SMART BIPV GLASS-GLASS CURTAIN WALL BASED ON SPHELAR® TECHNOLOGY

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ABSTRACT: In 2008, Japanese KYOSEMI Corporation and Spanish Technology Corporation TECNALIA signed a Collaboration Agreement for the development of a BIPV curtain wall based on KYOSEMI's Sphelar® technology and TECNALIA's developed concept of distributed architecture. In this paper, the main aspects of the product design and the validation plan, as well as the first tests results carried out by TECNALIA are presented. They show that the proposed BIPV solution presents higher efficiency and lower cell-occupated area than other BIPV products already available in the market, for the same power. Additionally, new features are achieved: unique aesthetical design and indoor lighting, possibility of different patterns and drawings without compromising efficiency, variable ranges of cell occupation, continuous monitoring of PV module performance, more efficient light capture by means of proper selection of glass and selective glass coatings, etc. First results show that the proposed combination is a really attractive option to be taken into account for building applications as solar power-generating glazing systems. The first prototypes will be concluded in October and ready to be installed in KUBIK®, the experimental building that TECNALIA has designed and built to serve as a testing laboratory on the performance of energy efficient products in buildings.

Keywords: Building Integrated PV, Façade, PV module,

1 INTRODUCTION

1.1 Background

In April 2008, Japanese KYOSEMI Corporation and Spanish Technology Corporation TECNALIA signed a Collaboration Agreement for the development of a BIPV curtain wall based on KYOSEMI's Sphelar® technology [1] and TECNALIA's developed concept of distributed architecture [2]. This collaboration had started in 2005 with the evaluation of Sphelar® technology carried out by TECNALIA. The corresponding results were published in [3].

From these results it can be concluded that the combination of both technologies in a unique product increases the added value of both of them. After an intensive evaluation of Sphelar® technology, it can be stated that this product presents remarkable properties so as to be considered a promising solution for BIPV applications: (1) great advantages in terms of shadows effects, since energy losses are more proportional to the affection of shadows (2) invulnerability to a large range of disorientation angles, while maintaining high efficiency (3) availability to capture incoming light from all directions, including indoor back reflections, etc. On the other hand, the distributed architecture concept, which consists in applying a DC-DC converter directly to each PV module, brings additional advantages, such as the extraction of maximum power or the monitoring of the electrical parameters from each PV module instantaneously by means of power line communications, which allows quick failure detection with suitable monitoring software.

The aim of this paper is to describe the main aspects of the BIPV curtain wall design and its validation plan, as well as the first results of the tests carried out by TECNALIA. These results show that the proposed glass-glass module presents a higher efficiency and a larger cell-free area than other BIPV products already available in the market. Additionally, new features are achieved: unique aesthetical design and indoor lighting, possibility of different patterns and drawings without compromising the high efficiency of PV cells, variable ranges of cell occupation (values over 50% are easily achieved), continuous monitoring of PV module performance, more efficient light capture by means of proper selection of glass and selective glass coatings, etc. First results indicate that the proposed combination is a really attractive option to be taken into account into building applications as solar power-generating glazing system.

1.2 The smart BIPV curtain wall system

In short, the product will be composed of:

- A glass-glass encapsulated module containing the spherical cells.
- A double glazing system where the external glass is the encapsulated module and the internal glass is a laminated glass.
- An electronic control for each module optimizing the I-V output.
- A curtain wall frame incorporating the double glazing system and the electronics.
- A communication system to facilitate the monitoring of the installation.

