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See-through photovoltaic glazing solutions based on back contact solar cells

Project report

ONYX SOLAR

April 2017

www.pvsites.eu

Summary

This document describes the development of laminated glazing units with back-contact solar cells. Background information on this cell technology is additionally provided, and a cost competitiveness analysis of the developed products is conducted.

Acknowledgements

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The present report was prepared by PVSITES project partner ONYX SOLAR. The report was originally submitted to the European Commission as Project Deliverable D3.4 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
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Contents

Tables

Figures

1 EXECUTIVE SUMMARY

1.1 Description of the deliverable content and purpose

High efficiency solar cells with low production costs is the main objective pursued by the photovoltaic industry, and the research developments actions are focusing to give a solution. On the other hand, in BIPV applications, more aesthetic photovoltaic modules are demanded, looking for new designs to be integrated in the buildings envelops.

In this regard, in the last decade, the interest in back contact cells has been growing and a gradual introduction to industrial applications is emerging [22]. Back contact cells have both the positive and negative external contact pads positioned on the rear surface, and their use can improve the device performance avoiding the front contact shadow loss. In addition, back contact cells create a homogeneous appearance without any reflectance or visible cells interconnections on the front of the cells, and they are also a good option for semi-transparent BIPV applications combining less cell density, high efficiency levels and attractive appearance.

This report contains the development of welding process for back contact solar cells within a glass-glass lamination process, and the results of the actions deployed in Task 3.3 Back-contact solar cells implemented as see-thru glazing/glazing BIPV solution. The work carried out shows a see-thru product for specific building solutions such as skylights and curtain walls.

This report consists on different sections, with the purpose of achieving the objectives regarding the PVSITES project in terms of the improvement of aesthetical characteristics of PV modules maintaining energy performance and passive properties, regulation and standards compliance, not geometry or formats restrictions, and costs below a target limit set:

- The background section briefly explains the status of the technology today, the state of the art. It also includes the evolution of the back contact cells development and their main characteristics.
- The second section shows how the prototype has been developed; the configuration and the design, the existing alternatives and how the problems encountered have been resolved. The final results achieved are presented, as well as the optimized manufacturing process description.
- An analysis of the costs and payback periods calculation is presented in Section 4.
- The final section includes the main conclusions in regards to the PVSITES framework.

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 foundation for effective development and exploitation of results into the market, therefore, some results of the tasks of this WP 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 considerably 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 BIPV glass-glass modules with back contact solar cells 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-catalogues 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	BIPV glass-glass modules with back contact solar cells will be demonstrated in a real building: the solution consists on a PV ventilated façade system for an office building located in Spain. 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 D3.4.
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.

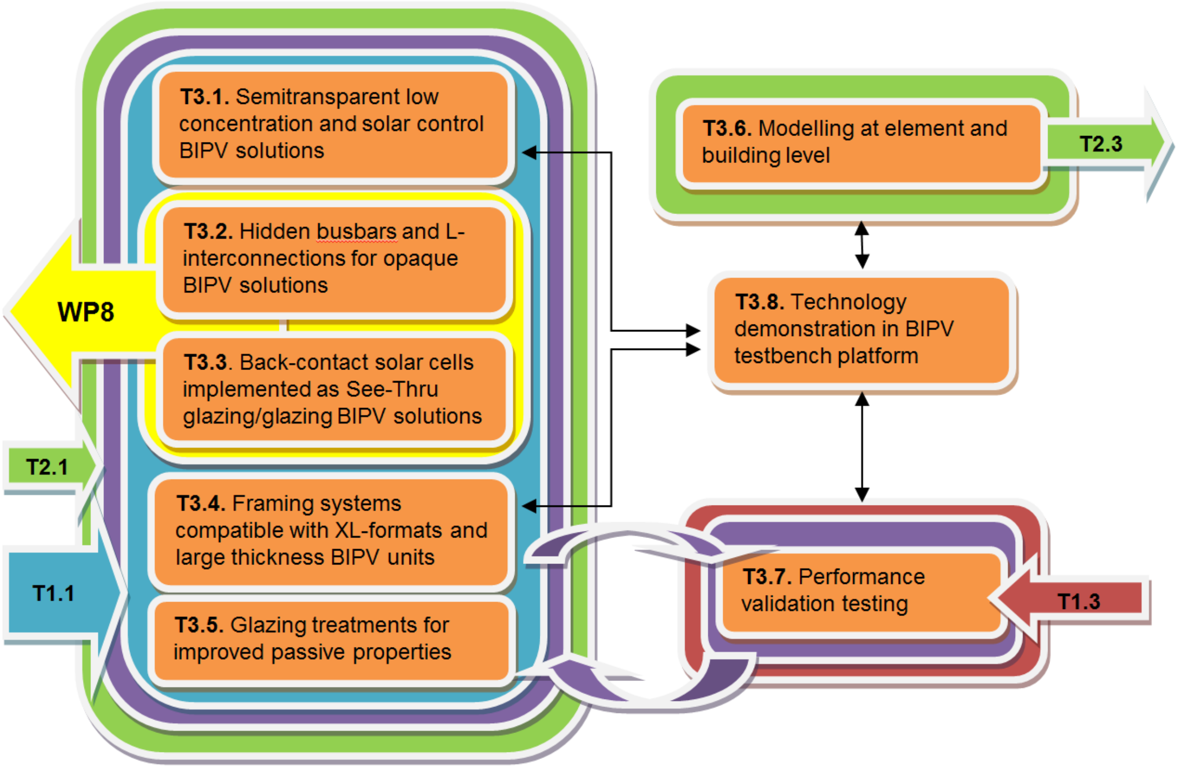


Figure 1.1 Relationship between T3.3 and other tasks

1.3 Reference material

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

1.4 Abbreviation list

BC: Back Contact

BC-BJ: Back-Contact Back-Junction solar cell

BIPV: Building Integrated Photovoltaics

c-Si: Crystalline silicon

D: Deliverable

EWT: Emitter Wrap Through

IBC: Interdigitated Back Contact

MWT: Metal wrap-through

PV: Photovoltaics

STC: Standard Test Conditions

WP: Work Package

2 BACKGROUND

2.1 Introduction

Solar energy is rapid growing and shows a shining-looking future. PV products based on c-Si technology are the most widespread and predominant on the market, accounting for an estimated 75-90% share of BIPV installations. A good balance in efficiency, cost and major performance stability justifies this market lead. However, from the point of view of BIPV field, this technology has still some critical points to solve regarding aesthetical considerations.

Interdigitated back contact (IBC) solar cells offer numerous advantages over conventional solar cells including significant improvement in short circuit current achieved from zero shading loss; simpler interconnection techniques and a higher packing density [11]; improved aesthetics; lower resistive losses and consequently higher efficiencies [22]. Nevertheless, the back-contact technology available on the market today is extremely expensive if highly efficient (Back-Contact Back-Junction solar cell or Interdigitated Back Contact), or not very efficient if cost-effective (Metal Wrap-Through).

Back contact solar cells are used by Sunpower in their SunTile product, achieving a homogeneous black appearance, seamlessly integrated in the roof. On the other hand, IMEC has developed in the past years Eurotron concept for PV modules manufacturing with back-contact solar cells and interconnection on a conductor sheet. This technology has been in the market for 6 years now but has not taken off, mainly because the process needs specially manufactured cells, which cannot be used for other kind of modules. These cells do not provide efficiency enhancements which justify their use either. Busbars are eliminated, but front metallization is still high, so the result is still not aesthetically pleasing.

Experts are convinced that low-cost and high-efficiency BC-BJ/IBC cells and modules will be possible, and the technology will have an important role and market position in the future. Even though the highest power advantage is becoming smaller and smaller, there are still a number of applications, mostly in the building segment, that make IBC an extremely attractive option.

2.2 Back Contact Cells Characteristics

Schwartz and Lammert introduced in 1975 the concept of the back-contact back-junction solar cells (IBC: Interdigitated Back Contact), as an alternative to conventional cells with a front and rear contact. Ever since his first publications, back-contact has remained a research topic. Nevertheless, in the last decades, the interest in back contact solar cells on behalf the industry has been increased, but only a few of these more advanced technologies were introduced into industrial production [22].

