This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement Nº 691768

Opaque photovoltaic glazing solutions based on crystalline silicon with hidden busbars and L interconnections

Project report

ONYX SOLAR

April 2017

Summary

This document describes the development of a prototype consisting on a photovoltaic c-Si based module with an innovative solution to hide the cell and string connections, in order to improve the aesthetical appearance without other disadvantages. Background information on the materials used is additionally provided, and a cost competitiveness analysis of the developed products is conducted.

Acknowledgements

The work described in this publication has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement Nº 691768.

The present report was prepared by PVSITES project partner ONYX SOLAR. The report was originally submitted to the European Commission as Project Deliverable D3.3 in April 2017.

Disclaimer

About the PVSITES project

PVSITES is an international collaboration co-funded by the European Union under the Horizon 2020 Research and Innovation program. It originated from the realisation that although building-integrated photovoltaics (BIPV) should have a major role to play in the ongoing transition towards nearly zero energy buildings (nZEBs) in Europe, the technology in new constructions has not yet happened. The cause of this limited deployment can be summarised as a mismatch between the BIPV products on offer and prevailing market demands and regulations.

The main objective of the PVSITES project is therefore to drive BIPV technology to a large market deployment by demonstrating an ambitious portfolio of building integrated solar technologies and systems, giving a forceful, reliable answer to the market requirements identified by the industrial members of the consortium in their day-to-day activity.

Coordinated by project partner Tecnalia, the PVSITES consortium started work in January 2016 and will be active for 3.5 years, until June 2019. This document is part of a series of public reports summarising the consortium's activities and findings, available for download on the project's website at www.pvsites.eu.

The PVSITES consortium:

Tecnalia Research & Innovation	CTCV	FormatD2
Onyx Solar	Flisom	Vilogia
BEAR-iD	Cricursa	R2M Solution Research to Market
Nobatek	CEA	CADCAMation
Film Optics	Acciona Infraestructuras	WIP - Renewable Energies

Contents

Tables

Figures

1 EXECUTIVE SUMMARY

1.1 Description of the deliverable content and purpose

The improvement of the aesthetic characteristics of solar panels is a key factor to overcome the most significant obstacles for the integration of photovoltaic technologies in building envelopes. Today, architectural sector demands construction materials without limits in terms of shapes, sizes and colors,. In that context, the BIPV industry aims to find solutions according to those requirements without compromising the panel performance or efficiency.

This report contains the development of an innovative glass-glass BIPV product and shows the result of the activities performed in the framework of Task 3.2: Hidden busbars and L-interconnections for opaque BIPV solutions.

The purpose of this task is to provide an answer to the market needs, improving the characteristics of the photovoltaic glazing products based on crystalline silicon technology. The aimed result is the development of a fully black photovoltaic unit, enhancing the aesthetical appearance of the existing opaque products, but without losing its passive properties or electric efficiency. In order to be able to offer a product which meets the requirements of the customers, its customization in terms of geometry and formats has to be possible. It is also important to achieve an established target price and a target power, and, at the same time, to comply with the current regulations and standards.

This report consists of different sections, with the purpose of achieving the objectives regarding the PVSITES project:

- The first section shows market needs in the framework of the state of the art of the technology today and in the future.
- The following sections explain the different steps followed in the development of the prototypes and the final results which comply with the objectives established: study of the existing materials and selection of the most appropriated, different process followed for the development of the product and their results, the optimized manufacturing sequencing selected and the final results.
- The costs and pay-back analyses are also included in another section, to compare with the established target.
- Finally, the conclusions show the compliance with the objectives of the PVSITES project.

1.2 Relation with other activities in the project

Table 1.1 depicts the main links of this deliverable to other activities (work packages, tasks, deliverables, etc.) within PVSITES project. The table should be considered along with the current document for further understanding of the deliverable contents and purpose.

Table 1.1 Relation between current deliverable and other activities in the project

Project activity	Relation with current deliverable
WP1	WP1 sets the foundations for the effective development and exploitation of results into the market. Therefore, some results of this WP tasks have been taken into account in the development of this deliverable, mainly the actions related to the characterization of the markets, stakeholders and needs, and the regulatory and standardization framework. On the other hand, the conclusions that arise from this report will be used to further develop the tasks related to the exploitation, business model, commercialization and global risks analysis.
Task 2.1	Specifications for BIPV modules: this task includes the definition of the technical specifications for the PV modules and their manufacturing processes, the design requirements of the BIPV products for the different climates within the European Union and the architectural and aesthetical considerations. All this aspects are very important in the development of the current deliverable and their associated actions, because they establish the basis for the PV products design.
Task 2.3	BIPV products portfolio: all the products resulting from the PVSITES project will form part of a BIPV products portfolio, so its content is very much related to the content of the current deliverable.
Task 3.6	Modelling at element and building level. This task will provide advanced information of the passive and active properties of the WP3 products through a complete computational simulation.
Task 3.7	Performance validation testing. The aim of this task is to guarantee the compliance with the PV crystalline silicon standards and construction regulations. The required samples of opaque BIPV modules with hidden busbars and L-interconnections will be manufactured (D3.8 Samples for indoor validation tests, c-Si based products) and the results of the tests will be included in D3.9 Report on indoor validation tests, crystalline-silicon based BIPV elements)
D7.5	E-catalogs delivery. This deliverable shows the results of the Task 7.2: BIM objects for PVSITES products, included in the WP7 which focus on the development of a BIVP software tool and its validation. D7.5 will contain BIM objects representing PVSITES products, so input from the current deliverable will be needed.
WP8	The product analysed in this deliverable: Fully opaque BIPV modules with hidden busbars and L-interconnections will be demonstrated in a real building: the solution consists on a PV ventilated façade system for a residential building located in France. Therefore, all the tasks included in the WP8: Large scale demonstration and assessment of BIPV systems in real buildings, are strongly linked to the development of the product included in this deliverable D3.3.
WP9	Conclusions and knowledge resulting from this deliverable will be disseminated in order to show the reliability of the project and encourage future actions in the development of this field.

The following figure schematizes the relation between the mentioned tasks.

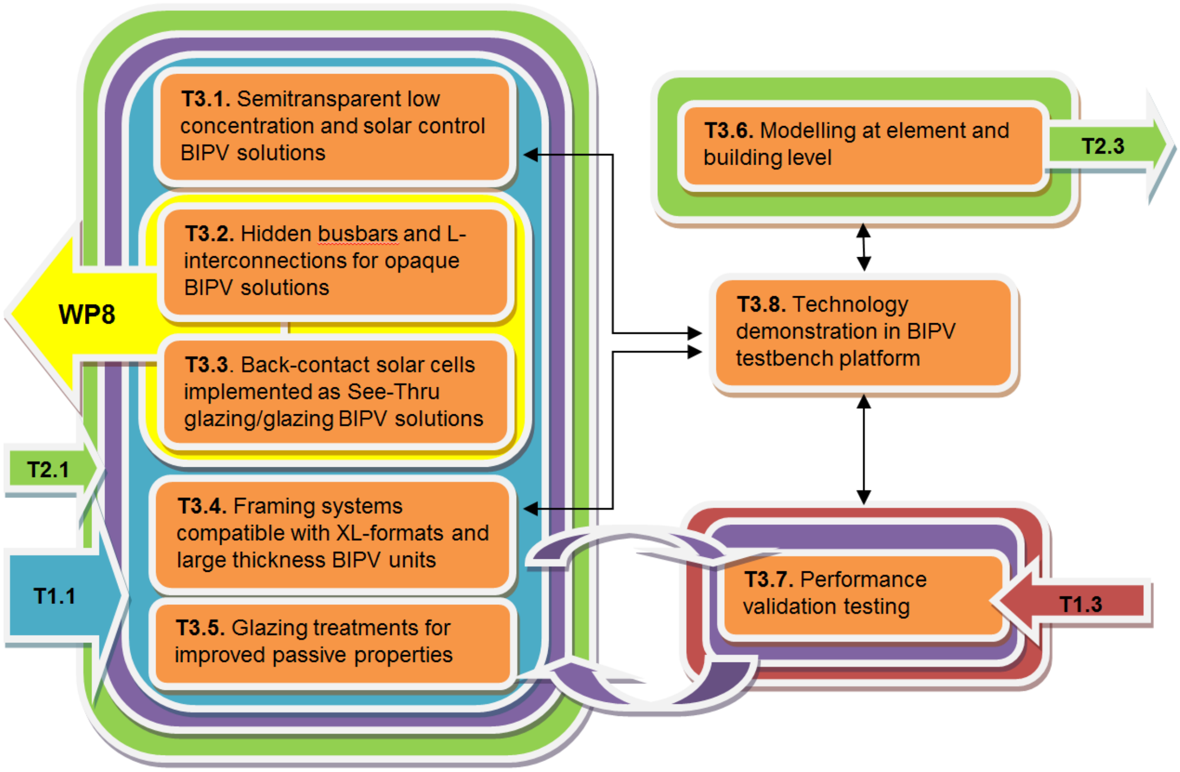

Figure 1.1 Relationship between T3.2 and other tasks

1.3 Reference material

This deliverable has used some data from PVSITES deliverable D2.1: Technical specifications for BIPV modules.