As a starting point for the development of this product, the following specifications were agreed by KYOSEMI and TECNALIA:

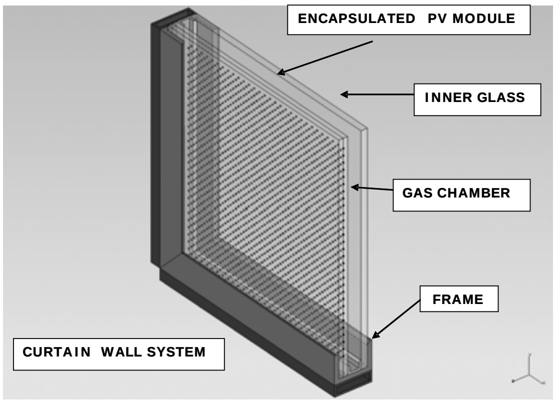


Figure 1: Curtain wall system schematics

- Percentage of cell-free area: 40%-70%.
- Power ranges: 50-105 Wp/m^2 or the equivalent 62,5-400 Wp/module. Typical 3m x 1,2m, 70% cell-free area: 180 Wp.
- Distance between cells: spheres distribution to be designed by considering aesthetical and harmony issues.
- No maintenance for the photovoltaic part (lifetime over 25 years @ 80% nominal power) is proposed, together with a minimum maintenance for the electronic devices (MTBF around 20 years). In case of breakdown, the design has to permit a simple and easy replacement procedure.
- Electronic device: DC-DC converter with maximum power point tracking (MPPT) and communications. Integrated into the frame, accessible for maintenance, easy to replace, plug & play concept, including monitoring of current, voltage, power and state variable.
- Glazing system: double glazing system composed by an external laminated glass - gas space - internal laminated glass. Thickness to be calculated according to legal regulations. The glazing will provide thermal isolation and solar control functions by means of selective coatings.
- Curtain wall: accomplishing with all the essential requirements stated by legal regulations on construction products.
- Cost similar to BIPV products already in market.

On this basis, both TECNALIA and KYOSEMI started to work on the design of this innovative BIPV curtain wall in 2008. The first prototypes will be concluded in October 2009 and will be ready to be installed and monitored in KUBIK®, the experimental building that TECNALIA has designed to test the performance of energy efficient products in buildings.

2 TECHNOLOGIES

2.1 Sphelar® technology

The use of large amounts of silicon in standard PV cells manufacturing has pushed up the development of innovative technologies that aim to decrease consumption of costly silicon. During the past years, KYOSEMI Corp. has developed a spherical, crystalline silicon photovoltaic solar cell with efficiency comparable or even superior to that of traditional wafer-based silicon solar cells, which only dispose of one planar surface for light absorption. KYOSEMI's spherical solar cell was registered in 2004 with the name Sphelar®.

Ideally, this design offers lower costs and higher flexibility, while using less silicon compared with wafers manufacturing, as no silicon cutting process is needed. Additionally, it allows the use of several substrates (background material holding solar cells, opaque or transparent) that can be integrated in different applications.

Sphelar® technology is based on 1.8 mm silicon spheres. We briefly describe sphere processing. First, a small segment on the sphere was formed. It was followed by oxidation process. Next, the outer oxide was removed excluding the small segment. Selectively diffused on the surface of a *p*-type spherical silicon is phosphorus, such a thin *n*-type outer layer is provided to form a spherical *p*-*n* junction parallel to the surface of the sphere. After that, small electrodes on the top and the bottom were formed to produce a link between the *n*-shell and the *p*-core (see Figure 2). This enables the cell to receive light three-dimensionally [4].

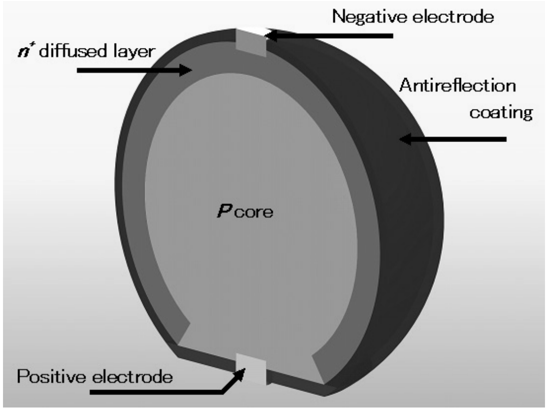


Figure 2: Cross-section of a Sphelar® solar cell.