Back-contact solar cells exhibit both polarities of the metal electrodes (emitter and base electrodes) on the back cell side. Due to this fact the back-contact solar cells exhibit some major advantages over the conventional solar cell with metal contact on the front side.

The main advantages of the back-contact technology are:

- Increasing efficiency (from ~ 16% to ~ 25%).
- Improvement in short circuit current achieved from zero shading loss.
- Simpler interconnection techniques.
- Higher packaging density.
- Improved aesthetics.

- Lower resistive losses.
- Front surface can be optimized for optimum light trapping and surface passivation properties (due to the absence of the front side metal grid).

Nevertheless, this technology also presents some disadvantages:

- The process is complex and risky.
- High cost of production.

2.3 Types of Back-Contact Cells

Back contact cells are divided into three main classes and each introduced as logical descendants from conventional solar cells:

- Back-Contact Back-Junction solar cell (BC-BJ) also called Interdigitated Solar Cell (IBC).
- Emitter Wrap Trough (EWT) solar cells.
- Metallization Wrap Through (MWT) solar cells.

Figure 2.1 to 2.4 show the logical evolution from conventional solar cells through the schematic representation of the characteristics of these three major categories of back contact cells.

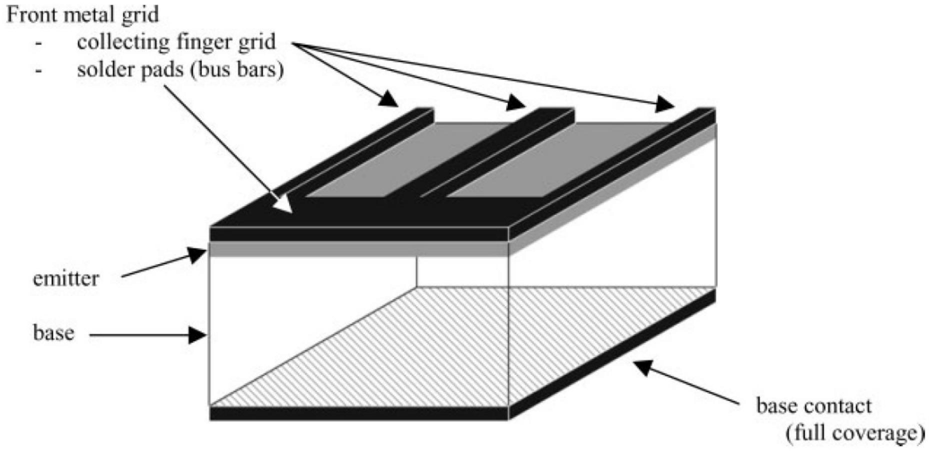


Figure 2.1 Schematic representation of a conventional solar cell [22]

Conventional bulk crystalline silicon solar cell (Figure 2.1): The silicon base is the main part of the mechanical structure. The emitter is located near the top or front surface. A metal grid to extract the carrier from the device contacts each of these silicon regions and the rear surface is often fully covered [22].

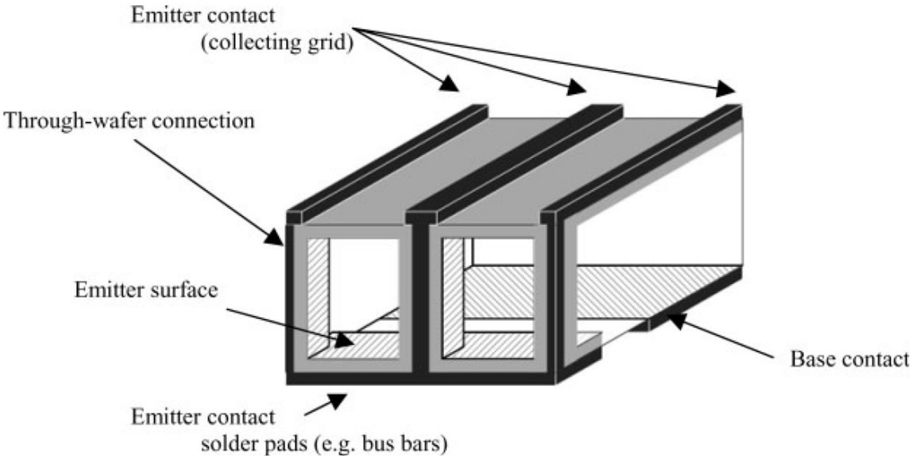


Figure 2.2 Schematic representation of a metallization wrap-through solar cell [22]

Metallization Wrap Through (MWT) solar cells (Figure 2.2) in which the front surface collecting junction and the front metallization grid are connected to the interconnection pads on the back surface via laser-drilled holes [6].

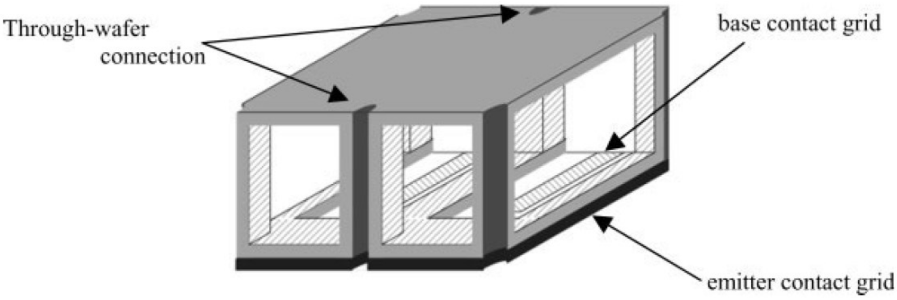


Figure 2.3 Schematic representation of an emitter wrap-through solar cell [22]

Emitter Wrap Through (EWT) solar cells (Figure 2.3), in which the front surface collecting junction is connected to the interdigitated contacts on the back surface via laser-drilled holes [6].

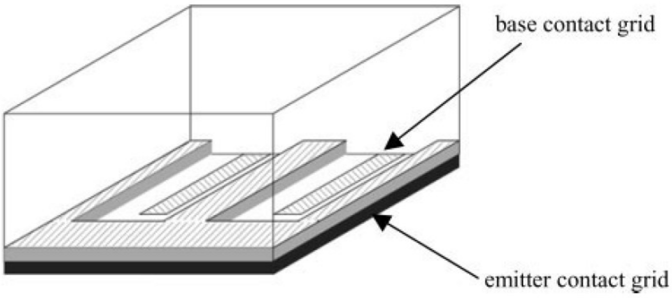


Figure 2.4 Schematic representation of a back-junction solar cell [6]

Back-Contact Back-Junction (BC-BJ) solar cells (Figure 2.4), also called Interdigitated Back Contact (IBC) solar cells, which have both contacts and the collecting junction placed on the back side of the cell [6].

Today, however, there are many module technologies on offer for BC solar cells, but there are very few manufactures producing this type of cell. Among them, IBC is the most hopeful concepts in further improving cell efficiency. The only feasible way of launching BC technology on the market, is by means of a cost-effective IBC module manufacturing process [12].

2.4 Historical IBC Evolution

In 1975 Schwartz and Lammert introduced the concept of the back-contact back-junction solar cell, designed or high-concentration solar systems. Both emitter and base metal contacts are placed on the back cell side in a form of an interdigitated grid. Also the emitter and back surface field diffusions are in the form of the interdigitated grid [6].

