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Building integrated photovoltaic system for a solar infrastructure: Liv-lib' project

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Abstract

The growing importance of sustainability and passive house design requires the reconsideration of integrating the solar PV modules in both buildings and architectural design processes. The architectural integration of photovoltaic systems is one of the fundamental themes of contemporary architecture to optimize efficiency while taking into account the proportions, morphology and aesthetics of the project. The direct conversion of solar energy into electrical energy using photovoltaic systems appears to be a consolidated technology of exploitation of renewable energy sources. In addition to the availability of the source, its characteristics are its reliability and that it needs low maintenance. In this paper, we present, as a case study, a solar canopy specially designed for the Liv-lib' project at Solar Decathlon Europe 2014. Canopy's shape was designed to maximize the performance of the solar conversion by integrating in series two innovative solar technologies, Luminescent Solar Concentrators (LSC) and Copper Indium Gallium diSelenide (CIGS) solar cells. LSC are constituted by slabs of transparent materials (PMMA) doped with a fluorescent dye that captures a fraction of the sun rays passing through the panel. The dye molecules then re-emit light at a longer wavelength inside the slab which, due to the total internal reflection, traps and guides this light toward its edges. Strips of solar cells are optically coupled to the edges and convert into electric energy the light gathered by the slab. Liv-lib' is a self - sustainable passive house run by University Paris-Est, thanks to the joint work of staff and students from "ENSA Paris-Malaquais", "ESTP", "ESIEE Paris", and "Chimie ParisTech" with academic and industrial partners, among which, for the LSC, the Department of Physics and Earth Sciences of the University of Ferrara.

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1. Introduction

As a result of technological development since the Industrial revolution, the exponential growth of energy demand is a debate discussed in recent decades compared to the progressive development of energy resources [1].

The greenhouse gas emissions covered by the Kyoto Protocol have increased by 80% since 1970 and 30% since 1990 [2]. Today, in COP21, the aim is to reduce greenhouse gas emissions to limit the global temperature increase to 2 °C above pre-industrial levels, promoting energy efficiency through the use of modern technologies and the renewal of these energy sources [3]. The need to reduce energy consumption in the field of construction leads to research into innovative solutions that combine experimentation of new materials and new technologies with the use of renewable energy sources.

The direct conversion of solar energy into electrical energy using photovoltaic systems appears to be the most relivable technology of exploitation of renewable energy sources. In addition to the availability of the source, its characteristics are reliability and low maintenance [4]. The growing importance of sustainability issues and passive house design requires rethinking innovatively the integration of solar PV modules in building design. The architectural integration of photovoltaic systems is one of the fundamental themes of contemporary architecture to optimize efficiency while taking into account the proportions, morphology and aesthetics of the project.

Until a few years ago the cost was relatively high, this made it dependent on public subsidies [5]. The recent decreasing of cost may be attributed partly to improvements in manufacturing processes and to economy of scale [6]. In last year's Concentrating photovoltaic systems (CPV) are viewed with great interest by the scientific community whose objective is to maximize the generation process, along with the conversion of energy, in order to rationalize consumption and minimize losses. These systems have advantages related to high conversion efficiency, large energy output/MW installed compared to conventional flat panels, potential cut costs due to the reduced size of the photovoltaic cells and the low capital investment to provide the transition of this technology on an industrial scale [5]. However the optical collectors constituting these systems capture the solar radiation with tracking systems that require continuous control and maintenance. Moreover, the energy efficiency of the system is undermined by high temperatures that can damage the cells on which the solar radiation is focused. In addition, the curved shape represents the most important issue related with the architectural integration of these systems [6].

In the last decade, research on the production of solar energy is moving towards new innovative systems such as Luminescent Solar Concentrators (LSC) that are not only capable to promote the integration of panels and good performance, but also able to ensure a fast production with less expensive economical and energy stipends [7,8].

In this paper we present, as a case study, a solar canopy specially designed for Liv-lib' project at Solar Decathlon Europe 2014 [9] (SDE2014) in Versailles, integrating an innovative system for energy production, LSC jointly with Copper Indium Gallium diSelenide (CIGS) solar cells.

