many of the commercial solutions found partially fulfil the plug & play definition, since all need a non-prefabricated structural framing.

The design of a GIPV to be located in Soria (Spain), with a surface area of approximately 30 m^2, half covered with conventional clear glass and half with semi-transparent a-Si modules, was carried out, with the objective of comparing crop productions and evaluating the economic viability of GIPV. The main conclusions were:

- The most adequate PV module transparency degree would be 30%, otherwise the number of possible crops would be seriously compromised;
- The pre-design greenhouse with a surface area of 32,3 m^2 had surfaces with a nominal peak power lower than 500 Wp, for which there are no inverters available; consequently, the components of a standalone PV system were selected, considering a simple estimation of the daily electricity consumption. The annual electricity production was estimated to be 1015 kWh;
- The minimum dimensions for a grid connected GIPV (surface area of 51,7 m^2) were identified and the adequate inverters were selected. The annual electricity production was estimated to be 2006 kWh;
- The second design was the most economically viable, with estimated total costs for the GIPV of approximately 60,000 €.

Overall, the results of the research work were very positive. Concerning the design of lightweight BIPV modules, many economically interesting configurations were found, and the produced samples had almost no defects. Regarding the design of the GIPV, the configuration of a potentially economically viable GIPV was found, which was grid connected, with a surface area similar to the one proposed at the beginning, capable of having many crop productions and producing enough energy to power all electronic devices. The good results combined with the very positive forecast of the BIPV market make it a great opportunity to continue research in order to obtain final commercial products. In that way, it is suggested as future research:

- Undergoing the lightweight experimental samples through impact and wind tests;
- Combining the lightweight samples with the analysed plug & play solutions, implanted on building façades and evaluate their performance;
- Implementing the grid connected GIPV and compare the crop productions on both sides of the GIPV;
- Calculating the return on investment of the grid connected GIPV.

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A Minimum possible dimensions of c-Si/pc-Si modules

Table A.1 shows the possible dimensions of 2.5+2.5 mm c-Si/pc-Si BIPV solutions with 2 strings.

Table A.1 Possible dimensions of 2.5+2.5 mm c-Si/pc-Si BIPV solutions with 2 strings

2.5+2.5 mm		**N. of strings**		**Weight [Kg]**	**AR**
		2			
		Length [mm]	**Width [mm]**		
N. cells/ string	2	350	346	1.5	1.0
	3	509	346	2.2	1.5
	4	668	346	2.9	1.9
	5	827	346	3.6	2.4
	6	986	346	4.3	2.8
	7	1145	346	5.0	3.3
	8	1304	346	5.6	3.8
	9	1463	346	6.3	4.2
	10	1622	346	7.0	4.7
	11	1781	346	7.7	5.1
	12	1940	346	8.4	5.6
	13	2099	346	9.1	6.1
	14	2258	346	9.8	6.5

Table A.2 shows the possible dimensions of 2.5+2.5 mm c-Si/pc-Si BIPV solutions with 4 strings.

Table A.2 Possible dimensions of 2.5+2.5 mm c-Si/pc-Si BIPV solutions with 4 strings

2.5+2.5 mm		**N. of strings**		**Weight [Kg]**	**AR**
		4			
		Length [mm]	**Width [mm]**		
N. cells/ string	2	350	666	2.9	2.0
	3	509	666	4.2	1.3
	4	668	666	5.6	1.0
	5	827	666	6.9	1.2
	6	986	666	8.2	1.5
	7	1145	666	9.5	1.7

Table A.3 shows the possible dimensions of 2.5+2.5 mm c-Si/pc-Si BIPV solutions with 6 strings.

Table A.3 Possible dimensions of 2.5+2.5 mm c-Si/pc-Si BIPV solutions with 6 strings

2.5+2.5 mm		**N. of strings**		**Weight [Kg]**	**AR**
		6			
		Length [mm]	**Width [mm]**		
N. cells/ string	2	350	986	4.3	2.5
	3	509	986	6.3	2.0
	4	668	986	8.2	1.4

Table A.4 shows the possible dimensions of 3+3 mm c-Si/pc-Si BIPV solutions with 2 strings.