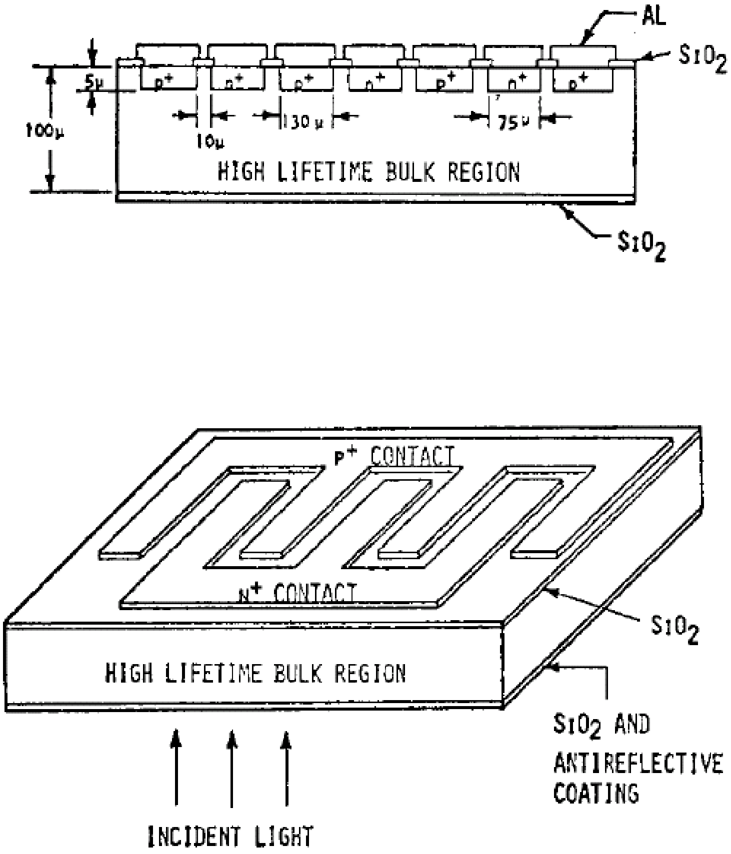


Figure 2.5 The structure of the interdigitated back contact IBC solar cell [16]

Almost ten years after, in 1984, Prof. Swanson changed slightly the design, but the consequences were important in the field of the IBC cells. The main difference of this type of cell, where a point contact silicon solar cell is introduced, is that there is only an array of small points which produce rear side diffusion, increasing the efficiency of the cell because of the reduction of the dark saturation current.

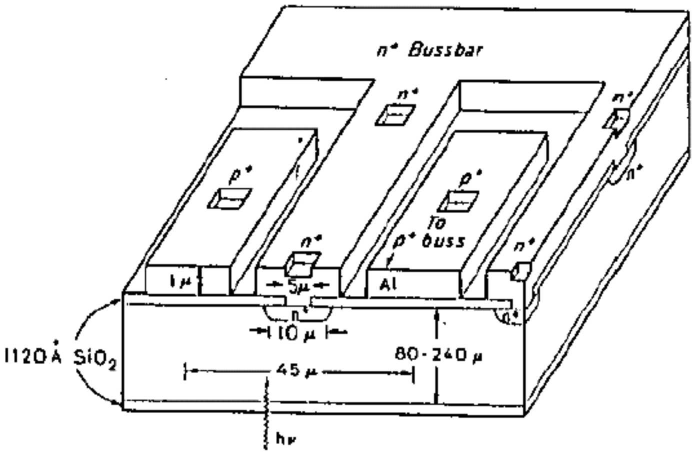


Figure 2.6 Structure of a point contact solar cell [21]

In the following years the photovoltaic group at Standford University led by him, made the most important contributions in the development of this technology:

- Non-textured point contact concentrator solar cell achieved an efficiency of 19,7% under 88-suns concentration in 1984 [21].
- In 1986 a further optimized point contact solar cell with an efficiency of 27,5% under 100 suns concentration was achieved by Sinton et al. [19].
- Shortly after, increased device cell efficiency up to 28% under 150 suns was after presented by Sinton et al. [17].
- In 1988 Sinton et al. [20] reported point contact solar cells with an efficiency of 28,4% at power densities up to 200 suns.

The back-contact back-junction solar cell structure was also optimized for the applications under standard one-sun illumination:

- In 1985 Verlinden et al. presented an IBC solar cell with a one-sun illumination efficiency of 21% [24].
- One year later Sinton et al. introduced a point contact solar cell with 21,7% one-sun efficiency. The area of these solar cells was 0,15 cm^2. [19].

In 1988, with the aim of reducing the high manufacturing costs, a self-aligned method for an interdigitated contact grid was introduced. In 1990 Sinton et al. [18] presented a simplified back-side solar cell, which used this self-aligned contact separation and allowed for reduction of the masking steps to one. For the simplified processing sequence a 10,5 cm^2 one-sun solar cell with an efficiency of 21,9% was reported.

2.4.1 Sun Power Corporation

With the objective of commercializing high-efficiency back contact silicon solar cells, in 1985 Swanson founded The Sunpower Corporation, and from this moment, the company has gradually improved the results:

- 1997: optimization of edge passivation and substrate doping achieving a record one-sun efficiency of 23,2% reported in 1997 by Verlinden et al. [23].
- 2002: process simplification reducing costs by 30% reported by Cudzinovic et al [2].

- 2004: A-300 product achieves a maximum of cell efficiency of 21,5. To reduce fabrication costs, SunPower has developed low cost screen-printing technology to replace photolithography in the fabrication the rear contact solar cells [14].

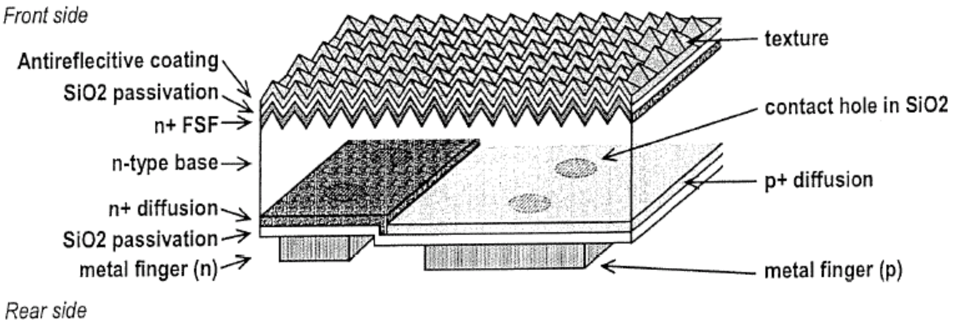


Figure 2.7 Schematic diagram of the Sunpower's A-300 solar cell [15]

- 2008: Back-Side contact solar cell with doped polysilicon regions with "tunnel oxide" (2008). Maximum efficiency reported: 25% for a solar cell. Patent: US 7468485 B1.
- 2012: Back-Side contact solar cell with formed polysilicon doped regions. This solar cell is similar to the previous one but without the "tunnel oxide" (and the manufacture process is different). Patent US 8242354 B1.

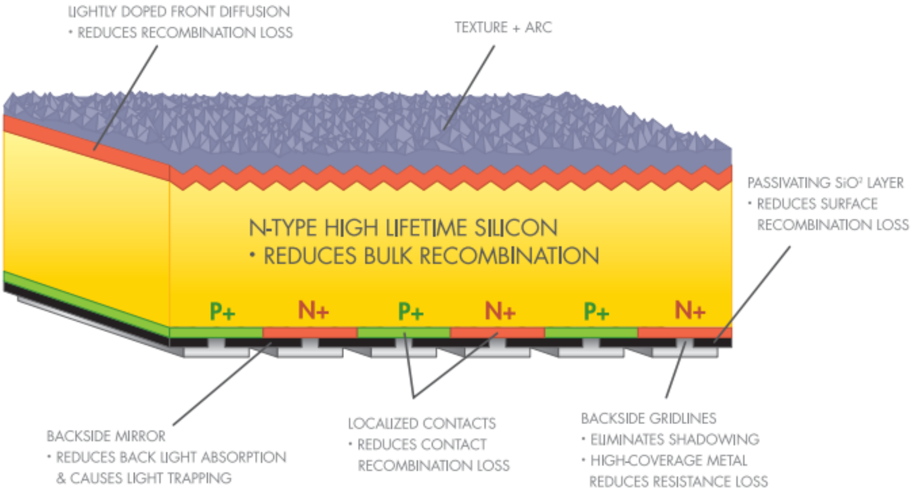


Figure 2.8 Current solar cells by SunPower [25]

- Maxeon GEN II solar cells in E-series modules (product): average efficiency of ~20% for modules and ~22,5% concerning solar cells.
- Maxeon GEN III solar cells in X-series modules (product): average efficiency of ~21,5% for modules and ~24% concerning solar cells.

The manufacturing method is described in the patent "Back-Side contact solar cell structure and fabrication processes" in 2012 (Patent US 8163638 B2).

2.4.2 Institute for Solar Energy Research Hamelin

2006-2007 Engelhart at al. [7, 10] from the ISFH, developed a solar cell structure called RISE (Rear Interdigitated contact scheme, metalized by a Single Evaporation). The solar cell is fabricated using a mask-free process, in which the laser ablation of Si and laser ablation of protective coatings are applied. With this cell structure a designated area efficiency of 22% was achieved on a 4 cm^2 laboratory solar cell [6].