2. Liv-lib' project

The Liv-lib' project aims to create an urban vertical infrastructures, called 'hubs', while converting and managing energy, collecting and handling food losses, wastes, and rainwaters, controlling air and comfort, linking people on site and to the rest of the city. Each hub have several 'ports' capable of receiving a 'capsule'(private home) that is plugged into it. The capsule's 'plug' serve as the center of all the energetic and material exchange between the capsule and the hub, which can thus be controlled and linked to an individual responsibility. The starting point is the separation of the habitation into two parts: an urban structure and a private capsule. The former was introduced as a mean to redesign the city, the latter as the expression of the rapid access of the individuals to the ever renewing technologies. These two paradigms are not borrowed here: the urban structure is, for us, a network of small interventions, localized strategically in the urban tissue to favor mobility through the network; the capsule is a house that can be designed to be energetically efficient (actually highly insulated), economically accessible, modular, and movable. The principal goal of Liv-lib' is the integration of new energetically efficient technologies in the architecture of solar powered buildings and at the definition of new concept in architectural design based on these technologies, with the ultimate goal of proposing new solutions that combine high aesthetic quality to an optimum energy yield, low cost. Fig. 1

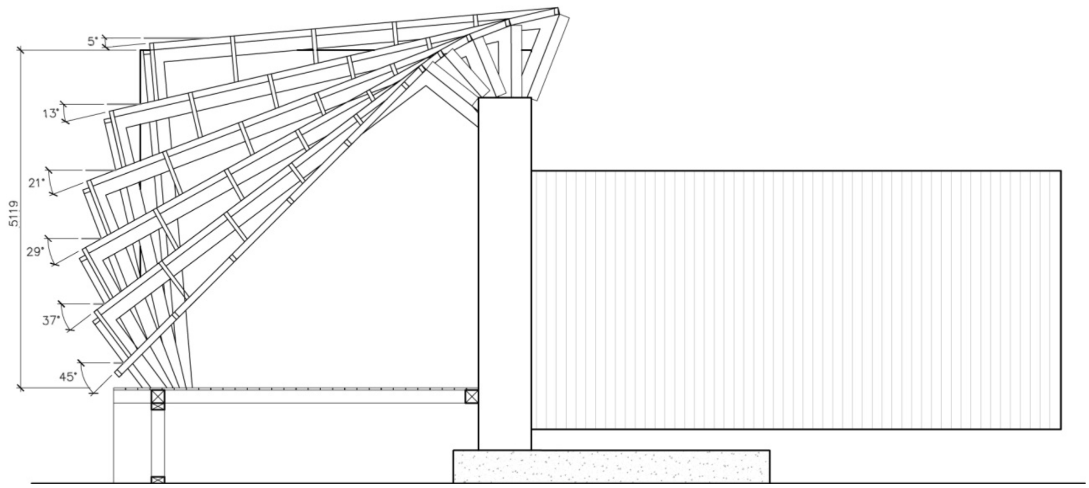

Fig.1. Canopy Front elevation

The Versailles' prototype represented a fraction of a hub with two capsules plugged in, one housing a home, the other a telecommuting station. This configuration shows the versatility and diversity of proper function of the capsule's concept and the advantage of gathering all technological complexity in the hub. The hub is naturally the place where architecture fosters public activities or simply promenades, which was represented in the competition through a windowed solar atrium with greenery.

2.1. Architectural concept

For Versailles' prototype the space is organized on the base of a 25 m2 modulus, a size that has been chosen to make transportation simple and not expensive (2 to 3 trucks per capsule). Protected by the solar canopy, hub is oriented southeast and it is bright all day long. The translucent solar panels are in transparent red PMMA that enables light and some heat to pass thought. Since it was possible to bend them, we decided to design a curved canopy that follows the sun path to have a structure architecturally interesting, innovative and energetically efficient.