1.4 Abbreviation list

BIPV: Building Integrated Photovoltaics

c-Si: Photovoltaic crystalline silicon technology

D: Deliverable

EVA: Ethyl Vinyl Acetate

HVAC: Heating, Ventilation and Air Conditioning

STC: Standard Test Conditions

PVF: Polyvinyl Fluoride

PA: Polyamide

PET: Poly-Ethylen-Terephthalate

PV: Photovoltaic

PVF: Polyvinyl Fluoride

PVDF: Polyvinylidene Fluoride

U: Thermal transmittance

WP: Work Package

2 BACKGROUND

Crystalline silicon (c-Si) is one of the most efficient among all BIPV technologies and for many decades it has dominated the market due to its cost-effectiveness, so the improvement of this technology in order to increase its integration of buildings (BIPV) is crucial to optimise sustainability in the building sector.

Conventional c-Si panels are built using a white substrate, usually polyvinyl fluoride (PVF), so the dark crystalline cells give a contrast which makes their integration in buildings mostly unattractive for the architects and construction sector, even if, sometimes, the visual impact of the cells in c-Si technology is used to inspire and show a visible commitment to the environmental and energy efficiency. In order to solve this, some manufacturers offer the use of coloured PVF substrates, but another aesthetic limitation consists in the interconnection of the cells. The c-Si photovoltaic modules have a silver thin wire that collects current from the front surface and another thicker wire that connects the electrodes. These silver stripes present a marked contrast with the uniform appearance of the silicon cells. In addition, the stripes can go in different directions so that may provide a strange aesthetic of the product.

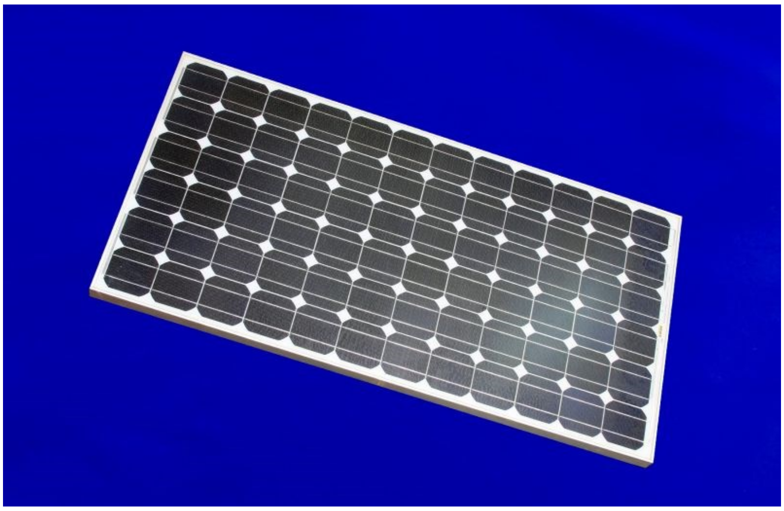

Figure 2.1 Conventional photovoltaic module [7]

On the other hand, for several architectural applications a glass-glass configuration is preferred instead of glass-tedlar. In other words, the PV material should behave as a building material. This modification allows working with the module in a similar way to a conventional architectural glass, which makes easier its integration with conventional structural systems. Better light transmission properties can be also obtained when using this configuration. In addition, the use of a glass-glass configuration leads to a better stability from a mechanical point of view. In consequence, the frequently used aluminum frame can be discarded, also improving aesthetics. The selected glass thickness normally depends on mechanical requirements of the integration, module size and structural supports.

Taking these considerations into account, ONYX has been working on the development of black fully opaque PV glass-glass units. Nowadays, the use of the colour in PV construction glass has still some limitations depending on the photovoltaic technology and the colour strategy adopted: durability, color deterioration, lifespan, compatibility of materials… For example, the main handicap of the use of coloured PV cells is that depending on the colour of the cells, consequent loss of efficiency may occur. In the same sense, there is not enough knowledge on the long term performance of the materials involved on coloured bus-bars and the adhesives used for glass-glass back contact cell technology.

Nowadays, the strategies adopted to obtain hidden bus-bars consist on the addition of several layers above the cell connections, but the process could be slow and costly. In this regard, this report shows the following different strategies for the development of two generations of black c-Si glass-glass modules:

1) First generation: Integration of different fully plastic sheets compatible with glass lamination process to hide the L- interconnections and use of black frit patterned rear glazing.

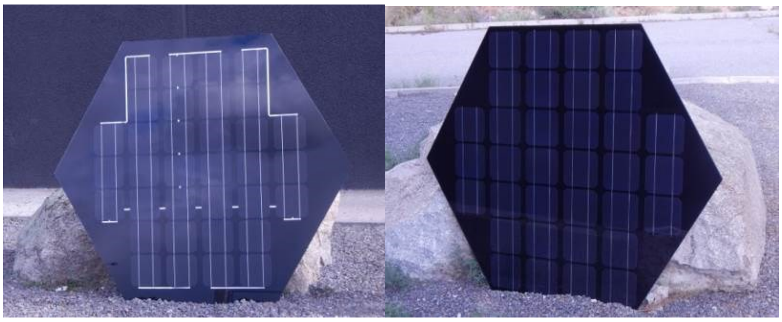

Figure 2.2 Strategy for hiding L interconnections by means of polymers foils (ONYX)

2) Second generation: use of black frit patterned rear glazing and implementation of black conductive ribbons over the welded cells in a string and L-interconnections.

2.1 Frit Patterned Glass

The use of frit patterned glass allows for diverse design options in architecture through the use of a wide variety of patterns and colours creating a subtle or bold look for a building. Therefore, silk-screened glass enhance the solar control performance and, combined with other substrates and coatings, can reduce the solar transmission and glare, decreasing solar gains in buildings (less cooling demand) and avoiding bird-on-glass collisions. More information about frit patterned is included in Deliverable D3.6: Glazing treatments for improved passive properties, report on materials and processes.

2.2 Plastics Sheets

Photovoltaic c-Si solar modules are composed of solar cells, contactors, and “packaging” materials. The function of these “packaging” materials, typically processed as polymeric sheets, is the protection of the cells. Depending on the position, it is possible to define three different types.

The front sheet is the first layer of the PV unit, and, for rigid crystalline silicon PV cells, is made of glass. Nevertheless the demand for plastic front sheets is increasing because of its lighter weight and low brightness.

The second “packaging” layer is the encapsulant, which is used to provide adhesion between the solar cells, the top surface and the rear surface of the PV module, through the lamination. An encapsulant is used to provide adhesion between the solar cells, the top surface and the rear surface of the PV module. The encapsulant has to be transparent and depending on the technology of the PV cell, the composition changes. The most commonly used encapsulant material for c-Si based modules is EVA (ethyl vinyl acetate).

The backsheet is the third layer of the PV unit, and, in most conventional modules, a thin polymer sheet is used as the rear surface. Nevertheless, this backsheet can be replaced by glass, to obtain a laminated photovoltaic glazing unit which provides a better mechanical resistance for BIPV applications.