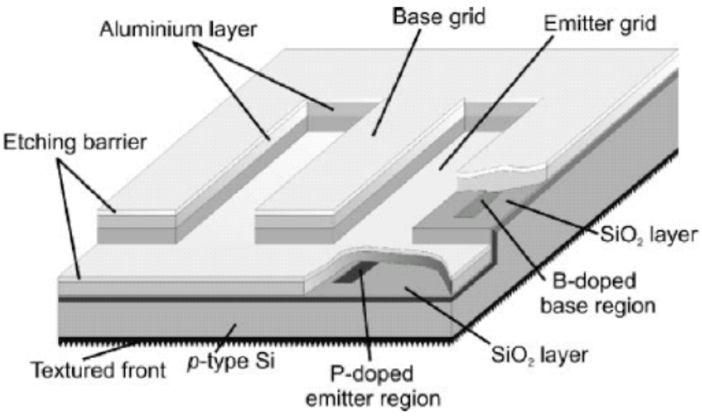


Figure 2.9 Schematics of the RISE back junction solar cell [7]

2.4.3 Technology from Fraunhofer Institute for Solar Energy Systems (Fraunhofer ISE)

2002-2003: At Fraunhofer ISE, a rear-contacted (RCC) silicon solar cell with line contacts was processed using the photolithography masking. An efficiency of 22,1% was reported by Dicker et al. [3, 4]. The photolithography masking is used for processing the line contacts [5].

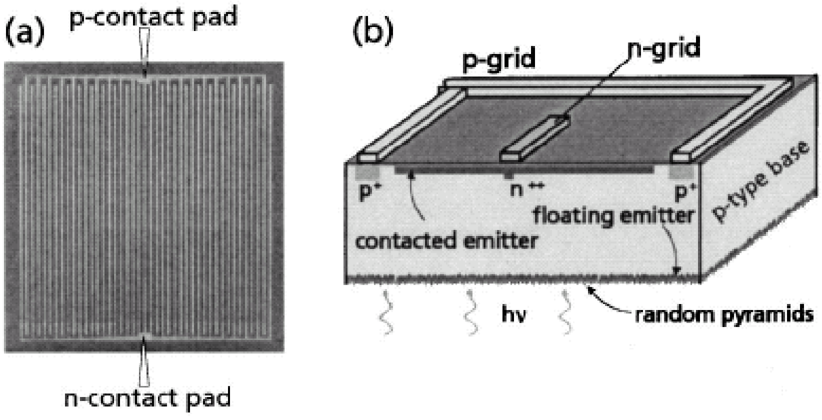


Figure 2.10 Structure of the RCC fabricated at Fraunhofer ISE. (a) View of the rear side of the RCC showing the interdigitated contact pattern. (b) Details of the solar cell structure, with the cell shown upside down [4]

2005: Mohr [13] adapted the RCC solar design for concentrated sunlight applications developing a rear-line-contacted concentrator cell (RCLL) achieving a maximum efficiency of 25% at 100 suns.

2008: an “n-type” high efficiency Back-Contact Back-Junction silicon solar cell processed at Fraunhofer ISE shows best efficiency reported of 21,3% (on 1 Ω cm n-type FZ Si with the designated area of 4 cm^2.

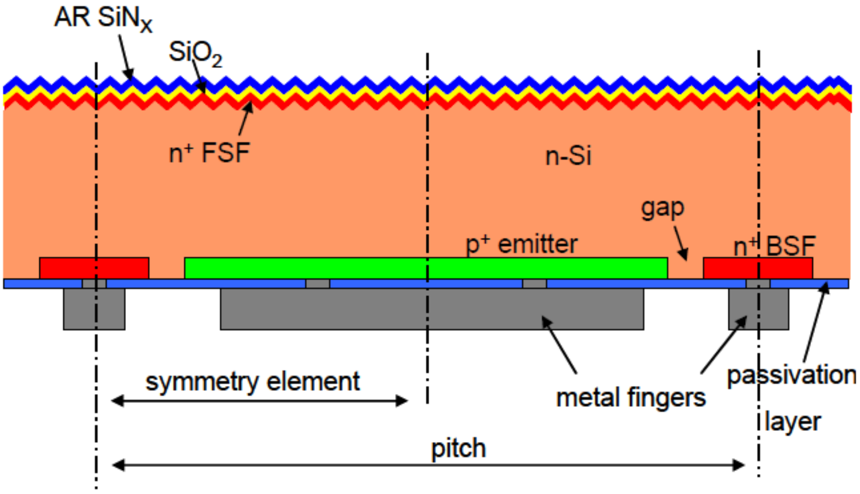


Figure 2.11 Schematic cross-section of an "n-type" high efficiency Back-Contact Back-Junction silicon solar cell processed at Fraunhofer ISE [5]

Another structure of solar cell with locally overcompensated boron emitter is proposed too, it enables a strong increase in the emitter coverage on the cell rear side and at the same time enables equal width of the emitter and base metal fingers.

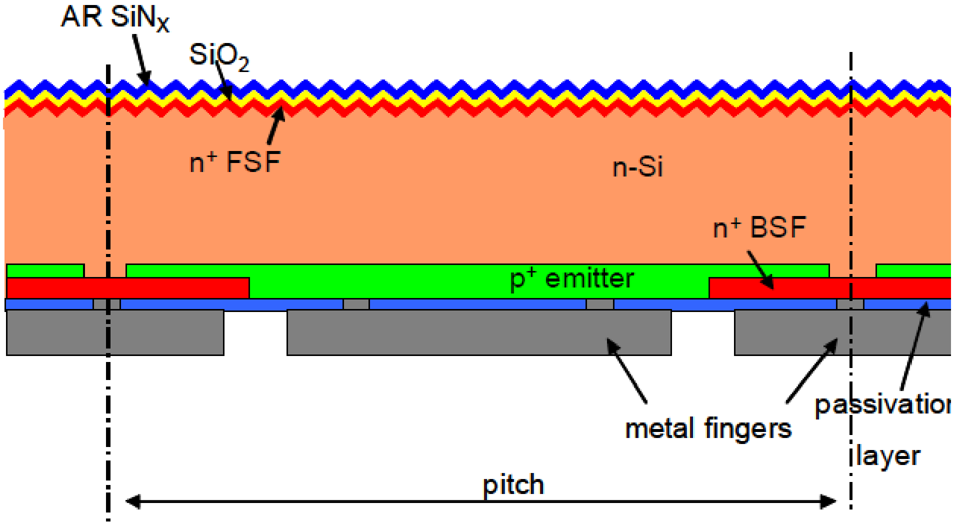


Figure 2.12 BC-BJ cell structure with locally overcompensated boron emitter [5]

2.4.4 Technology from University of New South Wales, Sydney, NSW

- 2004-2005: Guo from the UNSW developed a proceeded cell without the use of photolithography, applying a laser-grooved buried contact technology. The Interdigitated Backside Buried Contact (IBBC) solar cells, a low-cost approach to the BC-BJ structure, achieved a maximum one-sun efficiency of 19,2% as Guo et al reported [8, 9]. A low-cost approach to the BC-BJ solar cell structure was developed by Guo from the UNSW. The Interdigitated Backside Buried Contact (IBBC) solar cell is processed without the use of photolithography. The laser-grooved buried contact technology is applied. A maximum one-sun efficiency of 19,2% was reported by Guo et al.

- 2012: p-type high efficiency back-contact back junction silicon solar cell processed at University of New South Wales, Sydney. Efficiency reported: 14,5% for a solar cell.

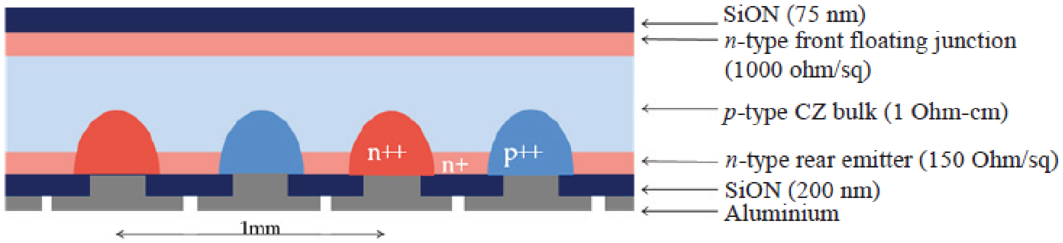


Figure 2.13 Schematic cross-section of the p-type high efficiency back-contact back junction silicon solar cell processed at University of New South Wales, Sydney [1]

3 DEVELOPMENT OF THE PROTOTYPE

The following sections show the selected configuration and materials, and the results obtained through an optimized manufacturing process for operational BIPV see-through glass-glass prototypes with back contact solar cells.