Table A.4 Possible dimensions of 3+3 mm c-Si/pc-Si BIPV solutions with 2 strings

3+3 mm		**N. of strings**		**Weight [Kg]**	**AR**
		2			
		Length [mm]	**Width [mm]**		
N. cells/ string	2	350	346	1.8	1.0
	3	509	346	2.6	1.5
	4	668	346	3.5	1.9
	5	827	346	4.3	2.4
	6	986	346	5.1	2.8
	7	1145	346	5.9	3.3
	8	1304	346	6.8	3.8
	9	1463	346	7.6	4.2
	10	1622	346	8.4	4.7
	11	1781	346	9.2	5.1

Table A.5 shows the possible dimensions of 3+3 mm c-Si/pc-Si BIPV solutions with 4 strings.

Table A.5 Possible dimensions of 3+3 mm c-Si/pc-Si BIPV solutions with 4 strings

3+3 mm		**N. of strings**		**Weight [Kg]**	**AR**
		4			
		Length [mm]	**Width [mm]**		
N. cells/ string	2	350	666	3.5	2.0
	3	509	666	5.1	1.3
	4	668	666	6.7	1.0
	5	827	666	8.3	1.2
	6	986	666	9.9	1.5

Table A.6 shows the possible dimensions of 3+3 mm c-Si/pc-Si BIPV solutions with 6 strings.

Table A.6 Possible dimensions of 3+3 mm c-Si/pc-Si BIPV solutions with 6 strings

3+3 mm		**N. of strings**		**Weight [Kg]**	**AR**
		6			
		Length [mm]	**Width [mm]**		
N. cells/ string	2	350	986	5.2	2.5
	3	509	986	7.5	2.0
	4	668	986	9.9	1.4

Table A.7 shows the possible dimensions of 2.5T mm c-Si/pc-Si BIPV solutions with 2 strings

Table A.7 Possible dimensions of 2.5T mm c-Si/pc-Si BIPV solutions with 2 strings

2.5T mm		**N. of strings**		**Weight [Kg]**	**AR**
		2			
		Length [mm]	**Width [mm]**		
N. cells/ string	2	350	346	0.8	1.0
	3	509	346	1.1	1.5
	4	668	346	1.4	1.9
	5	827	346	1.8	2.4
	6	986	346	2.1	2.8
	7	1145	346	2.5	3.3
	8	1304	346	2.8	3.8
	9	1463	346	3.2	4.2
	10	1622	346	3.5	4.7
	11	1781	346	3.9	5.1
	12	1940	346	4.2	5.6
	13	2099	346	4.5	6.1
	14	2258	346	4.9	6.5
	15	2417	346	5.2	7.0
	16	2576	346	5.6	7.4
	17	2735	346	5.9	7.9
	18	2894	346	6.3	8.4
	19	3053	346	6.6	8.8
	20	3212	346	6.9	9.3
	21	3371	346	7.3	9.7
	22	3530	346	7.6	10.2
	23	3689	346	8.0	10.7
	24	3848	346	8.3	11.1

Table A.8 shows the possible dimensions of 2.5T mm c-Si/pc-Si BIPV solutions with 4 strings.

Table A.8 Possible dimensions of 2.5T c-Si/pc-Si BIPV solutions with 4 strings

2.5T mm		N. of strings		**Weight [Kg]**	**AR**
		4			
		Length [mm]	Width [mm]		
N. cells/ string	2	350	666	1.5	2.0
	3	509	666	2.1	1.3
	4	668	666	2.8	1.0
	5	827	666	3.4	1.2
	6	986	666	4.1	1.5
	7	1145	666	4.8	1.7
	8	1304	666	5.4	2.0
	9	1463	666	6.1	2.2
	10	1622	666	6.8	2.4
	11	1781	666	7.4	2.7
	12	1940	666	8.1	2.9
	13	2099	666	8.7	3.2
	14	2258	666	9.4	3.4

Table A.9 shows the possible dimensions of 2.5T mm c-Si/pc-Si BIPV solutions with 6 strings.

Table A.9 Possible dimensions of 2.5T c-Si/pc-Si BIPV solutions with 6 strings

2.5T mm		**N. of strings**		**Weight [Kg]**	**AR**
		6			
		Length [mm]	**Width [mm]**		
N. cells/ string	2	350	986	2.2	2.5
	3	509	986	3.1	2.0
	4	668	986	4.1	1.4
	5	827	986	5.1	1.3
	6	986	986	6.1	1.0
	7	1145	986	7.1	1.2
	8	1304	986	8.0	1.3
	9	1463	986	9.0	1.5
	10	1622	986	10.0	1.6

Table A.10 shows the possible dimensions of 3T mm c-Si/pc-Si BIPV solutions with 2 strings.

