Available online at www.sciencedirect.com

ScienceDirect

Energy Procedia 91 (2016) 945 – 953

Energy Procedia

SHC 2015, International Conference on Solar Heating and Cooling for Buildings and Industry

S.M.O solution: an innovative design approach to optimize the output of BIPV systems located in dense urban environments

Francesco Frontini[a], Salim M Bouziri[a], Gianluca Corbellini[a], Vasco Medici[a]

[a] *Institute for Applied Sustainability to the Built Environment (ISAAC), SUPSI, University of Applied Sciences and Arts of Southern Switzerland, Trevano, CP 105, CH-6952 Canobbio, Switzerland*

Abstract

BIPV technologies applied to façades are strongly affected by complex and dynamic shadings especially when located in dense urban environments. In this case, the shading effects need to be evaluated in detail in order to properly estimate the energy yield and optimise the energy harvest of such PV systems.
The S.M.O (String Matching Optimisation) solution represents a new approach, entirely based on open-source software, which allows a very accurate study of the shading effects on façades and the investigation of electrical behaviour of BIPV strings under complex irradiation patterns. This solution has been validated with a real pilot BIPV façade located in southern Switzerland and the model was simulated on other theoretical PV façades with different levels of complexity. The presented method allows an accurate evaluation and optimisation of the energy yield of BIPV facades in complex urban environments.

Peer-review by the scientific conference committee of SHC 2015 under responsibility of PSE AG

Keywords: Building integrated Photovoltaic; PV Facades; Design optimisation; Urban environment; Shading.

1. Introduction

According to the European Directive 2010/31/EU, starting 2020 all new buildings will have to be Nearly Zero Energy (NZEBs) [1]. In addition, the unceasing reduction in cost of photovoltaic systems is leading to their increasing integration into contemporary architectural design and other constructions; not only on rooftops but also on buildings' façades. PV modules are not only technologies that aim to provide the electricity to the building but also allow the replacement of the old building elements by taking into consideration the architectural flair of façades and roofs. Solar power plays a strategic role in improving the energy efficiency of cities, especially the new urban regulations aiming to limit the extension of urban sprawl, promoting compact cities [2] [3]. For these reasons, this paper tackles the importance of simulating and design BIPV system with a detailed shading analysis in order to

Peer-review by the scientific conference committee of SHC 2015 under responsibility of PSE AG
doi:10.1016/j.egypro.2016.06.261

optimise the energy performance of the systems This is particularly important for construction in dense urban environments where the shadows paths can dramatically reduce the energy output. For such situation a PV string matching optimization is needed. The paper presents an approach based on different tools with the aim to suggest the user the best string configuration. This simulation analysis has been validated on a real case study situated in the south of Switzerland.

Nomenclature

BIPV	Building Integrated Photovoltaic
c-Si	Crystalline Silicon
a-Si	Amorphous Silicon
DHI	Diffuse Horizontal Irradiation
DNI	Direct Normal Irradiation
GHI	Global Horizontal Irradiation
NZEB	Nearly Zero Energy Building
PV	Photovoltaic
SMO	String Matching Optimisation

1.1. Objective of the string matching optimization solution

As photodiodes, PV cells directly convert the solar light hitting their surface into electrical power. One of the main causes of losses in energy generation within photovoltaic systems is the partial shading on the modules. Shaded cells cannot produce the same amount of power as non-shaded cells. Because all the cells in a PV module are habitually connected in series, differences in power cause differences in voltage. If one attempts to drive high current through a shaded cell its voltage actually becomes negative and the cell is consuming power instead of producing it. This effect can lead to a dramatically increase of the cell temperature and eventually burn; this is called the hotspot effect. The exact point at which the PV cell becomes a power consumer instead of producer changes between different types of cells and diodes, but usually a difference of 20% between the light hitting the surfaces of different cells in a substring is enough to cause the shaded cell to heat up. [4] In order to prevent this phenomenon the modules have diodes that allow the current flows through an alternative path, when cells are shaded or damaged. The configuration of the diodes in the module is very important and can leads to different module behaviours [5].