With the aim of achieving a fully black PV c-Si glass-glass, different alternatives of plastics sheets have been analyzed. The idea is to use a black polymer sheet to hide the L-interconections of the cells, so the main requirements to meet are the compatibility of materials and colour possibility. Therefore, the election is a black backsheet to be cut into strips, and to place them between the encapsulant and the front glass where the L-interconnections are positioned.

Figure 2.3 Black back sheet evaluated

Tedlar registered trademark by Dupont is tipically used and the composition is polyvinyl fluoride. (PVF). However, there are other options in which the core material is generally Poly-Ethylen-Terephthalate (PET), and there are others composed of different materials and structures: PP (polypropylene), PVF (Polyvinil fluoride), PA (Polyamide), PVDF (Polyvinylede fluoride) [2].

Depending on the final use and required performance, there are different available versions: solar extreme conditions, weatherability, or transparency or black colors for BIPV applications. The most important photovoltaic backsheet manufacturers are 3M in the U.S., Agfa-Gevaert in Belgium, Alrack in the Netherlands, Aluminium Féron in Germany, and Anhui in China.

2.3 Black Ribbons

In order to know the existing possibilities in terms of coloured ribbons to be integrated in PV glass-glass modules, a search of the providers which offers different products has been made, and 9 providers have been contacted. Some of them are still in an experimental phase of product development, but other have already the technology developed and different samples of the materials have been ordered and analysed (see Figure 2.4).

The option of a machine for painting photovoltaic ribbon has been also evaluated.

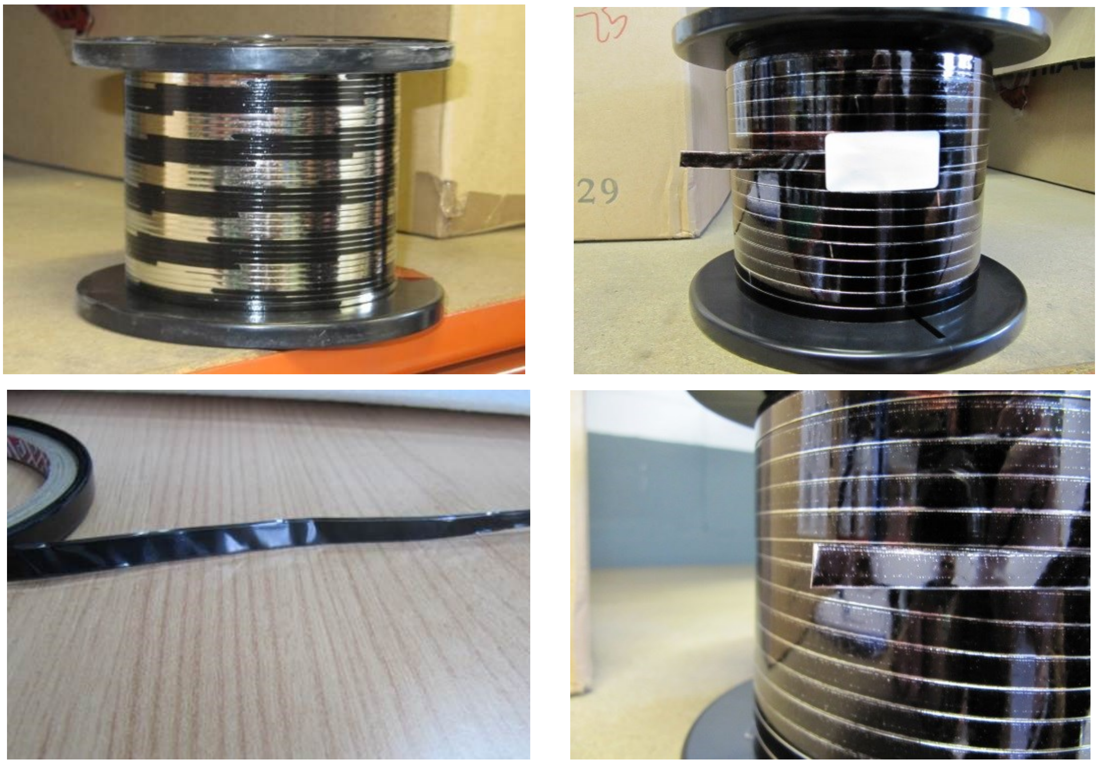

Figure 2.4 Different black ribbons tested

3 DEVELOPMENT OF PROTOTYPES

The following sections show the selected configuration and materials, and the results obtained through an optimized manufacturing process.

3.1 Selected Configuration and Materials

As it was explained above, two generations of the product will be developed:

- 1st generation: inter-cells: standard ribbon, L-strings: standard ribbon + black backsheet.
- 2nd generation: inter-cells: black ribbon, L-strings: ribbon covered with black plastic

Among the possible configurations, the following one has been selected for the development of the prototype: dimensions of 1700x1000mm, 6+6mm laminated glass, two layers of EVA encapsulation and 6" silicon mono-crystalline cells. These characteristics are chosen because they can meet with most of the buildings requirements. Nevertheless, it is possible to vary different parameters to adapt the product to the specific considerations of a project.

- Tempered front and rear glass are selected to achieve a final laminated glazing which compiles the current regulations for its use in building applications.
- Extraclear glass is selected as front glass, due to its appropriate optical characteristics, highly transparency level, high energy transmittance, very little residual colour (color neutrality) and less greenish appearance.
- A black frit patterned glass (frit on the outer surface) has been selected for the development of the product in order to avoid the contrast between the dark PV c-Si cells and the glass substrate.
- Cell Technology selected is Mono-Crystalline (3 busbars).
- Cell Dimensions are 156x156mm (6"x6").
- The module is built up with a configuration of 60 cells per module (6 strings/ 10 cells per string).
- The encapsulant selected is EVA.
- The junction box selected is PV-JBIWL-V MC (4 spring clamps).

3.2 Manufacturing Process

The manufacturing process of this product is shown in the deliverable D2.1: Technical specifications for BIPV modules.

3.3 Results

3.3.1 Manufactured prototypes

The following images show the final appearance of the manufactured prototypes (Figure 3.1 Figure 3.2) and some details of differentiating elements (Figure 3.3).

Figure 3.1 Front and back views of hidden busbars and L-interconnections product (1st Generation)

Figure 3.2 Front and back views of hidden busbars and L-interconnections product (2nd Generation)

Figure 3.3 Details of black ribbon and plastic sheets

3.3.2 Technical data and drawings

Technical data and drawings of the prototypes are detailed in the following figures and tables, including the following information:

- **Technical data sheet of final BIPV prototypes**. The parameters have been measured with ONYX´s solar testing simulator
- **Manufacturing drawings of final BIPV prototypes.**
- **Other properties**

Technical data sheets of final BIPV prototypes

PHOTOVOLTAIC GLASS	1700 x 6" Mono	1000 Crystalline
Electrical data test conditions (STC)		
Nominal peak power	260	P_{mpp} (Wp)
Open-circuit voltage	40,60	V_{oc} (V)
Short-circuit current	8,45	I_{sc} (A)
Voltage at nominal power	31,50	V_{mpp} (V)
Current at nominal power	8,28	I_{mpp} (A)
Power tolerance not to exceed	±10	%
STC: 1000 w/m², AM 1.5 and a cell temperature of 25°C, stabilized module state.		
Mechanical description		
Length	1700	mm
Width	1000	mm
Thickness	13,8	mm
Surface area	1,70	sqm
Weight	51,00	Kgs
Cell type	6" Mono	Crystalline
No PV cells / Transparency degree	60	0% (Opaque)
Front Glass	6 mm	Hidden connections
Rear Glass	6 mm	Tempered Glass+Black frit
Thickness encapsulation	1,80 mm	EVA Foils
Category / Color code		
Junction Box		
Protection	IP65	
Wiring Section	2,5 mm^2 or	4,0 mm^2
Limits		
Maximum system voltage	1000	Vsys (V)
Operating module temperature	-40…+85	°C
Temperature Coefficients		
Temperature Coefficient of Pmpp	-0,451	%/°C
Temperature Coefficient of Voc	-0,361	%/°C
Temperature Coefficient of Isc	+0,08	%/°C