Canopy is constituted of six wood half-portal frames, with twist angles. The geometric variation of the angle of each portal is repeating at regular intervals, giving the structure a particular "fan effect" that spreads both in plan and in elevation rise to the three-dimensional volume with a helicoid shape. The form follows the building regulation of the SD competition which determined orientation of the canopy toward SE instead of EW which decreased the amount of solar exposure on the canopy in during the afternoon hours (15p.m-19.m). Fig 2

Fig.2. (a) Night view of the Liv-lib'during the SDE 2014 competition, showing; (b) The LSC panels stand out on the roof; (c) Under the canopy the light gets a red hue caused by the re-emitted light that doesn't undergo total internal reflection

The structure is architecturally interesting, innovative and energetically active. LSC can be produced in different colors like yellow, orange, red, violet or totally translucent. For the Versailles' prototype we chose the red color to get better efficiency and aesthetic qualities. One of our main goals was to use those panels in a different way than what we usually see, on the roof of a building oriented straight south. We wanted to use them in a way that they are not an add-on on the building but a part of the building.

2.2. Engineering and construction

The structure of the hub is in reinforced concrete. The hub consists of three columns at the end of two orthogonal walls in L shape which guarantees stability by the very beginning of site operations. The wall's structure is made of concrete beams and columns with concrete prefabricated panels for bracing (and cladding). Each capsule has stand-alone structures, posed on a steel grid that is suspended to the hub through textile cables.

The canopy is made up of five identical modules and a half module. Each module is rotated by eight degrees relative to the previous one. The five wood half-portal frames are parallel to the N-W hub's wall and posed with twist angles, one in respect to the other, creating a helicoid that joins all the corners between the beam and the columns running from the N-W wall's head to the soil.

To have a good integration of PV panels in the canopy, we used a fairly new type of curtain wall system that can integrate all the boxes and connections of the photovoltaic panels. The solution is simple and effective thank to the integrated photovoltaic line of the aluminium profile. The aluminium profiles have a chamber in which all the cables can run.

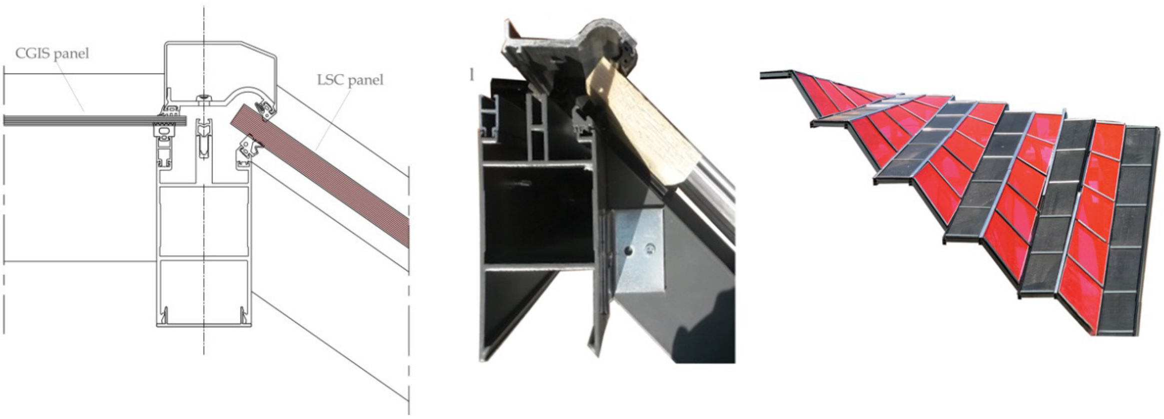

Fig.3. Detail of aluminum profiles. Panels were sealed with natural rubber gaskets while the wires run inside the aluminum extrusions.

By using this system it was possible for us to let the panels visible to the public since it looks like a window. From architectonic point of view, the integration of photovoltaic panels into a high performance canopy application offers an aesthetically pleasing. The system is specially designed to avoid shadows on the photovoltaic panels at all times. Moreover, the concept of the system permits ease of cabling during installation and guarantees accessibility for the cabling, necessary for the maintenance of the panels even after connection.