Opaque BIPV glass-glass prototypes can be also develop by combining back contact solar cells and the technologies used in task 3.2 to obtain fully opaque BIPV units with hidden busbars and L interconnections. In particular, plastic sheets to cover the connections between the back contact cells and a black ceramic backsheet are the technologies that would need to be combined with back contact cell technology in order to develop opaque prototypes (see Deliverable 3.3 for more detail). Nevertheless, see-through back contact BIPV units are considered as a good first approach to test this technology in BIPV glass-glass units as indicated in PVSITES Annex I.

3.1 Selected Configuration and Materials

As a relevant result of the work carried out, it was found that the only robust commercial back contact solar cells are the ones developed by Sunpower.

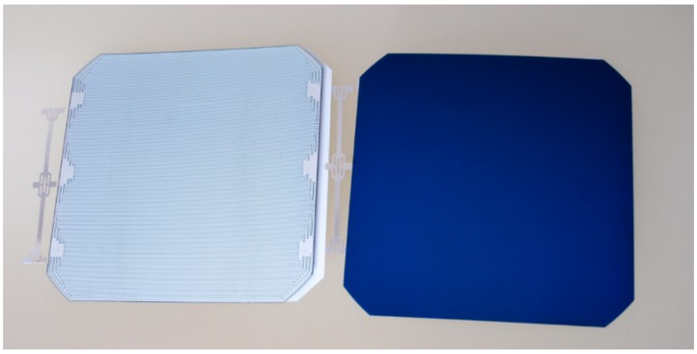


Figure 3.1 Sunpower cells used for the BIPV prototypes

Different dimensions and configurations of the module are possible. The following configuration has been selected for the development of the prototype: dimensions of 1700x1000mm, 6+6mm laminated glass, two layers of EVA encapsulation and 5” silicon mono-crystalline back contact 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. More characteristics of the prototypes are the following:

- Tempered front and rear glass are selected to achieve a final laminated glazing which compiles the current regulations for it 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 (colour neutrality) and less greenish appearance.
- Clear glass is selected as rear glass to preserve the visual transmission of the BIPV glass-glass units.
- Cell Technology selected is Mono-Crystalline back contact.
- Cell Dimensions are 125x125mm (5"x5").
- The module is built up with a configuration of 72 cells per module (6 strings/ 12 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

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

3.3.1 Manufactured prototypes

Figure 3.2 Final appearance of the BIPV prototype with back contact cell technology

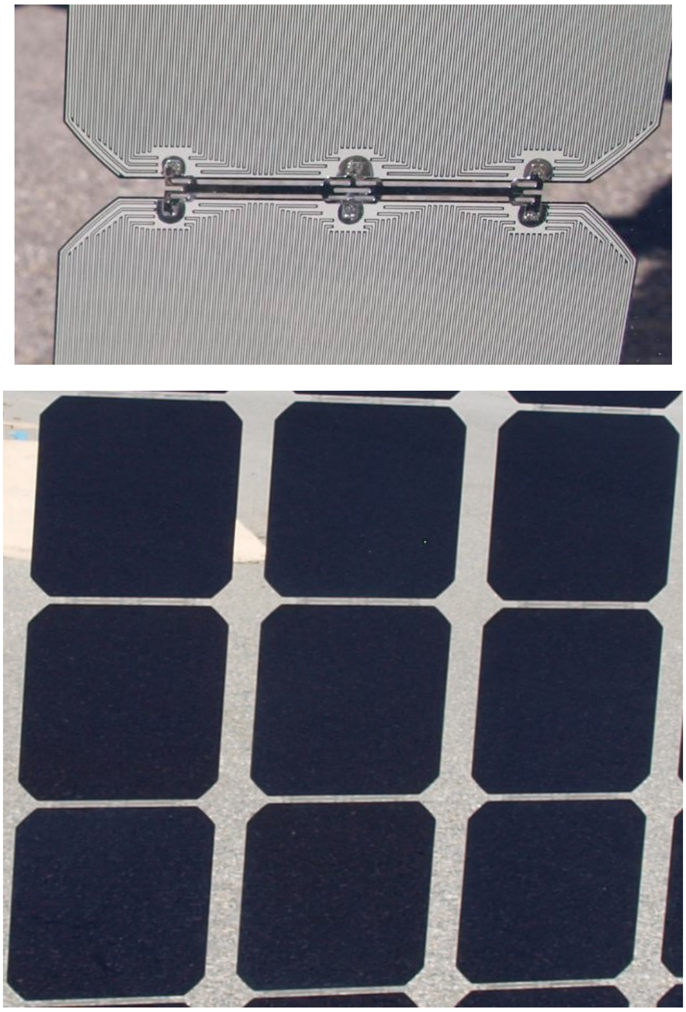
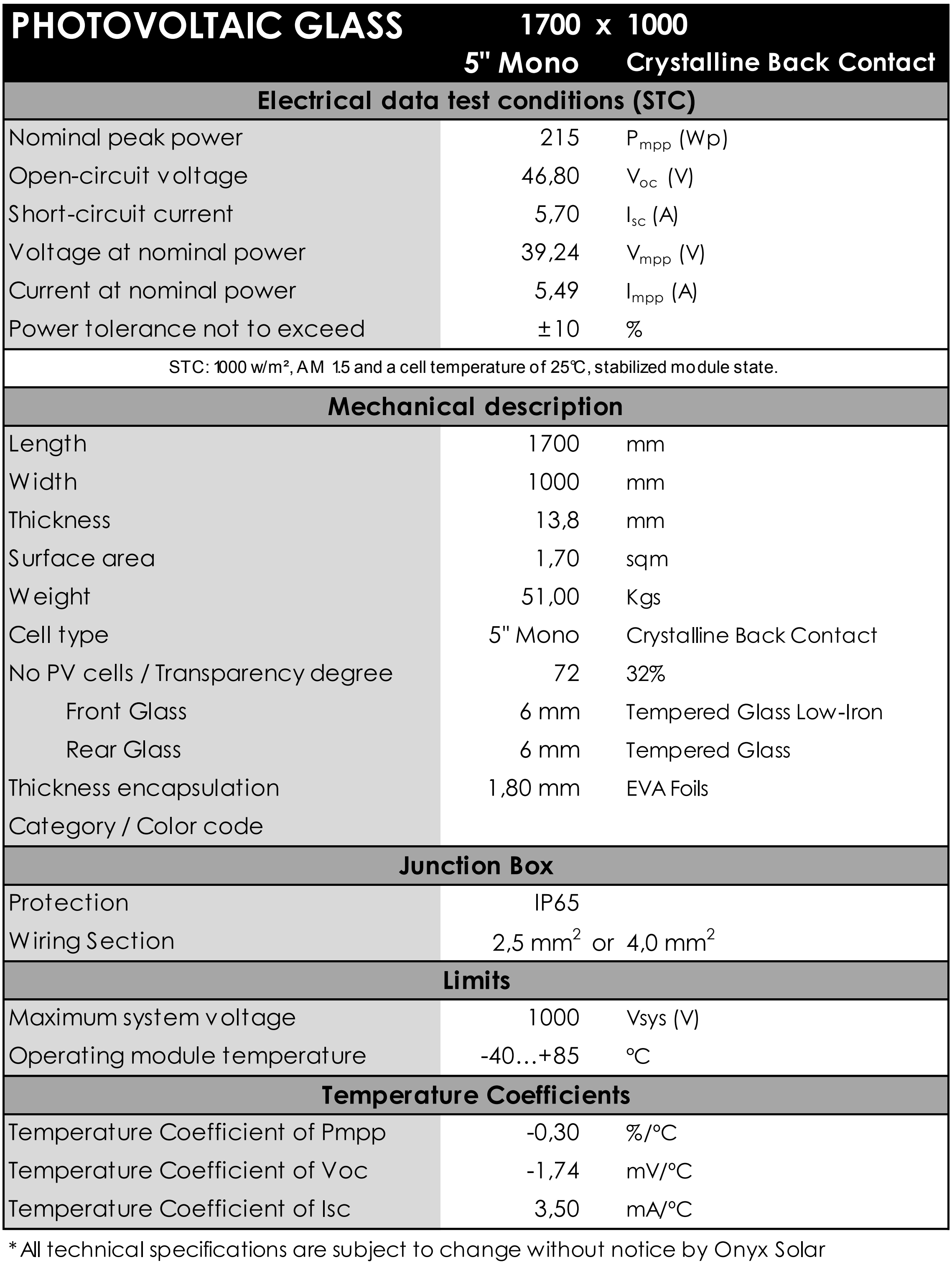