* All technical specifications are subject to change without notice by Onyx Solar

Figure 3.4 Technical data sheet of hidden busbars and L-interconnections product (1st Generation)

PHOTOVOLTAIC GLASS	1700 x	1000
	6" Mono	Crystalline
Electrical data test conditions (STC)		
Nominal peak power	260	P_{mpp} (Wp)
Open-circuit voltage	38,10	V_{oc} (V)
Short-circuit current	9,05	I_{sc} (A)
Voltage at nominal power	31,44	V_{mpp} (V)
Current at nominal power	8,26	I_{mpp} (A)
Power tolerance not to exceed	±10	%
STC: 1000 w/m², AM 1.5 and a cell temperature of 25°C, stabilized module state.		
Mechanical description		
Length	1700	mm
Width	1000	mm
Thickness	13,8	mm
Surface area	1,70	sqm
Weight	51,00	Kgs
Cell type	6" Mono	Crystalline
No PV cells / Transparency degree	60	0% (Opaque)
Front Glass	6 mm	Black ribbon connections
Rear Glass	6 mm	Tempered Glass+Black frit
Thickness encapsulation	1,80 mm	EVA Foils
Category / Color code		
Junction Box		
Protection	IP65	
Wiring Section	2,5 mm^2 or	4,0 mm^2
Limits		
Maximum system voltage	1000	Vsys (V)
Operating module temperature	-40…+85	°C
Temperature Coefficients		
Temperature Coefficient of Pmpp	-0,451	%/°C
Temperature Coefficient of Voc	-0,361	%/°C
Temperature Coefficient of Isc	+0,08	%/°C

* All technical specifications are subject to change without notice by Onyx Solar

Figure 3.5 Technical data sheet of hidden busbars and L-interconnections product (2nd Generation)

Manufacturing drawings of final BIPV prototypes

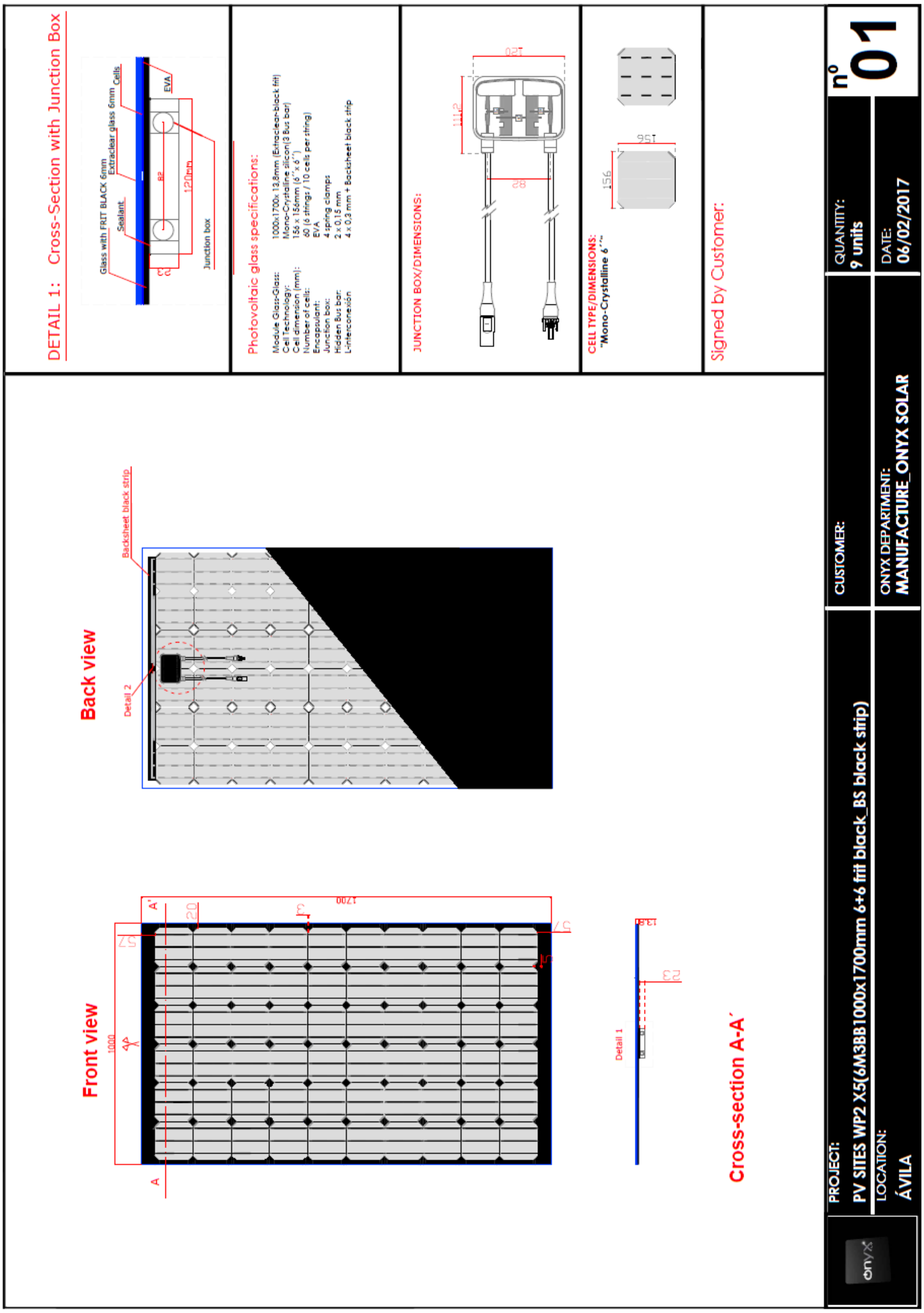

Figure 3.6 Manufacturing drawing of hidden busbars and L-interconnections product (1st Generation)