We studied four different long profiles and three crossbars to assure the correct angles of PMMA (see image 3) and to consider the difference of edge thickness between PMMA and CIGS (15mm for PMMA and 6mm for CIGS). The aluminium profiles' lengths varies between 4.45m and 6.20m with a constant thickness of 0.18 m. Crossbars' length is 0.64m with a thickness of 0.12 m. Fig.3

2.3. Energy efficiency

The energy efficiency design of Liv-lib' is based on solutions of the envelope, of control/energy management and the use of renewable energy. All these issues were resolved with separation of the function of the hub from that of the capsule and linking them with a plug. For the capsule, the thermal dispersions through the envelope were reduced through the choice of modular elements based on wood. We chose three different stratigraphy that are composed of different layers of insulations of rock wood in order to have a total thermal transmittance less than 0.09 W/m^2 K.

Renewable energy conversion systems are represented both for offices and residential buildings by a luminescence photovoltaic system that concentrates the solar radiation inside a transparent film and the CIGS, PV thin film panels. The total surface covered on the hub is of about 125 m2.

These two emerging PV, CIGS and LSC, improved potential in terms of efficiencies, aesthetic and cost competitiveness. The shape of the hub's windowed roof and façade has been conceived to obey two principles:

- To create a continuous shape from the site's orientation to find the optimum solar orientation;
- To have several faces differently oriented toward the sun path, in order to reduce the peak production, smearing it on a wider lapse of time (even though the integral production is smaller than for a flat optimal surface) and to reduce negative impacts on the grid.

The photovoltaic installation is set on the glass roof of the hub. This choice was made in coherence with the Liv-lib' concept: all the technological setting belongs to the community and is located in the hub, independently from the capsules. As a consequence-the hub in the prototype being a fraction of what it could be in a complete building-the total available surface for the solar energy conversion is relatively small compared with the inhabited area, but the coherence of the proposal was deemed paramount. The photovoltaic electricity demand of the house is satisfied through 30 thin film CIGS solar panels (21.6 m2 at 120 Wp/m2 giving 2.6 kWp) and 25 LSC (Luminescent Solar Concentrators) panels (23.0 m2 at 16 Wp/m^2, giving 370Wp) for a total power of 2.97 kWp installed.

3. Power productions

3.1. LSC

Luminescent Solar Concentrators represent a novel technology that permits the development of transparent photovoltaic panels albeit with a lower efficiency than the common modules.

These concentrators are made up of a transparent plastic slab, which is typically PolyMethilMethAcrylate (PMMA), with a thickness of few millimeters doped with a small concentration (in the order of 100-1000ppm) of a fluorescent dye. The dyes can be organic compounds (i.e. perylene or naphtalene based dyes), rare earth complexes (i.e. europium) or quantum dots, each of these has its own advantages and drawbacks with organic dyes being the cheapest and most widely available. When the slabs are exposed to sunlight the dye molecules absorb a fraction of the incoming light then re-emitting it isotropically at a lower wavelength (fluorescence phenomenon), the emission spectrum is characteristic of each dye and gives it its distinctive color.

The light emitted inside a medium with refractive index is higher than the outside (1.488 for PMMA and ~1 for air) it undergoes total internal reflection if is emitted at a larger angle than the critical angle with respect to the normal to the surface.

In LSCs this phenomenon is used to guide the trapped light towards the sides of the slab where is collected by the solar cells, given that the PMMA slab is transparent and the cells are placed only on the sides, the entire system is transparent and the appearance is similar to a traditional window with a thin frame.

3.2. *Geometry simulations - LSC (choice of position of PV cells in the panels)*

Solar cells are connected on the sides of the LSC so any mismatch in the current produced by each cell would result in a significant efficiency loss, in particular for architectural purposes the shape of the LSC systems can often be irregular or curved (as is the case of the Liv-lib' project) amplifying the problem of the current mismatch.

In order to address this issue, numerical simulations of light transport inside the LSCs were carried out. Various optical setups were evaluated, in particular, the replacement of some cells with mirrors seeming very promising because the addition of mirrors helps to even out the profile of irradiance on the cells, and it reduces the amount of cells needed for a given system power and finally it simplifies the assembly process.

The simulations showed that the highest efficiency is provided by the setup of two opposing sides covered with solar cells and two sides covered with a mirror but due to the five trapezoidal shapes of the modules composing the canopy a significant current mismatch would arise between the arrays placed on the opposite sides.

Because of this problem the setup with only one side covered with cells and the others by mirrors was chosen instead, with this setup the current produced by the cells can be considered in first approximation as determined only by the module area.