Table A.10 Possible dimensions of 3T mm c-Si/pc-Si BIPV solutions with 2 strings

3T mm		**N. of strings**		**Weight [Kg]**	**AR**
		2			
		Length [mm]	**Width [mm]**		
N. cells/ string	2	350	346	0.9	1.0
	3	509	346	1.3	1.5
	4	668	346	1.7	1.9
	5	827	346	2.1	2.4
	6	986	346	2.6	2.8
	7	1145	346	3.0	3.3
	8	1304	346	3.4	3.8
	9	1463	346	3.8	4.2
	10	1622	346	4.2	4.7
	11	1781	346	4.6	5.1
	12	1940	346	5.0	5.6
	13	2099	346	5.4	6.1
	14	2258	346	5.9	6.5
	15	2417	346	6.3	7.0
	16	2576	346	6.7	7.4
	17	2735	346	7.1	7.9
	18	2894	346	7.5	8.4
	19	3053	346	7.9	8.8
	20	3212	346	8.3	9.3
	21	3371	346	8.7	9.7
	22	3530	346	9.2	10.2
	23	3689	346	9.6	10.7
	24	3848	346	10.0	11.1

Table A.11 shows the possible dimensions of 3T mm c-Si/pc-Si BIPV solutions with 4 strings.

Table A.11 Possible dimensions of 3T mm c-Si/pc-Si BIPV solutions with 4 strings

3T mm		**N. of strings**		**Weight [Kg]**	**AR**
		4			
		Length [mm]	**Width [mm]**		
N. cells/ string	2	350	666	1.7	2.0
	3	509	666	2.5	1.3
	4	668	666	3.3	1.0
	5	827	666	4.1	1.2
	6	986	666	4.9	1.5
	7	1145	666	5.7	1.7
	8	1304	666	6.5	2.0
	9	1463	666	7.3	2.2
	10	1622	666	8.1	2.4
	11	1781	666	8.9	2.7
	12	1940	666	9.7	2.9

Table A.12 shows the possible dimensions of 3T mm c-Si/pc-Si BIPV solutions with 6 strings.

Table A.12 Possible dimensions of 3T mm c-Si/pc-Si BIPV solutions with 6 strings

3T mm		**N. of strings**		**Weight [Kg]**	**AR**
		6			
		Length [mm]	**Width [mm]**		
N. cells/ string	2	350	986	2.6	2.5
	3	509	986	3.8	2.0
	4	668	986	4.9	1.4
	5	827	986	6.1	1.3
	6	986	986	7.3	1.0
	7	1145	986	8.5	1.2
	8	1304	986	9.6	1.3

Table A.13 shows the possible dimensions of 4T mm c-Si/pc-Si BIPV solutions with 2 strings.

Table A.13 Possible dimensions of 4T mm c-Si/pc-Si BIPV solutions with 2 strings

4T mm		**N. of strings**		**Weight [Kg]**	**AR**
		2			
		Length [mm]	**Width [mm]**		
N. cells/ string	2	350	346	1.2	1.0
	3	509	346	1.8	1.5
	4	668	346	2.3	1.9
	5	827	346	2.9	2.4
	6	986	346	3.4	2.8
	7	1145	346	4.0	3.3
	8	1304	346	4.5	3.8
	9	1463	346	5.1	4.2
	10	1622	346	5.6	4.7
	11	1781	346	6.2	5.1
	12	1940	346	6.7	5.6
	13	2099	346	7.3	6.1
	14	2258	346	7.8	6.5
	15	2417	346	8.4	7.0
	16	2576	346	8.9	7.4
	17	2735	346	9.5	7.9
	18	2894	346	10.0	8.4

Table A.14 shows the possible dimensions of 4T mm c-Si/pc-Si BIPV solutions with 4 strings.

Table A.14 Possible dimensions of 4T mm c-Si/pc-Si BIPV solutions with 4 strings

4T mm		**N. of strings**		**Weight [Kg]**	**AR**
		4			
		Length [mm]	**Width [mm]**		
N. cells/ string	2	350	666	2.3	2.0
	3	509	666	3.4	1.3
	4	668	666	4.4	1.0
	5	827	666	5.5	1.2
	6	986	666	6.6	1.5
	7	1145	666	7.6	1.7
	8	1304	666	8.7	2.0
	9	1463	666	9.7	2.2

Table A.15 shows the possible dimensions of 4T mm c-Si/pc-Si BIPV solutions with 6 strings.