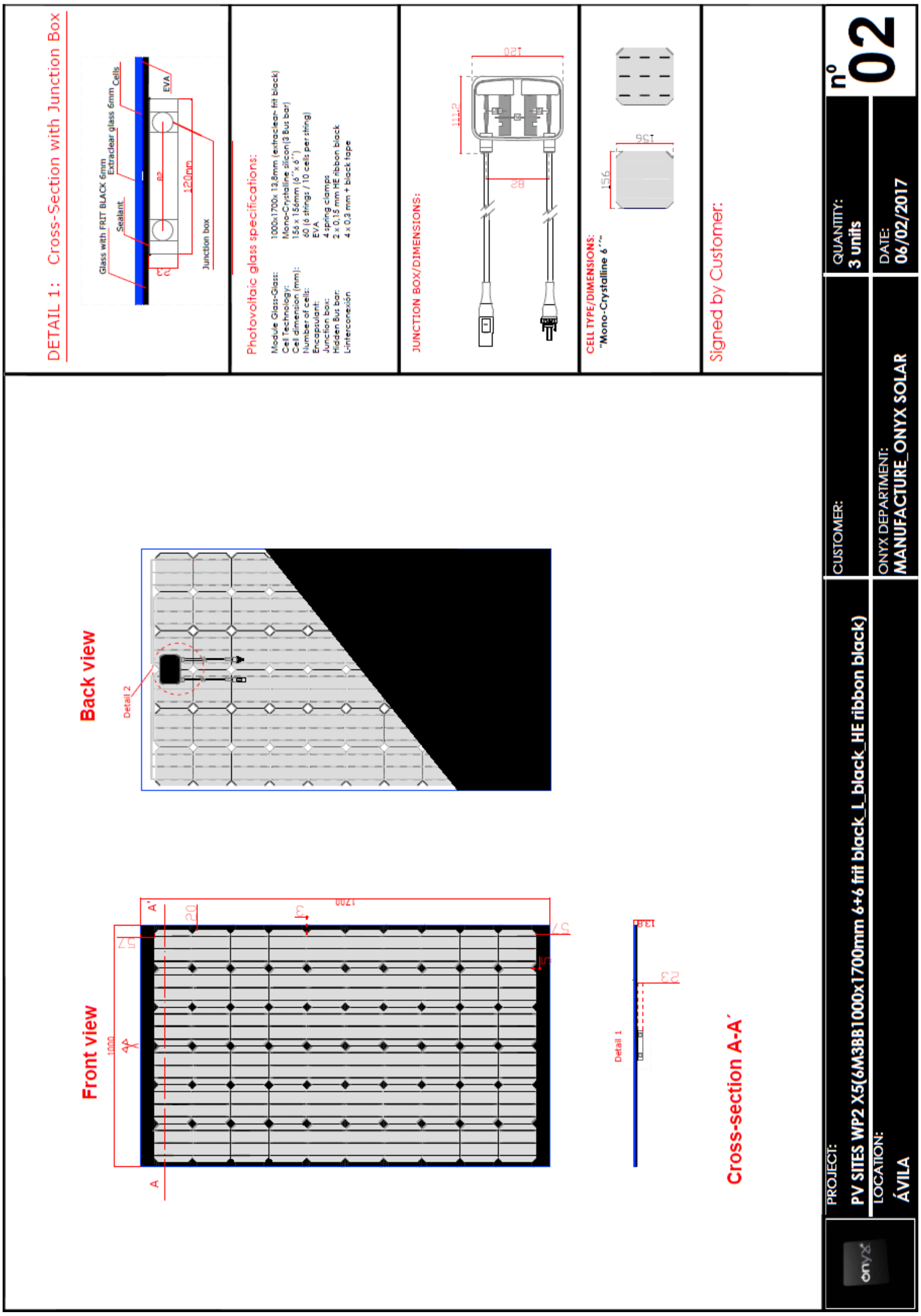

Figure 3.7 Manufacturing drawing of hidden busbars and L-interconnections product (2nd Generation)

3.3.3 Other properties

The results of different tests regarding thermal, mechanical, optical and electrical performance parameters of the prototypes developed will be included in D3.9 Report on indoor validation tests, crystalline-silicon based BIPV elements. An estimation of these values is presented in the D2.1 Technical specifications for BIPV modules.

4 COST ANALYSIS

Glass-based BIPV elements considered in PVSITES shall compete in terms of cost with architectural glazing getting as close as possible to materials parity, being the maximum overcost-net investment (price difference between BIPV glazing and non- PV glazing showing same passive properties performance) approximately 30% (100 €/m^2). This means that high performance BIPV glazing units shall meet a maximum price of 175-300€/m^2 by year 2018 for photovoltaic laminated glass and insulating glazing units with excellent thermal performance, achieving selling prices of 175-200 €/ m^2 by year 2021.

System efficiency has to provide reasonable ROIs for the final client. BIPV products must demonstrate business cases within the aforementioned targeted prices, with payback times of 5-7 years maximum. Efficiency must be therefore within the range of 70-160W/m^2 depending on the technology, passive properties and architectural integration.

4.1 Estimation of Cost

ONYX has estimated the necessary resources in the manufacturing of the new prototypes and calculated the costs and selling price of the solutions. The following table details selling price of the main solutions prototyped under this deliverable to produce BIPV units including a rear black frit, hidden busbars and L interconnections. The compliance with cost-effectiveness targets established in PVSITES project is indicated in next table and analyzed thereafter in next section:

Table 4.1 Cost, performance and payback of PVSITES PV products including a rear black frit, hidden busbars and L interconnections

	Fully opaque BIPV units	Comments
FINAL PRICE (€/ m^2)	295	Final price is calculated taking into account the overcosts of this product with respect to equivalent PV glass, including the costs of the frit patterned rear glass and overcosts in manufacturing derived from welding activities, lamination cycle optimization, etc.
TARGET PRICE (€/ m^2)	250-400	✓
PEAK POWER (W/m^2)	153	See detailed technical data in section 3.3.2
PERFORMANCE TARGET (W/m^2)	100-160	✓

Table 4.2 Cost analysis

1. FINAL PRICE OF BIPV UNITS WITH BACK CONTACT CELLS (€/ m^2)	2. PRICE OF PVSITES PRODUCTS APPLYING MARK-UP FOR MEDIUM ORDER (1000m^2) (€/ m^2)	3. PRICE OF EQUIVALENT CONVENTIONAL GLASS WITH THE SAME PASSIVE PROPERTIES (€/ m^2)	4.PRICE OF EQUIVALENT CONVENTIONAL PV PANEL (€/ m^2)
295	265	115	150
DIFFERENCE 2-3	150		
TARGET 2-3	Approximately 100 ✓		
DIFFERENCE 2-4	115		

4.2 Economic Analysis

4.2.1 Methodology

The economic study has been conducted considering the energy savings by the BIPV products under different scenarios. BIPV solutions generate free electricity for buildings while providing thermal and acoustical insulation, day lighting and sun control, as required by design. This combination of active and passive properties leads to outstanding return on the investments. Consequently, the building will also eliminate a significant amount of CO2 emission.

Therefore, it is important to take into account not only the electricity production of the photovoltaic glass, but also the improvement of the building envelope which means a lower consumption of lighting systems, cooling or heating, and the enhancement of the indoor comfort due to the radiation filtration with optimal natural light.

With the aim of having results of the reduction in the energy demand of a whole building due to fully black photovoltaic glass product developed in the current report, different models have been simulated with Design Builder software, including the outputs of the previous sections in the evaluation of the results. Design Builder software has been selected because it allows to obtain reliable results through dynamic simulations with 8760 hours per year, modelling in a multi-zone energy model scenarios. The geometry, the orientation and location, the constructive systems and their thermal properties, the HVAC and lighting systems characteristics, the occupants behaviour, and the filtration rates of the building are some of the factors that Design Builder software considers into their calculations increasing the reliability of the results.

An office building type has been chosen to simulate the energetic behavior under different scenarios. The south façade building is a conventional opaque wall and the idea is to analyze the implementation of different types of ventilated facades as an energy retrofit measure.

Ventilated façade is the selected system because it is the most appropriate to integrate the fully black photovoltaic product. The system is composed of an insulation material in the inner part, an air gap and a cladding material in the outer layer. The cladding layer can be made of different materials: wood, stone, composite, glass, photovoltaic glass…This system is implemented to reduce thermal exchanges and to avoid thermal bridges. Thanks to the ventilated air chamber and the application of insulating material, this system increases the acoustic absorption and reduces the amount of heat that buildings absorb in hot weather conditions. The difference between the density of hot and cold air within the air space creates natural ventilation through a chimney effect. This helps in eliminating heat and moisture, enhancing the comfort level of the occupants. By using a photovoltaic cladding material, the façade also produces clean electricity.

Therefore, the economic analysis is performed by comparing between the opaque existing conventional wall and the same wall with different ventilated façade systems. Also an economic analysis comparing the different conventional ventilated facades with the photovoltaic fully black (hidden bus-bars and L-interconections) modules is made to present the economic advantages of this innovative system with respect to other more conventional systems. In other words, the objective is to compare the products developed in the current report with other similar non-photovoltaic solutions.

The selected conventional ventilated façade systems are the following:

- Composite panel consisting of two aluminum cover sheets and a mineral-filled polymer core.
- Porcelain tiles.
- Conventional equivalent black glass (non-photovoltaic).

Furthermore, taking into account that the energy behavior of a building and the photovoltaic production depend on the climate conditions of the location, two different European cities with different solar irradiation have been selected in order to have more realistic results: Berlin and Madrid. As it is shown in the next figure, the level of irradiation in Madrid is high (1663 kWh/m^{2}year), and in contrast in Berlin is low (1004 kWh/m^{2}year).