Nowadays, trends toward urban installations are increasing the occurrence of such partial array shading, where careful considerations need to be taken about the configuration, size, number of strings, and their connections to the inverters, while taking into account the costs and complexity of the system. In this paper, the authors present a solution to predict accurately the impact of shading and optimise string configurations for PV systems located in dense urban environment where different strings are exposed to partial shadings throughout the year, due to the neighboring constructions and other obstructions.

2. Methodology

2.1. Validation of the simulation

In order to validate the proposed approach and the physical model behind the simulation a case study was identified.

The south facade of a residential building, in Chiasso, southern part of Switzerland fully covered by c-Si BIPV modules has been chosen. This building was originally constructed in 1965 with a support structure made from concrete and non-structural walls made of brick. The building has been renovated by the end of 2011 according to passive house standards that corresponds to the Swiss Minergie P label, including all the facades, balconies, and the roof [6]. In this phase, the building's structure was improved, and cladding of ceramic plates were changed to PV thin-film modules in the four facades, in addition to the integration of C-Si modules in a particular part of the south façade, which is the one representing our case of study for the S.M.O solution. See Fig. 1.

This South façade is composed of five different PV strings connected to three inverters, where each string has 10 c-Si modules in series.

Fig. 1. Palazzo Positivo C-Si South Façade.

The building Palazzo Positivo has been monitored by SUPSI since December 2013, and the full energy yield data for each inverter of the system has been acquired; therefore, the methodology of the simulation has been validated before proceeding with the SMO solution. This validation is mainly done by simulating the BIPV system using DAYSIM and DYMOLA, considering its actual string configuration and repeatedly comparing it to the monitoring output for the same defined periods of time, in order to correct as much inaccuracies as possible in the SMO model.

The weather file used during this validation was generated from the hourly GHI (Global Horizontal Irradiation) taken directly from the onsite sensors installed in the Palazzo Positivo building. These hourly values were then imported in Meteonorm in order to generate the hourly DHI (Diffuse Horizontal Irradiation) and DNI (Direct Normal Irradiation), for the whole year [7].

2.2. Urban shading analysis

In this first analysis, the tool that is used is ECOTECT Analysis, an Autodesk product, used as an environmental design tool coupling 3D modeling interface with extensive solar functions, which allows to accurately design the Palazzo Positivo, and the urban environment surrounding the concerned south façade for this simulation. Fig. 2 shows a representation of the 3D model designed with Ecotect. As result of the 3D design, ECOTECT offers the possibility to graphically represents the irradiation received on every selected sensor of the building calculated previously by other tool (such as Daysim), An example of such simulation referred to the BIPV modules installed in the South façade is showed in the Fig. 3.

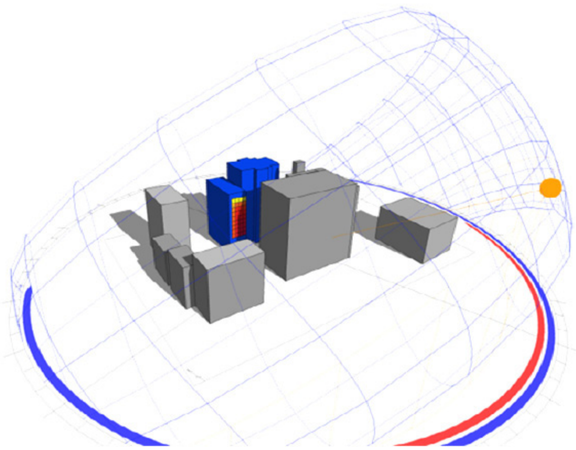

Fig. 2. Ecotect 3D Simulation of the Palazzo Positivo and the surrounding urban environment, the simulated façade is displayed by the coloured part of the blue building.