Table A.15 Possible dimensions of 4T mm c-Si/pc-Si BIPV solutions with 6 strings

4T mm		**N. of strings**		**Weight [Kg]**	**AR**
		6			
		Length [mm]	**Width [mm]**		
N. cells/ string	2	350	986	3.5	2.5
	3	509	986	5.0	2.0
	4	668	986	6.6	1.4
	5	827	986	8.2	1.3
	6	986	986	9.7	1.0

B Minimum possible dimensions of a-Si modules

Table B.1 shows the possible dimensions of 3.2+2.5 mm a-Si thin film BIPV solutions with 2 strings.

Table B.1 Possible dimensions of 3.2+ mm c-Si/pc-Si BIPV solutions with 2 strings

3.2+5 mm		**N. of strings**		**Weight [Kg]**	**AR**
		2			
		Length [mm]	**Width [mm]**		
N. cells/ string	2	350	346	1.8	1.0
	3	509	346	2.6	1.5

Table B.2 shows the possible dimensions of 3.2+3 mm a-Si thin film BIPV solutions with 2 strings.

Table B.2 Possible dimensions of 3.2+3 mm c-Si/pc-Si BIPV solutions with 2 strings

3.2+5 mm		**N. of strings**		**Weight [Kg]**	**AR**
		2			
		Length [mm]	**Width [mm]**		
N. cells/ string	2	350	346	1.8	1.0
	3	509	346	2.6	1.5
	4	668	346	3.5	1.9

Table B.3 shows the possible dimensions of 3.2+3 mm a-Si thin film BIPV solutions with 4 strings.

Table B.3 Possible dimensions of 3+3 mm c-Si/pc-Si BIPV solutions with 4 strings

3+3 mm		**N. of strings**		**Weight [Kg]**	**AR**
		4			
		Length [mm]	**Width [mm]**		
N. cells/ string	2	350	666	3.5	2.0
	3	509	666	5.1	1.3
	4	668	666	6.7	1.0

C Analysis and Evaluation of the Existing Solutions for Ventilated Facades

In annex C it is analysed the products of three companies (TRESPA®, Butech® and Euronit®), which have presently on the market lightweight solutions for ventilated facades, particularly the AR mostly used.

C.1 TRESPA®

Table C.1 shows the dimensions of the products for ventilated façades of TRESPA®IZEON®.

Table .C.1 Dimensions of the products of TRESPA®IZEON® for ventilated façades [117]

Dimensions [mm]	AR	Thickness [mm]
2130 x 1420	1.5	6
3050 x 1530	2.0	

Table C.2 shows the dimensions of the products for ventilated façades of TRESPA®METEON®.

Table C.2 Dimensions of the products of TRESPA® METEON® for ventilated façades [117]

Dimensions [mm]	AR	Thickness [mm]
4270 x 2130	2.0	6
3650 x 1860	2.0	8
2550 x 1860	1.4	10
3050 x 1530	2.0	13

C.2 Butech®

Table C.3 shows the dimensions of the products for ventilated façades of Butech®.

Table C.3 Dimensions of the products of Butech® for ventilated façades [118]

Dimensions [mm]		AR	Thickness [mm]
Length [mm]	Width [mm]		
596	596	1.0	10
659	435	1.5	10.5
660	420	1.6	11
800	400	2.0	11.5
800	800	1.0	12
900	143	6.3	
900	220	4.1	
900	450	2.0	
1200	193	6.2	
1200	294	4.1	
1200	596	2.0	
1500	165	9.1	
1500	250	6.0	
1800	294	6.1	
1800	596	3.0	

C.3 Euronit®

Table C.4 shows the dimensions of the products for ventilated façades of Euronit® NATURA.

Table C.4 Dimensions of the products of Euronit® NATURA for ventilated façades [119]

Dimensions [mm]		AR	Thickness [mm]
Length [mm]	Width [mm]		
2500	1250	2.0	8
3100	1250	2.5	12

Table C.5 shows the dimensions of the products for ventilated façades of Euronit® PRO ANTIGRAFFITI.

Table C.5 Dimensions of the products of Euronit® PRO ANTIGRAFFITI for ventilated façades [119]

Dimensions [mm]		**AR**	**Thickness [mm]**
Length [mm]	**Width [mm]**		
2500	1250	2.0	8
3100	1250	2.5	12

Table C.6 shows the dimensions of the products for ventilated façades of Euronit® PICTURA ANTIGRAFFITI.