The cells are wired so that they can be easily connected in series or in parallel, enabling the creation of modules in many different shapes (see Figure 3). This wiring system is compatible with the use of transparent substrates such as glass or silicone. If a Sphelar® cell is encapsulated in acrylic resin, it can be turned into a flexible Sphelar® sheet, a thin solar cell module whose shape can flexibly be changed into a curved form. A module made with Sphelar® cells connected in parallel on silicone resin achieves a photoelectric conversion efficiency of 19% [5].

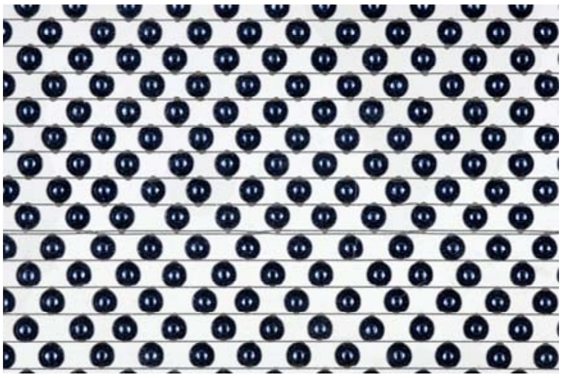


Figure 3: Mesh of Sphelar® cells.

2.2 Modular architecture in the building environment

In order to connect PV systems to the grid, it becomes necessary to convert DC energy from solar cells into AC power, by means of a PV inverter. Only a few years ago, most of medium and large PV plants used a central inverter. An alternative to centralized systems arose in the mid 1990s. It lies in the use of several small power distributed inverters, up to 5 kW, so that the number of PV panels connected to one MPPT gets significantly reduced. At present, the efficiency of PV plants is still low and last issues about PV systems performance show average values of PR below 0.80 [6], which means more than 20% of losses.

The causes of these poor efficiencies are diverse, from load mismatching (although most PV systems have MPPT-incorporated in the inverter), to shadows and obscurances, losses in PV inverter, dust or MPPT losses. Great part of these losses are due to mismatching of PV modules, caused by differences in the working temperature of PV modules, the inclination or orientation angles, differences in the I–V characteristic coming from the manufacturing process, etc.

The situation of losses becomes worst in complex configurations, such as those integrated in buildings (roofs and facades), since there is a great number of modules and great differences in the level of irradiance over the PV area due to different orientations or leaning planes. The complexity represents also an additional problem in maintenance and control operations, since a failure in one PV module placed at a big facade becomes most times difficult to detect. Recently, some new architectures have arisen in order to decrease these losses, the so called modular PV systems.

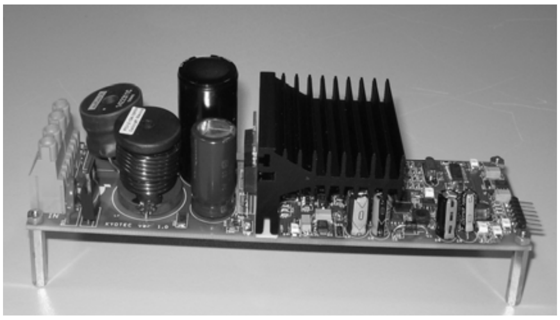


Figure 4: Current design of DC-DC converter

In this context, TECNALIA has developed a modular system based on the DC–DC converters (see Figure 4**).** Each PV module incorporates a DC–DC converter with MPPT function that leads to a significant reduction of power losses (specially mismatching losses), a better monitoring, due to Power Line Communications, and hence, a quick detection of faults in large PV systems, such as those integrated in buildings [7].

Both technologies, Sphelar® cells and distributed architecture based on DC-DC converters applied to PV module are the basis of new BIPV curtain wall, as exposed in the following chapters.

3 DESCRIPTION OF BIPV CURTAIN WALL COMPONENTS

3.1 Encapsulated glass-glass module

The encapsulated glass-glass module refers to the external laminated glass containing the photovoltaic cells (see Figure 1). The specifications for the encapsulated glass-glass module, understood as a laminated glass, have been defined from thermal, optical and mechanical considerations on the PV module, integrated within a double glazing system.