Results of the simulation on the SD module: the irradiance is 1.6·108 photons/m2 and fig. shows the number of photons per linear millimeter collected by the cells that are placed on the side 1206mm long, the reflectance of the mirrors is set at 85%. Fig. 4_ a

3.3. Laboratory tests - LSC (choice of red color)

The choice of the dye used in the LSC installed on the canopy of the Liv-lib' house was based on tests carried out at the University of Ferrara [10] where commercial organic dyes were chosen due to their concurrent ready availability in good quantity, performances and good blending into PMMA. In order to identify the compound providing the best system efficiency five organic dyes were evaluated: Lumogen® F Violet 570, Lumogen® F Green 850, Lumogen® F Yellow 083, Lumogen® F Orange 240, Lumogen® F Red 305, all are perylene-based.

The dye that provided the best system efficiency was Lumogen® F Red 305 that was therefore used for the LSCs of the Liv-lib' project which were manufactured with dye a concentration of 300ppm as it represents a good tradeoff between the slab transparency and the power production.

The graph below (Fig. 4_b) shows the results of the tests on LSCs with different dyes. The numbers 25 and 50 refer to the length of the sides in the different systems (25cm and 50cm respectively), these systems were not optimized for maximum efficiency but to show the difference in efficiency among the dyes.

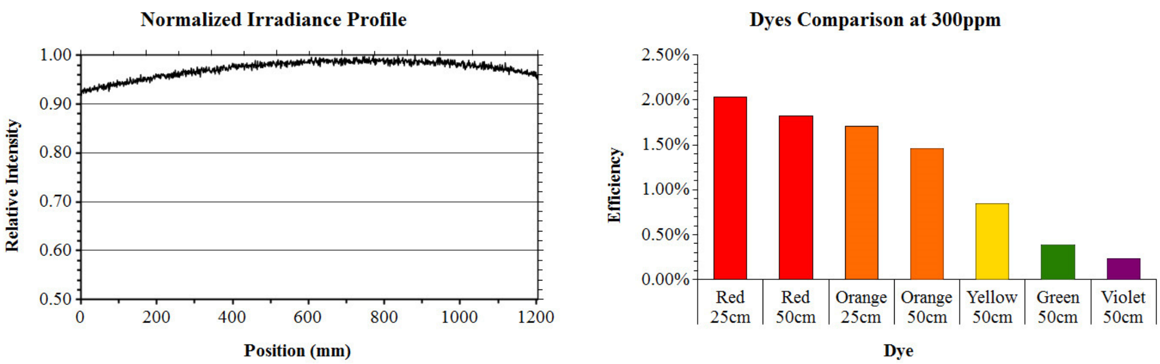

Fig.4. (a) Irradiance profile-SD5 module-1.6*10^6 n/m^3-85% Reflectivity; (b) Dye Comparison at 300 ppm.

4. Solar radiation model

We design the hub as a solar infrastructure that harvests energy from the sun with several solar angles, rather than optimize it over time and the day of maximum production angle. The idea is that even if this geometry is not economically efficient on the local level of a single panel (reduction of the amplitude of the peaks), it can be globally more efficient as it extends the time of being exposed to the solar radiation. We take into account four different inclinations of the bands of panels LSC as shown in fig 5:

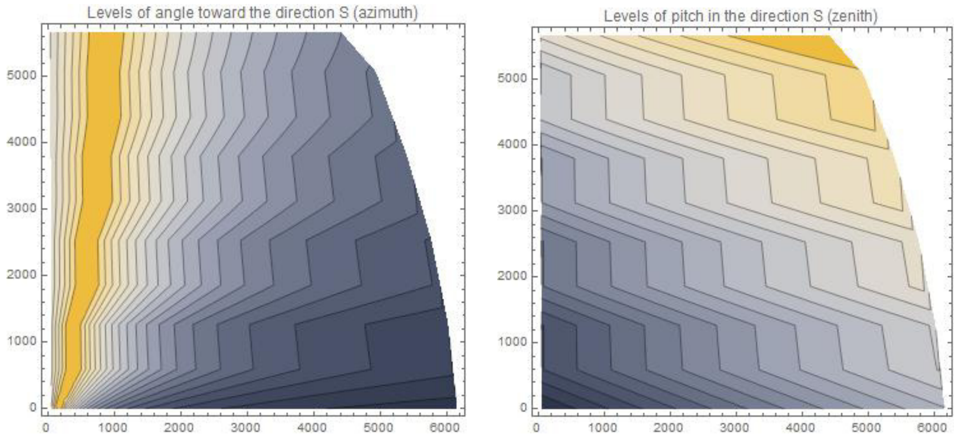

Fig.5. (a) Level of azimuth angle in canopy surface; (b) Level of Zenith angle in canopy surface

Table 1. Zenith and azimuth angles

	Zenith	Azimut
1	15°	0°
2	27.5°	30°
3	40°	37.5°
4	52.5°	45°

To find the best orientation of the canopy insuring a uniform energy production, we created a mathematical solar model that considers the variation of solar radiation (direct and diffuse energy) as continuous function of time. First we calculate the total extra-terrestrial radiation (solar constant corrected by a yearly sinus function of amplitude 3.3 % accounting for the earth elliptical orbit due to distance between the sun and earth) for four different surfaces of LSC. After passing through the Earth's atmosphere, solar radiation includes both a direct component from the sun itself and a diffuse component made up from reflections off clouds, moisture vapour and other particulates within the sky. The solar radiation can be calculated from the sun path and predictive models of the atmospheric transmission ratio *Kt*, which is the ratio of the direct radiation on a horizontal surface to the ground and the extra-terrestrial radiation. A determination of *Kt* can be obtained from the relationship between the monthly average daily global radiation on the ground (EU data [11]) and the monthly average daily extra-atmospheric radiation on a horizontal surface (calculated). In order to perform these calculations, we introduce a factor of solar exposure, ø, given by the product of positive part of the scalar product of the unit vector position of the sun and the unit vector normal to the measurement surface. ø is a number in [0,1].

To calculate the fraction of direct and diffuse irradiance on an inclined surface we used the simplified model of the atmosphere ASHRAE with clear sky [12]. The model is useful because it provides an estimate of the upper limit of direct radiation, estimated at clear sky. The model for the calculation of the direct radiation takes into account the thickness of the atmosphere (traversed by the solar rays) that is calculated as an average of the daily values of its thickness and not by the variation of this thickness throughout the day.

The fraction of direct irradiance transmitted was calculated using Fresnel equations depending only by θi (angle between sun rays and the normal of surface) and using Snell's law and trigonometric identities. The calculation takes into account the polarisation of the incident ray in electrical and magnetic field. The transmittance coefficient Γ(θi) is an average value containing an equal mix s- and p-polarisations because of unpolarisation of incident light. The fraction of diffuse irradiance transmitted was calculated by integrating the transmittance coefficient Γ(θi) over a half of sphere, taking into account the zenith. Fig.6

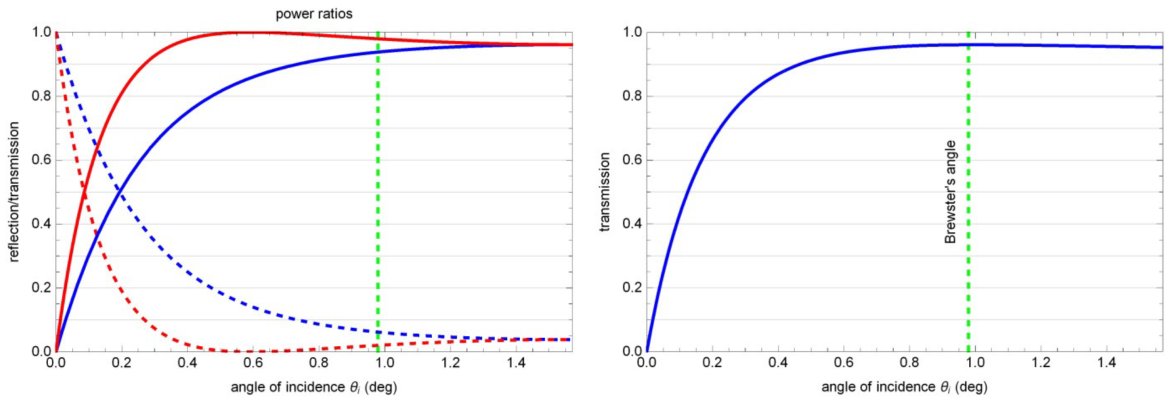

Fig.6. (a) Reflection and Transmittance coefficient for s- and p- polarization light; (b) Transmittance for un-polarization light