Table C.6 Dimensions of the products of Euronit® PICTURA ANTIGRAFFITI for ventilated façades [119]

Dimensions [mm]		**AR**	**Thickness [mm]**
Length [mm]	**Width [mm]**		
2500	1250	2.0	8
3100	1250	2.5	12

Table C.7 shows the dimensions of the products for ventilated façades of Euronit® TECTIVA-ETERCOLO.

Table C.7 Dimensions of the products of Euronit® TECTIVA-ETERCOLO for ventilated façades [119]

Dimensions [mm]		**AR**	**Thickness [mm]**
Length [mm]	**Width [mm]**		
2500	1250	2.0	8
3100	1250	2.5	12

Table C.8 shows the dimensions of the products for ventilated façades of Euronit® TEXTURA.

Table C.8 Dimensions of the products of Euronit® TEXTURA for ventilated façades [119]

Dimensions [mm]		**AR**	**Thickness [mm]**
Length [mm]	**Width [mm]**		
596	596	1.0	8
659	435	1.5	12

Table C.9 shows the dimensions of the products for ventilated façades of Euronit® TEXTURA.

Table C.9 Dimensions of the products of Euronit® TONALITY for ventilated façades [119]

Dimensions [mm]		AR
Length [mm]	Width [mm]	
300	150	2.0
1200	300	4.0
1600	400	4.0
2000	600	3.3

Table C.10 shows the dimensions of the products for ventilated façades of Euronit® BLUCLAD.

Table C.10 Dimensions of the products of Euronit® BLUCLAD for ventilated façades [119]

Dimensions [mm]		AR	Thickness [mm]
Length [mm]	Width [mm]		
2500	1250	2.0	10
2850	1250	2.3	10.5

Table C.11 shows the dimensions of the products for ventilated façades of Euronit® CEDRAL.

Table C.11 Dimensions of the products of Euronit® CEDRAL for ventilated façades [119]

Dimensions [mm]		AR	Thickness [mm]
Length [mm]	Width [mm]		
3600	190	18.9	10

Table C.12 shows the dimensions of the products for ventilated façades of Euronit® CEDRAL CLICK.

Table C.12 Dimensions of the products of Euronit® CEDRAL CLICK for ventilated façades [119]

Dimensions [mm]		AR	Thickness [mm]
Length [mm]	Width [mm]		
3600	190	18.9	10

Even though the products analysed have a significant variety of aspect ratios (AR), the average of AR is around 2, as it is possible to see on the following Table C.13. The most extreme aspects ratios were rejected from this analysis since they are not representative.

Table C.13 Aspect ratios and its average of the products of TRESPA®, Butech® and Euronit® [117, 118] [119]

TRESPA®		Buteck ®		Euronit®	
AR	**Average**	**AR**	**Average**	**AR**	**Average**
1.5	1.8	1.0	2.2	2.5	2.4
2.0		1.5		2.0	
2.0		1.6		2.5	
2.0		2.0		2.0	
2.0		1.0		2.5	
1.4		4.1		2.0	
2.0		2.0		2.5	
		4.1		1.0	
		2.0		1.5	
		3.0		2	
				4	
				4	
				3.3	
				2	
				2.28	

D Final competitive dimensions of c-Si/pc-Si modules

Table D.1 shows the possible dimensions of 2.5+2.5 mm c-Si/pc-Si BIPV solutions with 2 strings.

Table D.1 Most competitive dimensions of 2.5+2.5 mm c-Si/pc-Si BIPV solutions with 2 strings

2.5+2.5 mm		**N. of strings**		**Weight [Kg]**	**AR**
		2			
		Length [mm]	**Width [mm]**		
N. cells/ string	3	600	400	3.0	1.5
	4	700	350	3.1	2.0
	5	900	450	5.1	2.0

Table D.2 shows the possible dimensions of 2.5+2.5 mm c-Si/pc-Si BIPV solutions with 4 strings.

Table D.2 Most competitive dimensions of 2.5+2.5 mm c-Si/pc-Si BIPV solutions with 4 strings

2.5+2.5 mm		**N. of strings**		**Weight [Kg]**	**AR**
		4			
		Length [mm]	**Width [mm]**		
N. cells/ string	6	1000	700	8.8	1.4

Table D.3 shows the possible dimensions of 2.5+2.5 mm c-Si/pc-Si BIPV solutions with 6 strings.