The materials and processes involved in the fabrication of the encapsulated glass-glass module are described as follows:

- Glass panes: For each of the monolithic glass panes forming the laminate, the following characteristics have been defined: (1) Extraclear glass, with a low content in iron salts to maximize light transmission. Thermally toughened glass, intended for a higher mechanical resistance (resistance to impacts, resistance to bending), as well as an increased endurance with respect to high temperatures and temperature gradients. 4mm thickness for each glass pane, calculated on the basis of available European standards for glass thickness calculations. No coatings on the encapsulated module. Optical calculations determine that it's more convenient to place a coating on the internal glass of double glazing.
- Polymer interlayer: the convenience of using EVA (ethyl-vinyl acetate) or PVB (poly-vinyl butyral) is being analysed in terms of durability and compliance with legal regulations.
- Sealant: the edge sealant must be compatible with the interlayer polymer and able to protect the cells and electric conductors against the exposure to atmospheric agents. The research on a particular sealant fulfilling these conditions is still in progress by means of climatic tests.

3.2 Smart PV double glass system

The smart PV double glazing system includes the following elements: (1) External glass-glass module containing the cells (2) An internal laminated glass (3) Electrical components and electronics for each module.

Table I: Specifications of smart double glass-system

Specifications - External laminate	
Thickness	4+4 (mm)
Type of glass	Extraclear
Thermal treatment	Toughened
Coatings	None
Interlayer	EVA/PVB
Number of interlayer films	6 (min)
Cavity	
Thickness:	12 mm
Type of gas:	Air
Internal laminate	
Thickness	6+6 (mm)
Type of glass:	Clear float
Thermal treatment:	None
Coatings	low emissivity and solar control coating on face 3
Interlayer:	PVB
Number of interlayer films	2
Double glazing	
Dimensions	2600x1400 (mm^2)
Total thickness	35.2 (mm)
Weight	57.9 (kg/m^2)

The following specifications have been set for the components of the smart PV double glass system other than the encapsulated PV module:

- Internal laminate: two clear float, 6 mm glass panes with 2 PVB layers. Low emissivity, solar control coating on face 3 of the double glazing, with reflectance spectrum chosen so as to maximize back-reflected light towards cells.
- Electrical specifications: From the comfort tests results an optimal free of cells surface of 62% has been established. Due to architectural and aesthetical reasons, the selected dimensions for the PV double glass modules are 1400 x 2600 mm. According to this, the following electrical specifications have been defined:

Table II: Electrical **s**pecifications of PV module

Electrical specifications of PV module	
Peak power	150 W
Open-circuit voltage	24.15 V
Short-circuit current	8.1 A
Max. Power point voltage	19.75 V
Max. Power point current	7.6 A

Specifications for the electronics: The electrical specifications of the electronic DC-DC converter are fixed by the electrical features of the PV module. The maximum power has been 25% overestimated since an extra light capture is expected due to back radiation onto Sphelar® cells. The rest of parameters are selected according to the maximum ranges expected for the PV module.

Table III: Electrical specifications of DC-DC converter

Electrical specifications of DC-DC converter	
Maximum power	200 W
Input voltage	8-40 V
Input current	0-10 A
Output voltage	0-100V
Output current	10 A
Efficiency (Vmpp = 20V)	>94 %

3.3 Smart BIPV curtain wall

The integration of this novel technology on a construction system inevitably leads to the design of a new curtain wall system. This must have its geometrical characteristics adapted to the specific requirements of the system under development. The driven forces to carry out the curtain wall development were as follows, (1) plug and play concept and connectivity, (2) architectural aesthetics, (3) standardization, (4) CE marking and (5) maintenance.

Special care was taken to define the connector type for the PV modules. The connector represents the link between the active PV module and the electronics (DC–AC converter with MPPT function). Embedded connectors were identified as a promising solution, due to the fact that they would allow the system to be mounted in any curtain wall design. However, a more traditional approach was taken and a new clamping system was prototyped. These elements are mechanically fastened to the buses within the glazing units and extract the energy before being circulated. The former concept (embedded connectors) will be further investigated in the future.