Figure 3.3 Details of junction boxes, back connections and front uniform appearance of the BIPV prototype with back contact cell technology

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**



PHOTOVOLTAIC GLASS	**1700 x 5" Mono**	**1000 Crystalline Back Contact**
Electrical data test conditions (STC)		
Nominal peak power	215	P_{mpp} (Wp)
Open-circuit voltage	46,80	V_{oc} (V)
Short-circuit current	5,70	I_{sc} (A)
Voltage at nominal power	39,24	V_{mpp} (V)
Current at nominal power	5,49	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	5" Mono	Crystalline Back Contact
No PV cells / Transparency degree	72	32%
Front Glass	6 mm	Tempered Glass Low-Iron
Rear Glass	6 mm	Tempered Glass
Thickness encapsulation	1,80 mm	EVA Foils
Category / Color code		
Junction Box		
Protection	IP65	
Wiring Section	2,5 mm² or	4,0 mm²
Limits		
Maximum system voltage	1000	Vsys (V)
Operating module temperature	-40...+85	°C
Temperature Coefficients		
Temperature Coefficient of Pmpp	-0,30	%/°C
Temperature Coefficient of Voc	-1,74	mV/°C
Temperature Coefficient of Isc	3,50	mA/°C

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

Figure 3.4 Technical data sheet See-Thru BIPV glazing/glazing solution with back-contact cells

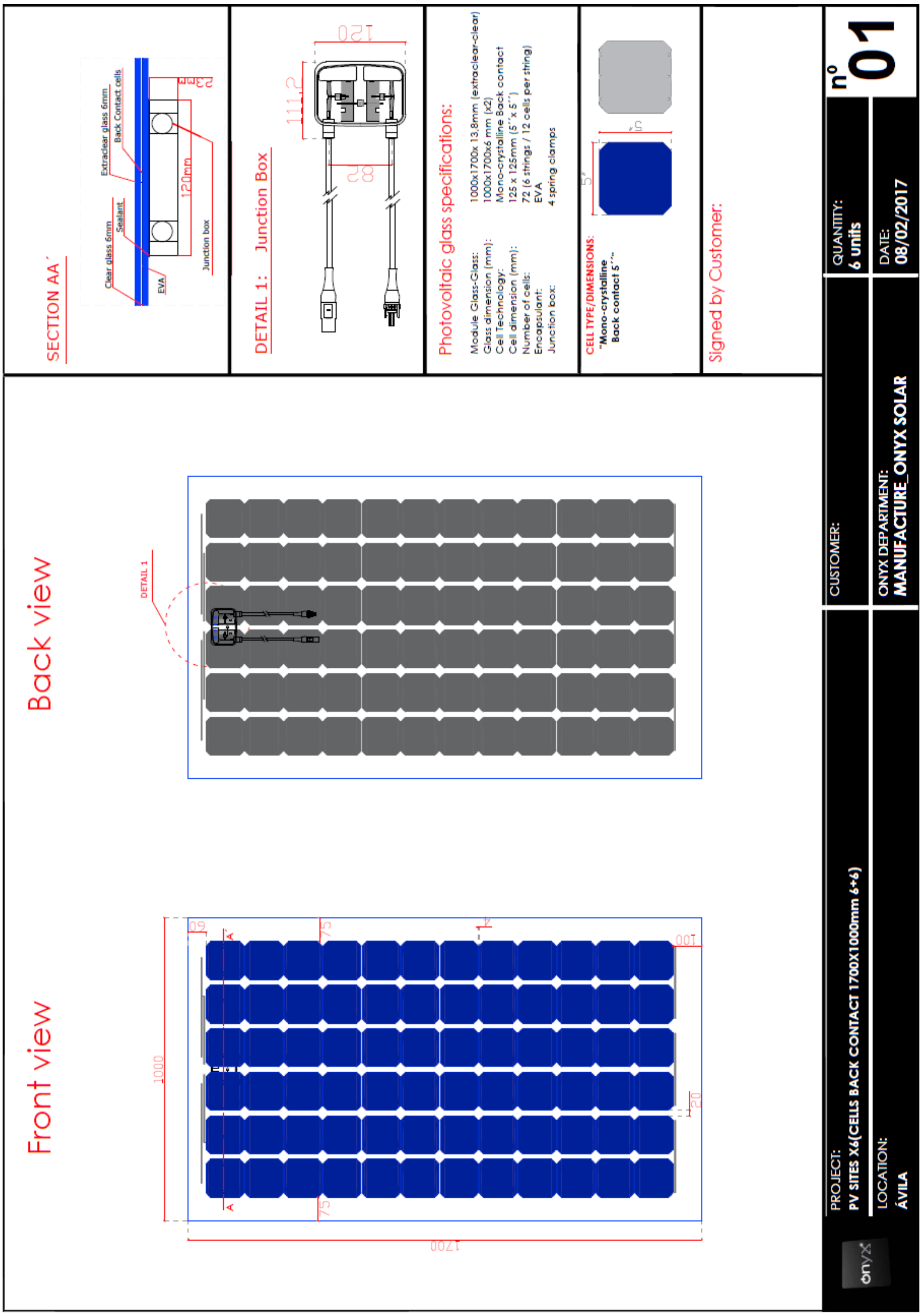


Figure 3.5 Manufacturing drawing of See-Thru BIPV glazing/glazing solution with back-contact cells

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 see-thru BIPV units with back contact solar cells. 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 BIPV units with back contact solar cells

	See-thru back contact BIPV units	Comments
FINAL PRICE (€/ m^2)	315	Final price is calculated taking into account the overcosts of this product with respect to equivalent PV glass, derived from welding activities, lamination cycle optimization, etc.
TARGET PRICE (€/ m^2)	250-400	✓
PEAK POWER (W/m^2)	126	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 SEE-THRU BACK CONTACT BIPV UNITS (€/m²)	2. PRICE OF PVSITES PRODUCTS APPLYING MARK-UP FOR MEDIUM ORDER (1000m²) (€/m²)	3. PRICE OF EQUIVALENT CONVENTIONAL GLASS WITH THE SAME PASSIVE PROPERTIES (€/m²)	4. PRICE OF EQUIVALENT CONVENTIONAL PV PANEL (€/m²)
315	280	85	175
DIFFERENCE 2-3	205		
TARGET 2-3	Approximately 100		
DIFFERENCE 2-4	105		

Even if the price difference of the back-contact PV glass with respect to equivalent non-PV glass systems surpass the pre-established ratio, the economic feasibility of this innovative product will be demonstrated in the following section: the high efficiency of the back-contact technology implies great energy production and consequently energetic and economic savings. On the other hand, the price difference in comparison with equivalent PV conventional panels is really attractive.

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 the see-thru photovoltaic glass with back contact cells, 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 behavior, 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. Three different constructive solutions have been selected to compare the results (more information in section 5.2.2 Hypothesis and Assumptions):

- Photovoltaic ventilated façade on the south façade.
- Curtain wall in the south façade.
- Skylight system on the roof.

In the first scenario, the south façade building is a conventional curtain wall and the idea is to analyze the implementation of a PV ventilated façade system as an energy retrofit measure, reducing the solar radiation transmission and therefore improving the indoor comfort. Ventilated façade systems are composed of an insulation material in the inner part, an air gap and a cladding material in the outer layer. This system is implemented also 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.

In the second scenario, the idea is to compare between a building with a curtain wall composed of conventional insulating glass and a building with the same glass including photovoltaic technology in order to elaborate the corresponding economic study.