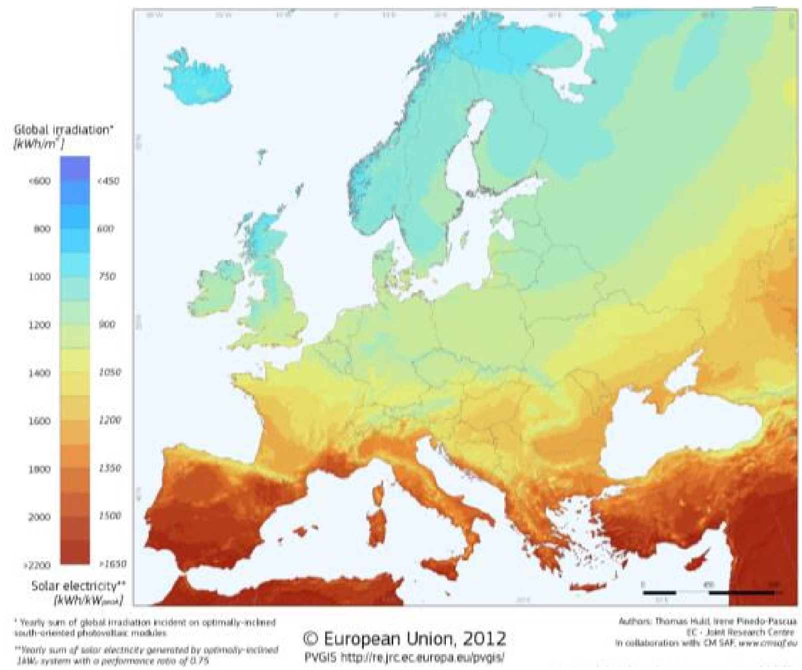

Figure 4.1 European solar irradiation map [6]

Energy data regarding electrical consumption of the building and photovoltaic production is obtained from dynamic simulations. With these data, the feasibility study can be carried out.

The following metric indicators have been calculated in order to evaluate the cost-effectiveness of the products developed:

- Average Reduction of Energy Demand: average reduction of energy demand per square meter of glass from energy generation and the HVAC (Heating, ventilation and air conditioning) savings in 30 years.
- Amount to Invest: investment needed to add photovoltaic properties to each sqm of glass and associated costs (balance of system, sub-structure…).
- Amount to Invest After Incentives: investment after applying possible incentives for solar photovoltaics. This report has not considered any possible incentives and/or feed in tariff system that the PV installation may qualify for.
- ROI (Return on Investment in 30 years): percentage increase or decrease of an investment over a set period of time. It is calculated by taking the difference between current (or expected) value and original value (profit-investment/investment).
- Payback Period: Time required for the return on the investment.
- IRR (Internal Rate of Return): average annual return during the first 30 years of the investment. It represents the interest rate at which the net present value of all the cash flows (both positive and negative) from a project or investment equal zero.
- Times the Investment: Number of times that the amount invested is received during the investment period of 30 years (average reduction of energy demand /investment).

Next section includes the results and an analysis. The financial conditions considered and other suppositions are shown in section 5.2.2. Hypothesis and Assumptions.

4.2.2 Results

The following figures show the 3D Design Builder models of the simulated three different façade systems on the south facade. The figure on the left represents a building with a conventional opaque facade; the figure in the middle corresponds to the same building with the implementation of a ventilated façade system, and the figure on the right to the equivalent building with a curtain wall system. The south façade is the changing one, and the rest of facades remain unchanged: conventional construction systems with conventional windows.

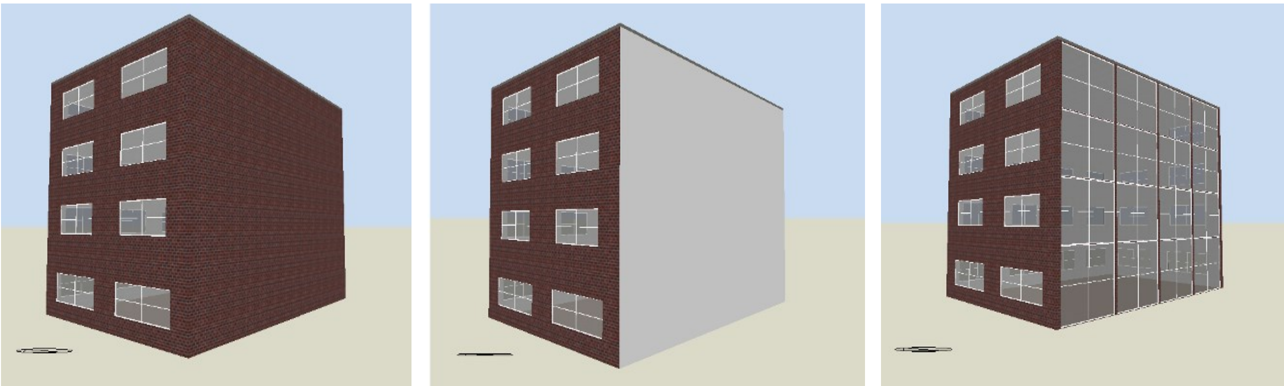

Figure 4.2 3D models for the conventional wall, ventilated façade and curtain wall economic studies

The following table summarizes the assumptions for the study.

Table 4.3 General assumptions taking into account in the economic study

	Madrid	Berlin
Total building area (m^2)	767,31	767,31
Net conditioned building area (m^2)	767,31	767,31
South façade area (m^2)	200	200
Peak power of PV fully black (W/m^2)	126	126
Local electricity cost (€/kWh)	0,2367	0,2981
Variation in electricity cost until 2020 (%) [4]	8,18	5,63
Variation in electricity cost from 2020 (%) [5]	1,00	1,00

4.2.2.1 Wall versus Wall with different types of ventilated façade systems

In this sub-section, as it was explained before, different alternatives of ventilated façade systems as retrofit measures are evaluated, in order to compare the benefits and the feasibility of the selected cladding materials and the photovoltaic fully lack units with hidden bus-bars an L-interconnections.The following table shows the different costs of the retrofit works.

Table 4.4 Costs estimation of ventilated façade system*[1]

	VENTILATED FAÇADE SYSTEM			
	Aluminium composite panels (€/m^2)	Porcelain tiles (€/m^2)	Conventional equivalent glass (€/m^2)	PV fully black glass (€/m^2)
Cladding material	49	130	115	265
Fixation system	62	80	70	70
Balance of system	0	0	0	107,10
Total	111,00	210,00	185,00	442,10

*[1]: indirect costs included

The most expensive system is the BIPV solution, but, as it will be demonstrated, the feasibility of the integration of this material in the analyzed scenarios is better than the conventional equivalent ones. The addition of photovoltaic properties to the glass not only produces electrical energy, but also contributes to decrease the energy consumption of Heating, Ventilation and Air Conditioner (HVAC) systems, thanks to the passive properties.

The following table shows the energy consumption and production of the building before the retrofit, the building after the implementation of a ventilated façade system (conventional), and the building after the implementation of a photovoltaic ventilated façade system (fully black glass). Energy demand reduction is higher in Berlin because the ventilated façade system increases the thermal insulation properties in cold seasons reducing the heating demand. In warm seasons the system also reduces the cooling demand of buildings, but the effect on the whole building is smaller. On the other hand, the energy production in Madrid is higher due to the better irradiation conditions of the location.

Table 4.5 Energy behavior of the building before and after the retrofit

	MADRID		BERLIN	
	HVAC energy consumption (kWh/year)	Renewable energy production (kWh/year)	HVAC energy consumption (kWh/year)	Renewable energy production (kWh/year)
Wall	52.140,72	0	68.222,79	0
Wall + conventional ventilated facade	50.829,31	0	63.340,75	0
Wall + photovoltaic ventilated facade	50.829,31	29.418,00	63.340,75	19.164,00

The following tables reflect the reduction in energy demand and cost in a period of 30 years when different ventilated façade systems are installed (equivalent conventional and photovoltaic). As it is shown in Tables 4.6 and 4.7, the energy savings of the whole building thanks to the developed product within the PVSITES project, reach a value of 53% in Madrid and 32% in Berlin, whereas with a conventional cladding material the percentages are limited to 3% in Madrid and 7% in Berlin. **This is a very interesting result and shows the advantage of the multifunctional BIPV solutions.**

Table 4.6 Total reduction of energy demand conventional ventilated façade systems