Two possibilities have been considered for the curtain wall design: (1) Traditional curtain wall or (2) Modular (or unitised) curtain wall. The modular solution was adopted and it was decided that the units should comprise the frame, the PV module (including the connector), the electronics and the inter-module plugging systems. Modular walling systems present important advantages for its installation, especially in the case that the curtain wall includes a photovoltaic installation, where a plug-and-play system for the interconnections is highly desirable. In addition to this, modularity allows customisation of the final product with fewer restrictions.

The integration of photovoltaic elements should not interfere with the rest of functionalities of the curtain wall, such as structural resistance, air and water tightness, etc. The mandatory tests have been scheduled to demonstrate compliance with building regulations and to obtain the desirable CE marking. Cladding to the structure of the building must allow for the flexibility of adaptation, while guaranteeing the compliance with mechanical requirements.

A modular curtain wall requires a thorough design of frames and cabling to be implemented within the frame. Complementing that, in-situ maintenance when the modular units have been assembled to the building structure must be ensured. Intermediate transoms were designed to hold both the electronics and the cabling and their design allows complete access to those elements for easy maintenance from inside the building. This measure even allows new connecting configurations (serial – parallel). Mullion and transom cover caps instead of structural silicon have been selected to allow maintenance of the PV modules, which can be substituted from outside the building.

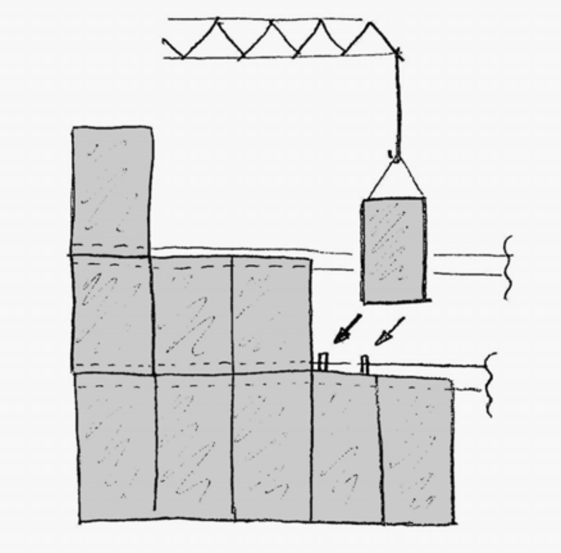


Figure 5: Hand-made design of the modular curtain wall

For the development of the modular curtain wall two possibilities are being considered:

1) Adopting an existing commercialized solution to which minor alterations are performed (manufacturing of already extruded profiles). As pros, shorter delivery times and minimisation of possible incidences. As cons, it would not be a final solution, it would imply a continuous dependence on suppliers, and the solution is

not specific for this product.

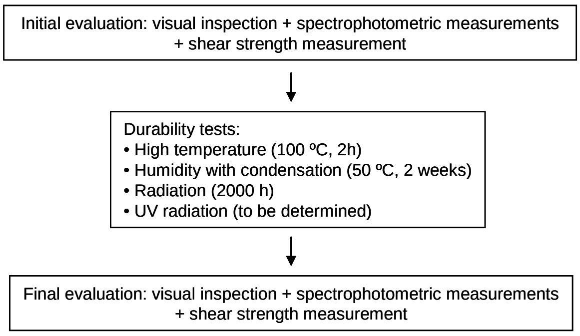
2) Development of a particular solution for this product, implying re-design of an existing design and the production of new extrusion matrixes. As cons, probably longer development times and the need to establish a collaboration agreement with a specific company. Finally this solution was adopted.

4 TEST RESULTS

Testing has been performed at three levels:

1) Evaluation of glass substrates: an optical characterisation of the monolithic glass substrates used for the laminated glass has been performed by means of UV-VIS-NIR spectrophotometry, following EN 410 standard [8]. The toughening of the glass substrates has also been evaluated by a fragmentation test, following EN 12150-1 standard [9].