The third scenario compares the same materials of the previous one but integrated in a skylight on the roof of the building instead of the curtain wall system.

Furthermore, taking into account that the energy behavior of a building and the photovoltaic production depend on the conditions of the location, two different European cities with different climates and solar irradiation levels have been selected in order to have more realistic results: Berlin and Madrid. As 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).

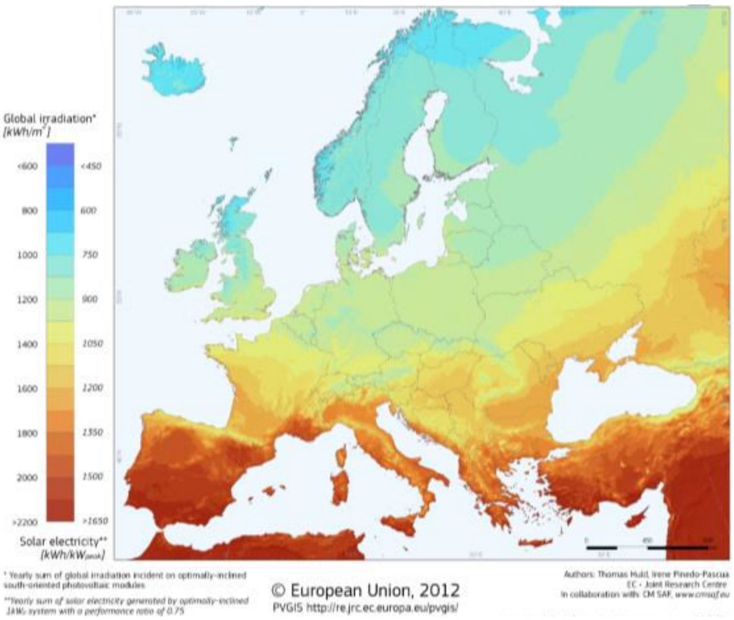


Figure 4.1 European solar irradiation map [30]

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 three scenarios. Figure 4.2 represents the comparison between the building with the conventional curtain wall system and the same building with the added photovoltaic ventilated façade.

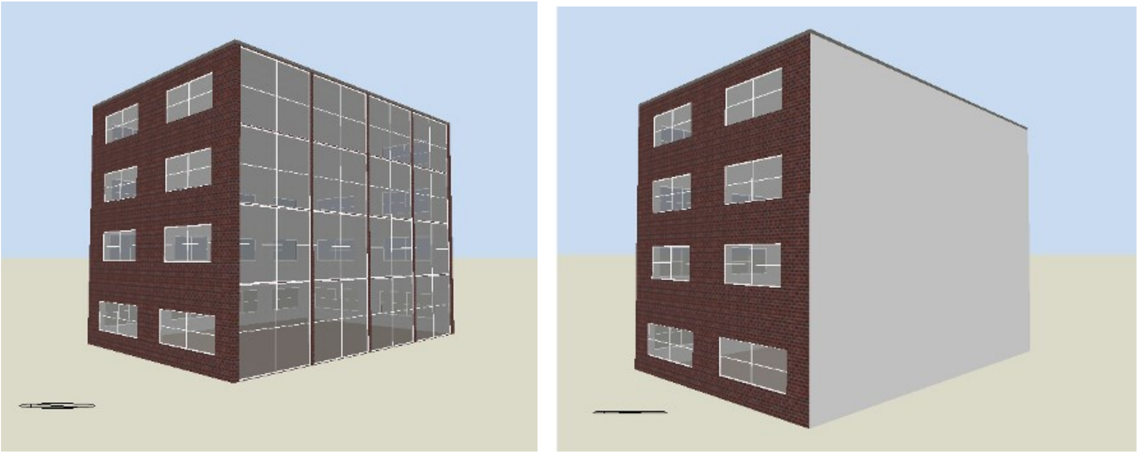


Figure 4.2 3D models for the first scenario proposed

Figure 4.3 shows the building for the curtain wall and skylight analysis with conventional glass and see-thru photovoltaic glass with back contact photovoltaic cells.

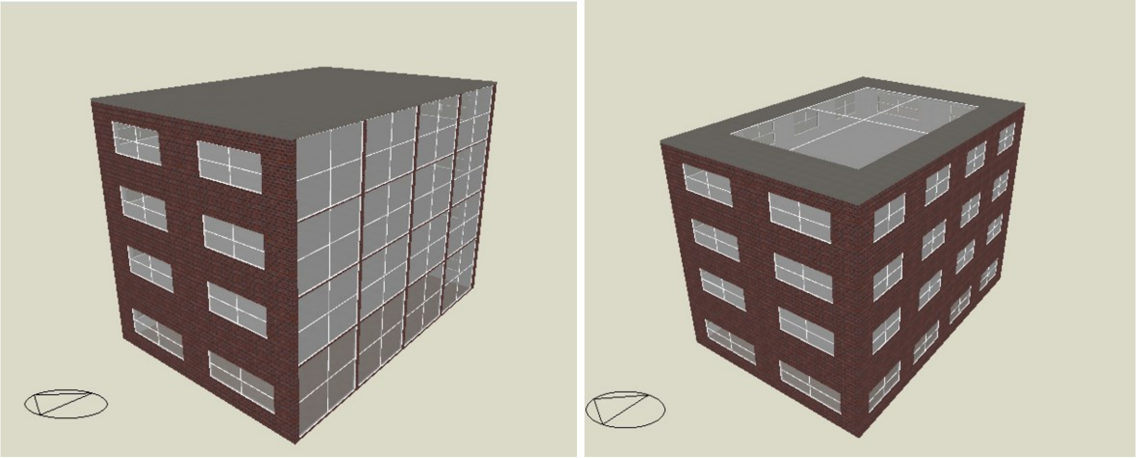


Figure 4.3 3D models for the second and third scenarios proposed

The following table summarizes de 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
Ventilated façade surface area (m^2)	200	200
Curtain wall surface area (m^2)	200	200
Skylight surface area (m^2)	100	100
Peak power of see-thru PV mass (W/m^2)	126	126
Local electricity cost (€/kWh)	0,2367	0,2981
Variation in electricity cost until 2020 (%) [28]	8,18	5,63
Variation in electricity cost from 2020 (%) [29]	1,00	1,00

The following tables show the estimated costs of the three different scenarios proposed for the economic feasibility analysis.

Table 4.4 Costs estimation of the installation of the see-thru photovoltaic ventilated façade system*1

	See-thru PV ventilated façade with back contact cells (€/m²)
Glazing	280
Fixation system	70
Balance of system	88,20
Total	368,20
*1: indirect costs included	

Table 4.5 Costs estimation of the skylight and curtain wall systems *1

	Conventional skylight or curtain wall (€/m²)	Photovoltaic skylight or curtain wall (€/m²)
Glazing	85*2	280*2
Fixation system	=	=
Balance of system	0,00	88,20
Total (excluding fixation system costs)	85	368,20
Over cost	227,90	
*1: indirect costs included *2: the glazing configuration for both construction systems (skylight and curtain wall) is the same: 6.6/13Air/6mm. The costs including in this table regarding the glazing refer to the external glass layer where the PV cells are integrated. Costs of the air chamber addition and internal glass layer are the same for all the scenarios proposed.		

4.2.2.1 Conventional curtain wall versus conventional curtain wall with PV ventilated facade

The objective of this sub-section is to show the feasibility of a retrofit project based on the implementation of a photovoltaic ventilated system covering the glazed south façade of a building, to improve the thermal behavior. In the following pages, it will be demonstrated how the HVAC demand of the building decreases because the back contact cells included in the glass reduce the solar thermal gains across the curtain wall system. Therefore, the solar cells produce free energy, so the solution becomes more attractive from an energetic and economic point of view.

Energy demand reduction is higher in Madrid, due to the higher demand of cooling systems in warm seasons, and also the energy production, due to the irradiation conditions of the location.

Table 4.6 Energy behavior before and after the implementation of the PV ventilated facade

	MADRID		BERLIN	
	HVAC energy consumption (kWh/year)	Renewable energy production (kWh/year)	HVAC energy consumption (kWh/year)	Renewable energy production (kWh/year)
Conventional curtain wall	62.744,47	0	72.604,29	0
Conventional curtain wall with PV ventilated facade	54.536,03	24.227,00	67.929,65	15.782,00

The following table reflects the reduction in energy demand and cost in a period of 30 years when a photovoltaic ventilated façade made of back contact cells is installed As it is shown, the energy savings of the whole building thanks to the developed product within the PVSITES project, reach a value of 48% in Madrid and 26% in Berlin, due to the different climate conditions of the cities.