5. Results and discussion

We compare our structure which is exposed principally to southeast with different inclinations, with a "standard" structure which is exposed only to the south with optimum inclination. The simulation's results show that the southeast exposure determines a better transmitted irradiance from the early hours of the morning (see Fig.7). Figure 8 shows the solar radiation transmitted in three panels inclined of 15°, 52.5° and 35° respectively. The first two, which are part of the structure, are exposed south (azimuth 0°) and southeast (azimuth 45°) and the last one (standard panel) south. More panels are inclined and oriented southeast, less they are exposed to solar radiation in the afternoon hours, thus reducing the production efficiency. As said, the canopy's form follows the building constraints of the SD competition which determined its orientation southeast decreasing the amount of solar exposure of panels during the afternoon hours. A possible improvement for the proposed LSC canopy is to orient it symmetrically (East-West) in relation to the south to have a continuous exposure all day long. Nevertheless, the maximum energy production does not vary much for the four cases study and "standard" structure: it is 37.4 W/m^2 if panels were oriented to the south (azimuth 0°) with the best inclination's angle (35°), while the set of panels inclined 52.5° and oriented southwest (azimuth 45°) have 36.8 W/m^2 as maximal production.

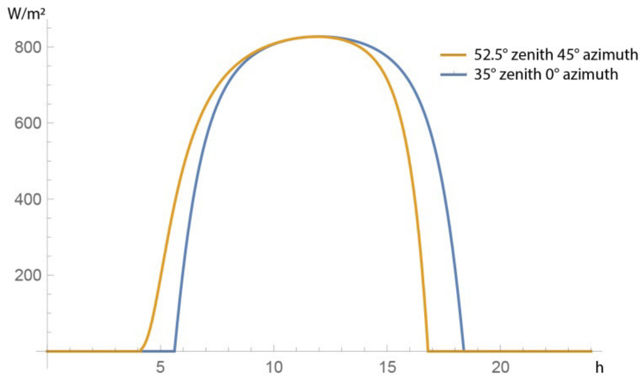

Fig.7. Direct radiation transmitted on 21 June in panels with fourth cases study: tilt and exposure (52.5° and 45° azimuth) and with "standard" position (35° zenith and 0° azimuth)