	WALL + CONVENTIONAL VENTILATED FAÇADE versus WALL						
	TOTAL REDUCTION OF ENERGY DEMAND IN 30 YEARS			PHOTOVOLTAIC ENERGY PRODUCTION IN 30 YEARS		ENERGY SAVINGS INDUCED BY THERMAL ENVELOPE IN 30 YEARS	
	Total reduction of energy demand due to the generation of energy and the savings in HVAC			Amount of Energy that our glass produces due to its photovoltaic properties		Amount of Energy that our glass saves due to its passive properties	
	(kWh)	(€)	(%)	(kWh)	(€)	(kWh)	(€)
Madrid	14.817	39.342	3%	0	0	14.817	39.342
Berlin	62.196	146.461	7%	0	0	62.196	146.461

Table 4.7 Total reduction of energy demand with PV fully black ventilated façade

	WALL + PHOTOVOLTAIC VENTILATED FAÇADE versus WALL						
	TOTAL REDUCTION OF ENERGY DEMAND IN 30 YEARS			PHOTOVOLTAIC ENERGY PRODUCTION IN 30 YEARS		ENERGY SAVINGS INDUCED BY THERMAL ENVELOPE IN 30 YEARS	
	Total reduction of energy demand due to the generation of energy and the savings in HVAC			Amount of Energy that our glass produces due to its photovoltaic properties		Amount of Energy that our glass saves due to its passive properties	
	(kWh)	(€)	(%)	(kWh)	(€)	(kWh)	(€)
Madrid	313.957	833.628	53%	299.140	794.286	14.817	39.342
Berlin	281.925	663.889	32%	219.729	517.428	62.196	146.461

Next tables show the main economic metric calculated for all the different ventilated façade systems. The use of non-photovoltaic cladding systems offers payback periods between 13 and 31 years, depending on the location and the chosen solution. As it was explained before, ventilated façade systems have a better behaviour in cold climates than in warm ones. However, by using photovoltaic materials, economic feasibility is similar for both locations, because the energy demand and energy production results are counterbalanced. Table 4.11 reflects a payback period lower than 10 years in Madrid and Berlin for the implementation of a fully black photovoltaic ventilated façade, including all the costs of mounting and electrical installation (not only the photovoltaic innovative glass).

Table 4.8 Economic metrics with aluminium composite ventilated facade

	WALL + ALUMINIUM COMPOSITE VENTILATED FAÇADE versus WALL						
	Average reduction of energy demand	Amount to invest	Amount to invest after incentives	ROI	Payback period	IRR	Times the investment
	(€/m²)	(€/m²)	(€/m²)	%	years	%	times
Madrid	74,08	111,00	111,00	-33%	< 31	-3%	0,67
Berlin	310,98	111,00	111,00	180%	< 13	8%	2,80

Economic metrics calculated of a 30 years period.
Madrid: Local electricity cost: 0,2367 €/kWh [3]; Variation in electricity cost until 2020: 8,18% [4]; from 2020: 1,00% [5].
Berlin: Local electricity cost: 0,2981 €/kWh [3]; Variation in electricity cost until 2020: 5,63% [4]; from 2020: 1,00% [5].

Table 4.9 Economic metrics with porcelain tiles ventilated facade

	WALL + PORCELAIN TILES VENTILATED FAÇADE versus WALL						
	Average reduction of energy demand	Amount to invest	Amount to invest after incentives	ROI	Payback period	IRR	Times the investment
	(€/m²)	(€/m²)	(€/m²)	%	years	%	times
Madrid	74,08	210,00	210,00	-65%	< 31	-6%	0,35
Berlin	310,98	210,00	210,00	48%	< 22	2%	1,48

Economic metrics calculated of a 30 years period.
Madrid: Local electricity cost: 0,2367 €/kWh [3]; Variation in electricity cost until 2020: 8,18% [4]; from 2020: 1,00% [5].
Berlin: Local electricity cost: 0,2981 €/kWh [3]; Variation in electricity cost until 2020: 5,63% [4]; from 2020: 1,00% [5]

Table 4.10 Economic metrics with conventional equivalent glass ventilated facade

	WALL + CONVENTIONAL GLASS (NON PV) VENTILATED FAÇADE versus WALL						
	Average reduction of energy demand	Amount to invest	Amount to invest after incentives	ROI	Payback period	IRR	Times the investment
	(€/m²)	(€/m²)	(€/m²)	%	years	%	times
Madrid	74,08	185,00	185,00	-60%	< 31	-5%	0,40
Berlin	310,98	185,00	185,00	68%	< 20	3%	1,68

Economic metrics calculated of a 30 years period.
Madrid: Local electricity cost: 0,2367 €/kWh [3]; Variation in electricity cost until 2020: 8,18% [4]; from 2020: 1,00% [5].
Berlin: Local electricity cost: 0,2981 €/kWh [3]; Variation in electricity cost until 2020: 5,63% [4]; from 2020: 1,00% [5]

Table 4.11 Economic metrics with PV fully black ventilated facade

	WALL + PHOTOVOLTAIC VENTILATED FAÇADE versus WALL						
	Average reduction of energy demand	Amount to invest	Amount to invest after incentives	ROI	Payback period	IRR	Times the investment
	(€/m²)	(€/m²)	(€/m²)	%	years	%	times
Madrid	1.569,78	442,10	442,10	255%	< 10	11%	3,55
Berlin	1.409,62	442,10	442,10	219%	< 10	10%	3,19

Economic metrics calculated of a 30 years period.
Madrid: Local electricity cost: 0,2367 €/kWh [3]; Variation in electricity cost until 2020: 8,18% [4]; from 2020: 1,00% [5].
Berlin: Local electricity cost: 0,2981 €/kWh [3]; Variation in electricity cost until 2020: 5,63% [4]; from 2020: 1,00% [5].

4.2.2.2 Photovoltaic ventilated façade versus different conventional ventilated façade systems

Now, a comparison between the fully black photovoltaic system and the selected conventional equivalent ventilated façade systems is made, with the aim of showing the economic benefits of the photovoltaic construction materials.

In the previous sub-section, a comparison between a building with only a conventional opaque wall, and the same building with different ventilated façade systems was made, in order to evaluate the energy and economic consequences of the implementation of different ventilated façade system as retrofit measures. In this case, the comparison is made between a photovoltaic ventilated façade and the other conventional ventilated façade systems selected. The economic metrics in this sub-section refer to the over-cost and benefits of the photovoltaic ventilated façade system with respect to other conventional ventilated façade systems, while the economic metrics of the previous sub-section refer to the over-costs and benefits of different ventilated façade systems with respect to a conventional opaque wall.

Next table shows the costs considered, including all expenses related to the implementation of the ventilated facade systems in a building. The table presents also the over cost of each conventional system when comparing with the photovoltaic one.

Table 4.12 Costs estimation of ventilated facade systems*[1]

	PHOTOVOLTAIC	CONVENTIONAL EQUIVALENT		
	PV fully black glass (€/m^2)	Aluminium composite panels (€/m^2)	Porcelain tiles (€/m^2)	Conventional equivalent glass (€/m^2)
Cladding material	265,00	49,00	130,00	115,00
Fixation system	70,00,	62,00	80,00	70,00
Balance of system	107,10	0	0	0
Total	442,10	111,00	210,00	185,00
Over cost of PV ventilated façade system by comparison of conventional equivalent		331,10	232,10	257,10
*[1]: indirect costs included				

For the analysis, the ventilated façade systems selected have the same thermal transmittance value (U value); for this reason, the HVAC consumption of all systems is the same, as it is shown in the following figure. However, only the photovoltaic ventilated façade system has the property of producing energy. According to the climate factors, In Madrid the energy production is higher and the energy demand lower than in Berlin.

Table 4.13 Energy behavior of a building with ventilated façade systems

	MADRID		BERLIN	
	HVAC energy consumption (kWh/year)	Renewable energy production (kWh/year)	HVAC energy consumption (kWh/year)	Renewable energy production (kWh/year)
Conventional	50.829,31	0	63.340,75	0
Photovoltaic	50.829,31	29.418,00	63.340,75	19.164,00

The values shown in the following table regarding the reduction in energy demand and cost in a period of 30 years comparing a conventional ventilated façade and a photovoltaic ventilated façade reflect higher energy savings in Madrid than in Berlin, due to the higher energy production. As mentioned, energy demand for both solutions is similar, so that the energy savings induced by thermal envelop in 30 years is 0 for both locations.