Table 4.7 Total reduction of energy demand with the PV ventilated façade implementation

	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	339.097	900.382	48%	246.355	654.129	92.743	246.253
Berlin	240.506	566.353	26%	180.952	426.114	59.553	140.239
Average increase of energy price until 2020: 8,18% [28] . Average increase of energy from 2020: 1% [29].							

The next table shows the main economic metric calculated and reflects a payback period lower than 9 years in Madrid and 12 years in Berlin.

Table 4.8 Economic metrics with the PV ventilated façade implementation

	Average reduction of energy demand (€/m^2)	Amount to invest (€/m^2)	Amount to invest after incentives (€/m^2)	ROI %	Payback period years	IRR %	Times the investment times
Madrid	1.695,49	438,20	438,20	287%	< 9	12%	3,87
Berlin	1.202,53	438,20	438,20	174%	< 12	8%	2,74

Economic metrics calculated of a 30 years period.
Madrid: Local electricity cost: 0,2367 €/kWh [27]; Variation in electricity cost until 2020: 8,18%[28]; from 2020: 1,00% [29].
Berlin: Local electricity cost: 0,2981 €/kWh [27]; Variation in electricity cost until 2020: 5,63%[28]; from 2020: 1,00% [29].

4.2.2.2 Conventional curtain wall versus PV curtain wall

The addition of photovoltaic properties to the glass not only produces electrical energy, but also contributes to decrease the energy consumption of HVAC systems, thanks to the passive properties. Photovoltaic glass can be used by architects to reduce the solar thermal gains across the glazing areas of the buildings and at the same time the system generates free and clean energy. Next table shows the energy demand and photovoltaic production for the building located in the two cities selected with a curtain wall (photovoltaic versus non-photovoltaic). Photovoltaic production and HVAC savings are higher in Madrid than in Berlin because of the more favorable climate conditions.

Table 4.9 Energy behavior of the building with curtain wall: conventional versus photovoltaic

	MADRID		BERLIN	
	HVAC energy consumption (kWh/year)	Renewable energy production (kWh/year)	HVAC energy consumption (kWh/year)	Renewable energy production (kWh/year)
Conventional	62.744,47	0	72.604,29	0
Photovoltaic	55.774,07	24.227,00	70.398,70	15.782,00

The values presented in the following table reflect the reduction in energy demand and cost in a period of 30 years when a see-thru PV glass with back contact cells instead of a conventional equivalent glass without incorporating PV technology is installed in the building. The calculated percentages of the total energy demanded by the building which can be saved thanks to the implementation of the BIPV solution are 46% in Madrid and 23% in Berlin.

Table 4.10 Total reduction of energy demand thanks to the photovoltaic curtain 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	325.109	863.241	46%	246.355	654.129	78.755	209.112
Berlin	209.051	492.282	23%	180.952	426.114	28.099	66.168

Average increase of energy price until 2020: 8,18% [28] . Average increase of energy from 2020: 1% [29].

Next table shows the main economic metrics calculated. The payback period is lower than 7 years in Madrid and lower than 9 years in Berlin.

Table 4.11 Economic metrics of the building with photovoltaic curtain wall

	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	1.625,55	283,20	283,20	474%	< 7	17%	5,74
Berlin	1.045,25	283,20	283,20	269%	< 9	12%	3,69

Economic metrics calculated of a 30 years period.
Madrid: Local electricity cost: 0,2367 €/kWh [27]; Variation in electricity cost until 2020: 8,18%[28]; from 2020: 1,00% [29].
Berlin: Local electricity cost: 0,2981 €/kWh [27]; Variation in electricity cost until 2020: 5,63%[28]; from 2020: 1,00% [29].

4.2.2.3 Conventional skylight wall versus PV skylight

The scenario analysed in the current sub-section is similar to the previous one, but now the glazing area corresponds to a skylight system. When comparing with the results achieved for the curtain wall, it is shown that the energy production per square meter increases for both locations. The skylight on the roof receives more solar light than the curtain wall of the south façade, which involves a higher energy generation. On the contrary, the annual energy demand of the whole building is lower when the building has a curtain wall instead of a skylight because of the lower exchange with the external environment.

Table 4.12 Energy behavior of the building with skylight: conventional versus photovoltaic

	MADRID		BERLIN	
	HVAC energy consumption (kWh/year)	Renewable energy production (kWh/year)	HVAC energy consumption (kWh/year)	Renewable energy production (kWh/year)
Conventional	66.871,72	0	75.516,99	0
Photovoltaic	58.319,09	16.868,00	72.471,45	10.184,00

As shown in the following table, the energy savings of the whole building thanks to the developed product within the PVSITES project integrated on a skylight system, reach a value of 35% in Madrid and 16% in Berlin, due to the different climate conditions of the cities.

Table 4.13 Total reduction of energy demand thanks to the photovoltaic skylight

	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	268.155	712.015	35%	171.524	455.436	96.631	256.579
Berlin	155.566	366.334	16%	116.767	274.968	38.799	91.366

Average increase of energy price until 2020: 8,18% [28] . Average increase of energy from 2020: 1% [29].

Next table shows the main economic metric calculated and reflects a payback period lower than 5 years in Madrid and 7 years in Berlin.

Table 4.14 Economic metrics of the building with photovoltaic skylight

	Average reduction of energy demand ($€/m^2$)	Amount to invest ($€/m^2$)	Amount to invest after incentives ($€/m^2$)	ROI %	Payback period years	IRR %	Times the investment times
Madrid	2.681,55	283,20	283,20	847%	< 5	27%	9,47
Berlin	1.555,66	283,20	283,20	449%	< 7	17%	5,49

Economic metrics calculated of a 30 years period.
Madrid: Local electricity cost: 0,2367 €/kWh [27]; Variation in electricity cost until 2020: 8,18%[28]; from 2020: 1,00% [29].
Berlin: Local electricity cost: 0,2981 €/kWh [27]; Variation in electricity cost until 2020: 5,63%[28]; from 2020: 1,00% [29].

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) [27].
- 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 2014: 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) [28].
- 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” [29].
- 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).
- Ventilated façade scenario: The south façade is a curtain wall (WWR is 100%) 6T.6T/13Air/6mm, where a ventilated façade system is added as a shading element. The WWR of the rest of the facades is 30%.
- Curtain wall scenario: The south façade is a curtain wall (WWR is 100%) 6T.6T/13Air/6mm, external laminated glass with and without photovoltaic back contact cells , which measures 200 m^2. The WWR of the rest of the facades is 30%.
- Skylight scenario: The window to wall ratio (WWR) for the four facades is 30%. The building also features a rectangular skylight which measures 100 m^2, and the composition of the insulating glazing unit (IGU) is 6T.6T/13Air/6mm, external laminated glass with and without back contact photovoltaic cells.
- 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).
- All HVAC equipment is 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 [26].

5 CONCLUSIONS

After the work carried out under this deliverable, **ONYX has provided an answer to market requirements in terms of integration, aesthetics and efficiency of c-Si BIPV solutions** by successfully manufacturing BIPV units with back contact solar cells implemented as see-through glazing units. 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 studied the state of the art of back contact solar cell technology, increasing its existing knowhow in the field. Based on this S.O.T.A a selection of back contact solar cells providers for BIPV applications has been carried out.
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. ONYX has overcome the main challenge related to back contact cell technology, which is the development of cell to cell welding process for back within a glazing/glazing lamination process. Manufacturing sequence, welding process and lamination cycle have been optimized to include the new used materials for developing BIPV units. 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 surpass pre-established ratio (difference of approximately 100 €/m^2). In this case the higher efficiency of back-contact cells with respect to conventional mono and poly c-Si cell types must be taken into account as more attractive ROIs and payback times will result from this technology in spite of higher price differences with respect to equivalent non-PV glass. Furthermore the price difference in comparison with equivalent PV conventional panels is really attractive (105 €/m^2). These competitive values guarantee a great adaptation to market and envision the approximation to materials parity by 2020.
    - 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 behaviour of the building associated to these variables.

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