Table D.3 Most competitive dimensions of 2.5+2.5 mm c-Si/pc-Si BIPV solutions with 6 strings

2.5+2.5 mm		**N. of strings**		**Weight [Kg]**	**AR**
		6			
		Length [mm]	**Width [mm]**		
N. cells/ string	3	550	1100	7.6	2.0

Table D.4 shows the most competitive dimensions of 3+3 mm c-Si/pc-Si BIPV solutions with 2 strings.

Table D.4 Most competitive dimensions of 3+3 mm c-Si/pc-Si BIPV solutions with 2 strings

3+3 mm		**N. of strings**		**Weight [Kg]**	**AR**
		2			
		Length [mm]	**Width [mm]**		
N. cells/ string	3	600	400	3.6	1.5
	4	700	350	3.7	2.0
	5	900	450	6.1	2.0

Table D.5 shows the possible dimensions of 3+3 mm c-Si/pc-Si BIPV solutions with 4 strings.

Table D.5 Most competitive dimensions of 3+3 mm c-Si/pc-Si BIPV solutions with 4 strings

3+3 mm		**N. of strings**		**Weight [Kg]**	**AR**
		4			
		Length [mm]	**Width [mm]**		
N. cells/ string	2	350	700	3.7	2.0

Table D.6 shows the possible dimensions of 3+3 mm c-Si/pc-Si BIPV solutions with 6 strings.

Table D.6 Most competitive dimensions of 3+3 mm c-Si/pc-Si BIPV solutions with 6 strings

3+3 mm		**N. of strings**		**Weight [Kg]**	**AR**
		6			
		Length [mm]	**Width [mm]**		
N. cells/ string	3	550	1100	9.1	2.0

Table D.7 shows the most competitive dimensions of 2.5T mm c-Si/pc-Si BIPV solutions with 2 strings.

Table D.7 Most competitive dimensions of 2.5T mm c-Si/pc-Si BIPV solutions with 2 strings

2.5T mm		**N. of strings 2**		**Weight [Kg]**	**AR**
		Length [mm]	**Width [mm]**		
N. cells/ string	2	350	346	0.8	1.0
	3	509	346	1.1	1.5
	4	668	346	1.4	1.9
	5	827	346	1.8	2.4
	6	986	346	2.1	2.8
	7	1145	346	2.5	3.3
	8	1304	346	2.8	3.8
	9	1463	346	3.2	4.2
	10	1622	346	3.5	4.7
	11	1781	346	3.9	5.1
	12	1940	346	4.2	5.6
	13	2099	346	4.5	6.1
	14	2258	346	4.9	6.5
	15	2417	346	5.2	7.0
	16	2576	346	5.6	7.4
	17	2735	346	5.9	7.9
	18	2894	346	6.3	8.4
	19	3053	346	6.6	8.8
	20	3212	346	6.9	9.3
	21	3371	346	7.3	9.7
	22	3530	346	7.6	10.2
	23	3689	346	8.0	10.7
	24	3848	346	8.3	11.1

Table D.8 Most competitive dimensions of 2.5T mm c-Si/pc-Si BIPV solutions with 2 strings

2.5T mm		**N. of strings**		**Weight [Kg]**	**AR**
		2			
		Length [mm]	**Width [mm]**		
N. cells/ string	3	600	400	1.5	1.5
	4	700	350	1.5	2.0
	5	900	450	2.5	2.0

Table D.8 shows the most competitive dimensions of 2.5T mm c-Si/pc-Si BIPV solutions with 4 strings.

Table D.9 Most competitive dimensions of 2.5T c-Si/pc-Si BIPV solutions with 4 strings

2.5T mm		**N. of strings**		**Weight [Kg]**	**AR**
		4			
		Length [mm]	**Width [mm]**		
N. cells/ string	2	350	700	1.5	2.0
	6	1050	700	4.6	1.5
	7	1200	800	6.0	1.5
	8	1400	700	6.1	2.0
	9	1500	750	7.0	2.0
	10	1750	700	7.7	2.5

Table D.9 shows the most competitive dimensions of 2.5T mm c-Si/pc-Si BIPV solutions with 6 strings.