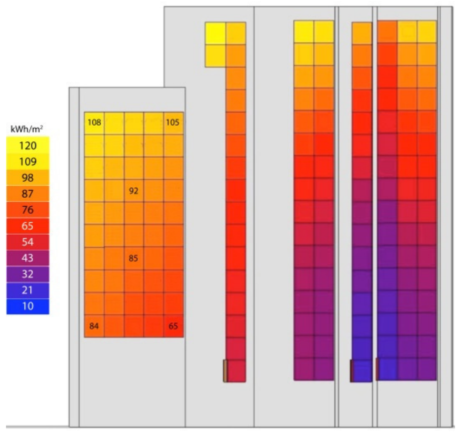

Fig. 3. Example of the ECOTECT 3D solar irradiation representation on different sensors of a façade, where the numbered part of the facade being our simulation case of study, composed of 50 PV modules.

2.3. Hourly module irradiation analysis

ECOTECT served as a 3D design tool enabling us to locate sensors on the façade and simulate an analysis grid on the BIPV façade where the solar irradiation data need to be collected on each module. For our case of study, a total of 50 irradiation sensors were selected, each one corresponding to a PV module. After the simulation of this Analysis grid, the 50 sensors allow us to know the yearly differences in the received irradiation on the facade. These data are then exported to DAYSIM, which enables to obtain a more accurate radiance simulation [8, 9, 10], with the hourly irradiation (in W/m2) at every sensor of the analysis grid, during one year. The sensors, represented in an analysis grid, are numbered from 1 to 50, following a specific order from bottom to the top and from left to right. See Fig. 4.

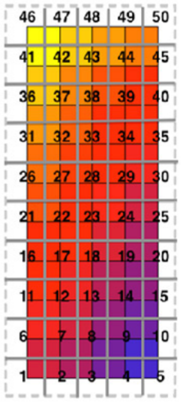

Fig. 4. (a) Analysis grid for the 50 sensors, each corresponding to a PV module on the simulated south façade. (b) DAYSIM Simulation of the Analysis grid imported from ECOTECT.

2.4. String configuration scenarios simulation

In this step, the resulting irradiation data from DAYSIM are used as inputs along with the different string configuration scenarios, the module and inverter technical characteristics, to simulate the energy performance of the PV façade for each scenario, and obtain the optimal string matching case for a maximum energy output on an hourly basis and therefore, for a full year of operation. The simulation of the whole system is done using an in house developed code on DYMOLA, which is a Modelica based simulation and modeling environment.

The model chosen for the modules' performance is the well-known single diode model (refer to equation below), the five parameters necessary to model the PV module's behavior have been estimated thanks to the measurement with a solar simulator in the SUPSI laboratory:

- I_{PH} the photocurrent
- I_0 : the diode reverse saturation
- N: the diode ideality factor (multiplied by the number of cells)
- R_{SH}: the shunt resistance
- R_{SH}: the series resistance

$$I = I_{PH} - I_0 \left(exp \frac{q(V + IR_S)}{N \cdot K \cdot T} - 1 \right) - \frac{(V + IR_S)}{R_{SH}} \quad (1)$$

The other terms present in the equation are represented by:

- q: the elementary charge
- T: the cell temperature
- K: the Boltzmann's constant

while I and Vare obviously representing the current and the voltage of the PV module.

The PV modules have been modeled including bypass diodes, useful in operation when modules, or submodules, are facing different irradiation; without the bypass diodes the modules would share the same current, causing so significant energy losses while thanks to their presence the arrays can limit this phenomenon.

2.5. S.M.O solution model

As a summary of the model, this simulation is based on a three tools:

- Autodesk ECOTECT Analysis: an environmental design tool used to couple 3D modelling interface with extensive solar functions, which allows us to design the Palazzo Positivo and the urban densification.
- DAYSIM Radiance: Radiance based software that allows the import of the ECOTECT modelling file in order to provide a very detailed shading and irradiation analysis on every single point of the facade.
- DYMOLA: a Modelica based simulation and modelling environment in order to simulate the power output of the BIPV system on an hourly basis, relying on the DAYSIM hourly irradiation files for each module.