2) Evaluation of the lamination process: durability and characterisation tests have been performed on laminated glass samples (no solar cells, no edge seal), according to EN 12543-4 [10] (see Figure 6).



Initial evaluation: visual inspection + spectrophotometric measurements + shear strength measurement

Durability tests:
- High temperature (100 ºC, 2h)
- Humidity with condensation (50 ºC, 2 weeks)
- Radiation (2000 h)
- UV radiation (to be determined)

Final evaluation: visual inspection + spectrophotometric measurements + shear strength measurement

Figure 6: Scheme for laminated glass testing

3) Evaluation of the encapsulated module properties: As there is no particular standard for glass-glass PV modules, EN 61215 standard [11] for crystalline silicon PV modules has been used as a reference both for tests and acceptance criteria.

This testing will be performed basing on the following scheme (see Figure 7).

Test results are in general satisfactory. Some of the tested polymers showed in certain conditions browning, opacities and delaminations during durability testing with and without edge sealing, with a corresponding loss of maximum power in some of the modules. Further testing is in progress to determine the causes for these effects and the determination of the optimal polymer and sealing products to be used in the final modules.

Temperature reached by cells in the proposed double glazing configuration was modelled by a finite elements calculation with NX6® software (with inputs from DISAC® software). Table IV shows the temperature at the cells and the glass panes of the double glazing system for winter and summer boundary conditions taken from ISO/DIS 15099 standard [12] in different configurations: double glazing with coatings, double glazing without coatings and encapsulated module alone.

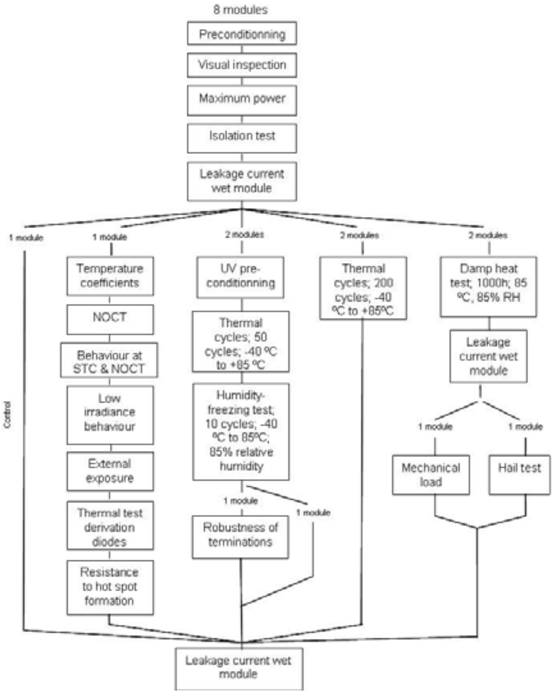


Figure 7: Procedure testing of modules, according to EN 61215

Table IV: Temperature simulations in the double glazing system

Temp. (ºC)		$G1_{ex}$	Cell	$G1_{in}$	$G2_{ex}$	$G2_{in}$
DG with coating	Summer	46.26	47.95	47.83	35.51	34.69
	Winter	7.48	8.88	9.22	20.16	20.34
DG without coating	Summer	42.54	43.79	43.59	38.28	37.22
	Winter	7.45	8.86	9.39	17.68	18.20
Encapsulated module	Summer	38.33	39.07	38.30		
	Winter	8.54	10.18	10.91		

For the summer conditions considered (relatively mild) and the double glazing configuration proposed, it has been found that the cells reach a temperature of 18 ºC over the external temperature.

The effect of assembling the encapsulated modules in a double glazing configuration is, as expected, a rising in the temperature of cells. For the summer conditions considered here, this increase is of 4.7 ºC. In the same way, the use of a solar control, low emissivity coating, which reflects the infrared incoming light back to the first glass, enhances this effect. The temperature increases 8.9 ºC with respect to the encapsulated module in the simple glass configuration.