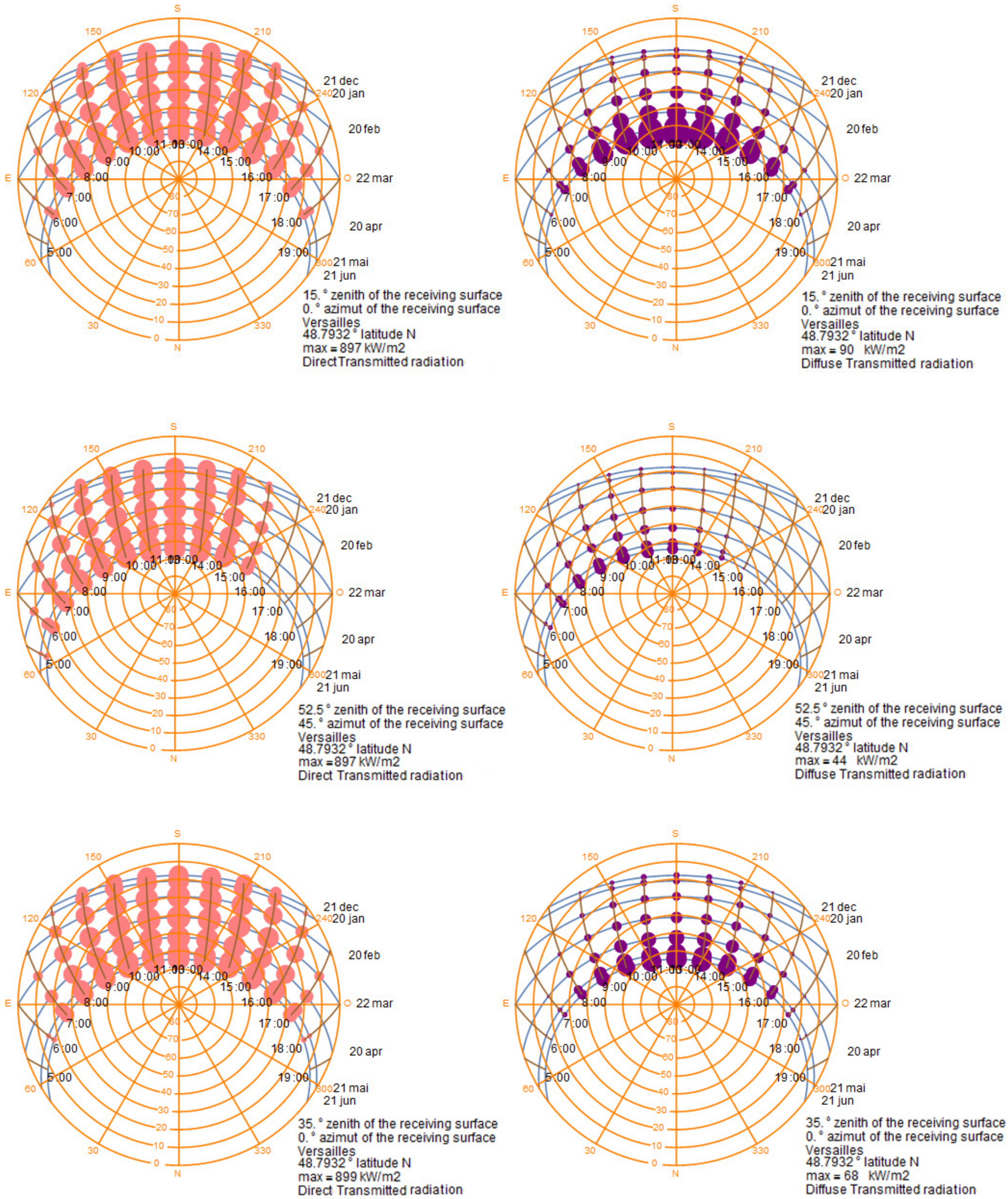

Fig.8. (a) Direct transmitted radiation (15° and 0° azimuth) (b) Diffuse transmitted radiation (15° and 0° azimuth)
(c) Direct transmitted radiation (52.5° and 45° azimuth) (d) Diffuse transmitted radiation (52.5° and 45° azimuth)
(e) Diffuse transmitted radiation (35° and 0° azimuth) (f) Diffuse transmitted radiation (35° zenith and 0° azimuth)

6. Conclusions

This paper presents a case study of a solar canopy specially designed for Liv-lib' project at Solar Decathlon Europe 2014. The canopy's shape was designed to maximize the performance of the solar conversion by integrating two innovative solar technologies, Luminescent Solar Concentrators (LSC) and Copper Indium Gallium diSelenide (CIGS) solar cells. We presented the design of canopy, its aesthetic quality in order of the building integration in Versailles' prototype. LSC represent a novel technology that permits the development of transparent photovoltaic panels with a lower efficiency than the common modules. The LSC technology fit our idea of canopy since it was translucent. We then decided to push our idea even further by using all the advantage of those kinds of panels. Since it was possible to bend them, we decided to design a curved canopy that follows the sun path to get the maximum time of exposure. The knowledge of the local solar-radiation is essential for the proper design of building energy systems and we propose using ASHRAE algorithm [12] which is widely used by the engineering and architectural communities. The energy production shows that there is negligible difference is in term of maximal production if panels were oriented perfectly south with optimum angle of inclination. However having several faces differently oriented southeast toward the sun path causes smearing energy production on a wider lapse of time in morning hours. We found that the symmetrically exposure EW would increase the energy production and longer time of exposure (also in afternoon hours) during the competition.

Acknowledgements

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