Table 4.14 Total reduction of energy demand with PV fully black ventilated facade

	PHOTOVOLTAIC VENTILATED FAÇADE versus CONVENTIONAL VENTILATED FACADES						
	TOTAL REDUCTION OF ENERGY DEMAND IN 30 YEARS			PHOTOVOLTAIC ENERGY PRODUCTION IN 30 YEARS		ENERGY SAVINGS INDUCED BY THERMAL ENVELOPE IN 30 YEARS	
	Total reduction of energy demand due to the generation of energy and the savings in HVAC			Amount of Energy that our glass produces due to its photovoltaic properties		Amount of Energy that our glass saves due to its passive properties	
	(kWh)	(€)	(%)	(kWh)	(€)	(kWh)	(€)
Madrid	299.140	794.286	52%	299.140	794.286	0	0
Berlin	219.729	517.428	27%	219.729	517.428	0	0

Next tables show the main economic metrics calculated, comparing the use of the photovoltaic material with each selected conventional solution. The payback varies from 6 to 10 years, depending on the solution and location. That means that, even if the costs of the photovoltaic fully black ventilated façade system is more expensive, in the long term the implementation of the BIPV units is feasible.

Table 4.15 Economic metrics with aluminium composite ventilated facade

	PHOTOVOLTAIC versus ALUMINIUM COMPOSITE VENTILATED FAÇADE						
	Average reduction of energy demand	Amount to invest	Amount to invest after incentives	ROI	Payback period	IRR	Times the investment
	(€/m^2)	(€/m^2)	(€/m^2)	%	years	%	times
Madrid	1.495,70	331,10	331,10	352%	< 8	14%	4,52
Berlin	1.098,65	331,10	331,10	232%	< 10	10%	3,32

Economic metrics calculated of a 30 years period.
Madrid: Local electricity cost: 0,2367 €/kWh [3]; Variation in electricity cost until 2020: 8,18% [4]; from 2020: 1,00% [5].
Berlin: Local electricity cost: 0,2981 €/kWh [3]; Variation in electricity cost until 2020: 5,63% [4]; from 2020: 1,00% [5].

Table 4.16 Economic metrics with porcelain tiles ventilated facade

	PHOTOVOLTAIC versus PORCELAIN TILES VENTILATED FAÇADE						
	Average reduction of energy demand	Amount to invest	Amount to invest after incentives	ROI	Payback period	IRR	Times the investment
	(€/m²)	(€/m²)	(€/m²)	%	years	%	times
Madrid	1.495,70	232,10	232,10	544%	< 6	19%	6,44
Berlin	1.098,65	232,10	232,10	373%	< 7	15%	4,73

Economic metrics calculated of a 30 years period.
Madrid: Local electricity cost: 0,2367 €/kWh [3]; Variation in electricity cost until 2020: 8,18% [4]; from 2020: 1,00% [5].
Berlin: Local electricity cost: 0,2981 €/kWh [3]; Variation in electricity cost until 2020: 5,63% [4]; from 2020: 1,00% [5].

Table 4.17 Economic metrics with conventional glass ventilated facade

	PHOTOVOLTAIC versus CONVENTIONAL GLASS VENTILATED FAÇADE						
	Average reduction of energy demand	Amount to invest	Amount to invest after incentives	ROI	Payback period	IRR	Times the investment
	(€/m²)	(€/m²)	(€/m²)	%	years	%	times
Madrid	1.495,70	257,10	257,10	482%	< 7	18%	5,82
Berlin	1.098,65	257,10	257,10	327%	< 8	14%	4,27

Economic metrics calculated of a 30 years period.
Madrid: Local electricity cost: 0,2367 €/kWh [3]; Variation in electricity cost until 2020: 8,18% [4]; from 2020: 1,00% [5].
Berlin: Local electricity cost: 0,2981 €/kWh [3]; Variation in electricity cost until 2020: 5,63% [4]; from 2020: 1,00% [5].

4.2.3 Hypothesis and Assumptions

This feasibility study has been carried out on a good faith basis under the following hypothesis and assumptions:

- Electricity prices have been obtained from EUROSTAT (second semester 2014) [3].
- Up to year 2020, the average price increase is at 8,18% for the buildings with annual consumption under 500 MWh, during the last 10 years in SPAIN (electricity price in 2004S1: 10,79 cents EUR/Kwh; electricity price in 2014S1: 21,65 cents EUR/Kwh); the average price increase is at 5,63% for the buildings with annual consumption under 500 MWh, during the last 10 years in GERMANY (electricity price in 2004S2: 17,20 cents EUR/Kwh; electricity price in 2014S2: 29,74 cents EUR/Kwh) [4].
- From year 2020 onwards, the price increase used is at 1% which considers the energy price forecast included in the European Commission report “EU Energy, Transport, and Greenhouse Gas Emissions Trends to 2050” [5].
- Energy savings are calculated from the simulations with the following software and database: Design Builder and Energy Plus.
- Photovoltaic energy production is estimated from simulations done with PVsyst developed by the Institute for the Sciences of the Environment Group of Energy, University of Genève, Switzerland. The energy estimations do not take into account shadows and system losses.
- The PV power output reduction in 30 years is estimated in 20%.
- Calculation estimates 30 years of building use.
- The building’s volume measures 12x17m. The total floor area of the building is 767 m^2 divided in four floors. The building’s largest façades surface is oriented at 0° and 180° (North and South). The south façade is opaque, and the window to wall ratio (WWR) for the rest is 30%.
- Passive properties of different construction systems and materials are obtained from the library data of the program, and the thermal transmittance values (U-value) of the different solutions are calculated according to the ISO 10292/ EN 673). The calculated U value of the opaque wall is 2,07 W/m^2K and the U value of the opaque wall with a ventilated façade system is 0,53 W/m^2K.
- All HVAC equipment are connected to the electricity grid.
- The simulation does not include additional energy savings in HVAC and load reduction or the improvements in thermal envelope.
- Balance of System cost has been extracted from the Solar Market Insight Report 2015 Q1 elaborated by the Solar Energy Industries Association of USA [2].

5 CONCLUSIONS

After the work carried out under this deliverable, **ONYX has provided an answer to market requirements in terms of integration and aesthetics and efficiency of c-Si BIPV solutions, maintaining the efficiency**. Therefore the objectives of this deliverable within Work Package 3 have been successfully fulfilled and several conclusions can be drawn, including the following:

1. ONYX has analyzed the market needs in the framework of the state of the art of the technology used for producing fully opaque BIPV units. In this sense a study of the S.O.T.A of the involved materials in producing fully opaque BIPV modules (black frits, plastic sheets, black ribbon, etc.) has been undertaken increasing ONYX´s existing knowhow in the field.
2. The different steps in the development of prototypes have been analyzed and a selection among existing materials has been carried out aiming to find the most appropriate way to manufacture the final prototypes.
3. Manufacturing sequence, welding process and lamination cycle have been optimized to include the new used materials. Prototypes have been successfully fabricated.
4. ONYX has estimated the necessary resources in the manufacturing of the new prototypes and calculated the costs, selling price and payback time of the solutions. In this sense:

   - Price of the solutions successfully meet pre-established targets (250-400 €/m^2) and final price is near to maximum limit of target prices by year 2018 (175-300€/m^2).

   - Price of the solutions with respect to equivalent non-PV systems at same passive property performance are in line with the pre-established ratio for 2018-2020 (difference of approximately 100 €/m^2). Furthermore, the price difference in comparison with equivalent PV conventional panels is attractive (115€/m^2). These competitive values guarantee a great adaptation to market and envision the approximation to materials parity by 2020. In this sense, manufacturing optimization processes will allow to reduce the difference in a short term basis. Pre-established performance target (100-160 W/m^2) is achieved.

   - Pre-established payback time target (5-7 years) is achieved for some scenarios in two selected cities in Europe corresponding to different climate conditions. It is important to take into account that BIPV applications feasibility depends on the location, the geometry, construction systems and use of the building, because of the active and passive properties of the photovoltaic glass. Depending on each situation, payback values and other economic metrics can change, depending on the energy production and energy behavior of the building associated to these variables.

6 REFERENCES

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