During the winter, the low emissivity coating also reflects light back towards the cells, contributing to a higher electrical output, and reduces radiation heat losses at the double glazing.

5 AND COMPETITORS?

The smart BIPV curtain wall based on Sphelar® technology and an optimal balance-of-system based on the distributed architecture concept and specially designed for this product is being confirmed as a compliant with all required quality standards and regulations.

Both technologies are being proven to be complementary in the sense that Sphelar® technology allows very flexible configurations, while the distributed architecture is very effective for non-uniformly patterned modules, which could be required to accomplish several requirements. Thus, power, current and voltage of Sphelar® PV modules can meet different BIPV specifications and can be easily adapted to any requirement by means of the electronic device that allows to connect modules with different levels of P, I and V.

The developed BIPV module shows a high efficiency in comparison with similar BIPV products currently in the market (see Figure 8). For instance, considering the peak power, some competitors produce 40-50 Wp/m^2 with 1-10% transparency, whilst Sphelar® technology easily reaches 75 Wp/m^2 with 40-50% cell occupation. Besides, due to its connection configuration, its performance is more stable to partial shadowing [3] and cells are capable of capturing potential indoor light due to reflections.

Figure 8: BIPV module based on Sphelar® cells

6 CONCLUSIONS

The main aspects of the product design, as well as the first tests results carried out by TECNALIA on the BIPV curtain wall based on KYOSEMI's Sphelar® technology have been presented. As expected, these results show that the proposed BIPV solution presents higher efficiency for a lower cell occupation in comparison with other BIPV products already available in the market.

The incorporation of a special electronic device to each PV module brings additional advantages, which in combination with Sphelar® technology, make this product a high-tech alternative to current semitransparent BIPV modules.

The first prototypes will be concluded in October 2009 and will be installed and monitored in KUBIK®, the experimental building that TECNALIA has designed to test the performance of energy products in buildings.

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7 REFERENCES

[1] Taira K., Ohtani S., Inagawa I., Omura E. and Nakata J."3-D GEOMETRY OF SPHELAR® CELLS" Technical Digest of the International PVSEC-17, Fukuoka, Japan, 2007. 7O-B12-02.

[2] Roman E., Martinez V., Jimeno J.C., Alonso R., Ibañez P., Elorduizapatarietxe S. Experimental results of controlled PV module for building integrated PV systems. Solar Energy Vol. 82 (2008) pp. 471–480. doi:10.1016/j.solener.2007.09.004

[3] Sanz A., Alonso R., Roman E., Nakata J., Taira K., Inagawa I. "Analysis results on spherical silicon solar cells". Proc. of the 22nd European PV Solar Energy Conference. Milan 2007. Pp. 3242-3244.

[4] Taira K. "Kyosemi sees many potential uses for Spherical Solar Cells". JEI August 2007, pp. 9

[5] "Spherical Surface Gives Sphelar Cell More Efficiency, Flexibility". JEI, February 2006, pp. 30.

[6] International Energy Agency – Photovoltaic Power Systems Programme, 2004. Country reports on PV Systems performance. IEA PVPS task 2, Activity 2.6.

[7] Román, E., Ibáñez, P., Elorduizapatarietxe, S., Alonso, R., Lopez-Alegría, I. Intelligent PV module for grid-connected PV systems. In: 30th Annual Conference of the IEEE Industrial Electronics Society, November, 2004, Busan, Korea. IEEE Transactions on Industrial Electronics 53(4), 1066–1073.

[8] EN 410: 1998. "Glass in building: Determination of luminous and solar characteristics of glazing."

[9] EN 12150-1: 2000. "Glass in building - Thermally toughened soda lime silicate safety glass - Part 1: Definition and description."

[10] EN ISO 12543-4:1998. "Glass in building: Laminated glass and laminated safety glass: Test methods for durability."

[11] EN 61215: 2006. "Crystalline silicon terrestrial photovoltaic (PV) modules. Design qualification and type approval."

[12] ISO/DIS 15099:1999. Thermal performance of Windows, Doors and Shading Devices –Detailed Calculations-.