Table D.10 Most competitive dimensions of 2.5T c-Si/pc-Si BIPV solutions with 6 strings

2.5T mm		**N. of strings**		**Weight [Kg]**	**AR**
		6			
		Length [mm]	**Width [mm]**		
N. cells/ string	3	550	1100	3.8	2.0
	4	700	1050	4.6	1.5
	9	1500	1000	9.4	1.5

Table D.10 shows the most competitive dimensions of 3T mm c-Si/pc-Si BIPV solutions with 2 strings.

Table D.11 Most competitive dimensions of 3T mm c-Si/pc-Si BIPV solutions with 2 strings

3T mm		N. of strings 2		Weight [Kg]	AR
		Length [mm]	Width [mm]		
N. cells/ string	3	600	400	1.8	1.5
	4	700	350	1.8	2.0
	5	900	450	3.0	2.0

Table D.11 shows the most competitive dimensions of 3T mm c-Si/pc-Si BIPV solutions with 4 strings.

Table D.12 Most competitive dimensions of 3T mm c-Si/pc-Si BIPV solutions with 4 strings

3T mm		N. of strings 4		Weight [Kg]	AR
		Length [mm]	Width [mm]		
N. cells/ string	6	1050	700	5.5	1.5
	7	1200	800	7.2	1.5
	8	1400	700	7.4	2.0
	9	1500	750	8.4	2.0
	10	1750	700	9.2	2.5

Table D.12 shows the most competitive dimensions of 3T mm c-Si/pc-Si BIPV solutions with 6 strings.

Table D.13 Most competitive dimensions of 3T mm c-Si/pc-Si BIPV solutions with 6 strings

3T mm		N. of strings 6		Weight [Kg]	AR
		Length [mm]	Width [mm]		
N. cells/ string	3	550	1100	4.5	2.0
	4	700	1050	5.5	1.5

Table D.13 shows the most competitive dimensions of 4T mm c-Si/pc-Si BIPV solutions with 2 strings.

Table D.14 Most competitive dimensions of 4T mm c-Si/pc-Si BIPV solutions with 2 strings

4T mm		N. of strings		Weight [Kg]	AR
		2			
		Length [mm]	Width [mm]		
N. cells/ string	3	600	400	2.4	1.5
	4	700	350	2.5	2.0
	5	900	450	4.1	2.0

Table D.14 shows the most competitive dimensions of 4T mm c-Si/pc-Si BIPV solutions with 4 strings.

Table D.15 Most competitive dimensions of 4T mm c-Si/pc-Si BIPV solutions with 4 strings

4T mm		N. of strings		Weight [Kg]	AR
		4			
		Length [mm]	Width [mm]		
N. cells/ string	7	1200	800	9.6	1.5
	8	1400	700	9.8	2.0

Table D.15 shows the most competitive dimensions of 4T mm c-Si/pc-Si BIPV solutions with 6 strings.

Table D.16 Most competitive dimensions of 4T mm c-Si/pc-Si BIPV solutions with 6 strings

4T mm		N. of strings		Weight [Kg]	AR
		6			
		Length [mm]	Width [mm]		
N. cells/ string	3	550	1100	6.1	2.0
	4	700	1050	7.4	1.5

E Final competitive dimensions of a-Si modules

Table E.1 shows the possible dimensions of 3.2+2.5 mm a-Si thin film BIPV solutions with 2 strings.

Table E.1 Most competitive dimensions of 3.2+2.5 mm a-Si thin film BIPV solutions with 2 strings

3.2+2.5 mm		**N. of strings**		**Weight [Kg]**	**AR**
		2			
		Length [mm]	**Width [mm]**		
N. cells/ string	3	600	400	3.6	1.5

Table E.2 shows the possible dimensions of 3.2+3 mm a-Si thin film BIPV solutions with 2 strings.

Table E.2 Most competitive dimensions of 3.2+3 mm a-Si BIPV solutions with 2 strings

3.2+3 mm		**N. of strings**		**Weight [Kg]**	**AR**
		2			
		Length [mm]	**Width [mm]**		
N. cells/ string	3	600	400	3.6	1.5
	4	700	350	3.7	2.0

Table E.3 shows the possible dimensions of 3.2+3 mm a-Si thin film BIPV solutions with 4 strings.

Table E.3 Most competitive dimensions of 3.2+3 mm a-Si thin film BIPV solutions with 4 strings

3.2+3 mm		**N. of strings**		**Weight [Kg]**	**AR**
		4			
		Length [mm]	**Width [mm]**		
N. cells/ string	2	350	700	3.7	2.0