Where the inputs are represented by:

- The geometry and architectural design of the building.
- Urban densification design (Surrounding buildings and obstructions).
- Weather File of the location, for our case of study, Chiasso (southern Switzerland). It's a yearly meteorological weather file at an hourly step, that includes 8760 value for each of the following data:
- Year | month | day | hour | Diffuse horizontal irradiation | Direct Normal irradiation | Global horizontal radiation | Temperature | Wind speed | Wind direction. Overall, 87600 data.
- Analysis grid sensors applied to the BIPV System: in our case, a grid of 50 sensors applied to 50 modules, one sensor at the center of each module. As shown in the Fig. 4. a.
- Module characteristics, tested at the SUPSI PV Lab: Short circuit current, Open circuit voltage, MPP (Maximum power point) current, MPP voltage, current temperature coefficient, voltage temperature coefficient, ideality factor, series resistance, shunt resistance.
- String matching scenarios for the desired part of the façade have been developed:

In our case, 8 possible scenarios based on irradiation differences and shading trends over the year.

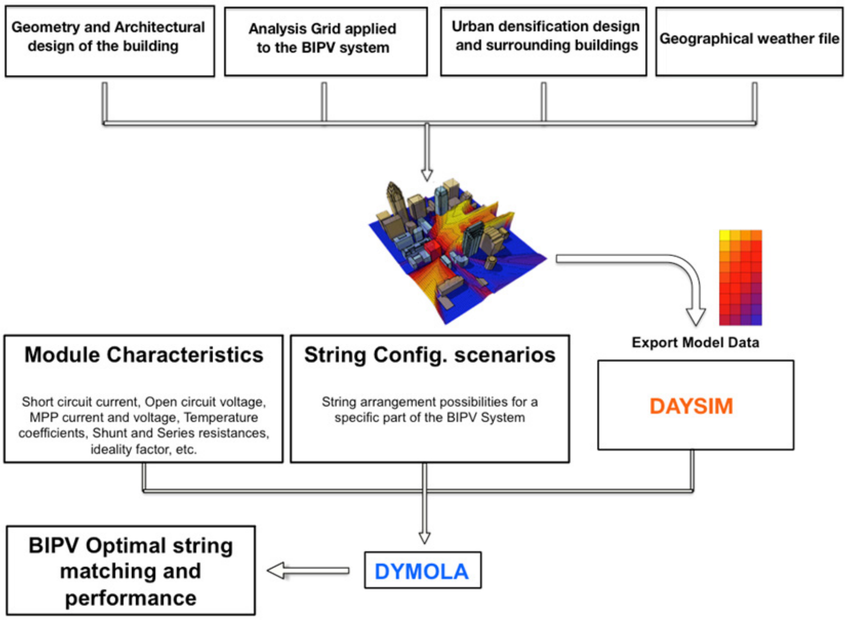

Fig. 5. S.M.O (String Matching Optimisation) solution model.

The adopted methodology is represented in the diagram in Fig. 5.

3. Results and discussion

Several configuration scenarios were simulated and compared to the initial reference case that has been implemented in the Palazzo Positivo. In total, eight different scenarios were selected, based on the yearly irradiation patterns obtained from the simulation (see Fig. 3). The investigated scenarios are shown in the Fig. 6.

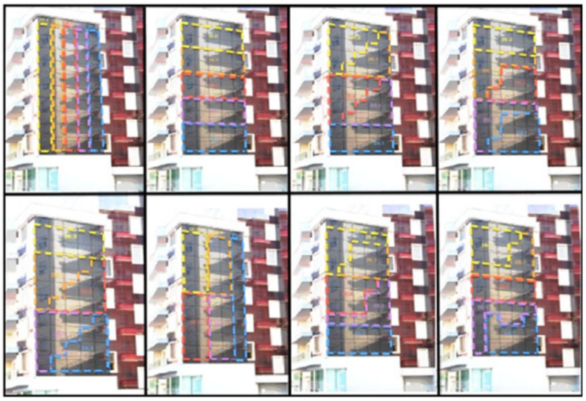

Fig. 6. The Eight simulated scenarios for the selected south façade (case of study)

As a result, the scenarios provided significant increase in the yearly energy production for the façade. The percentage increases for each scenario relative to the reference case are shown in the Fig. 7. The reference scenario has been considered the one propose by the façade manufacture.

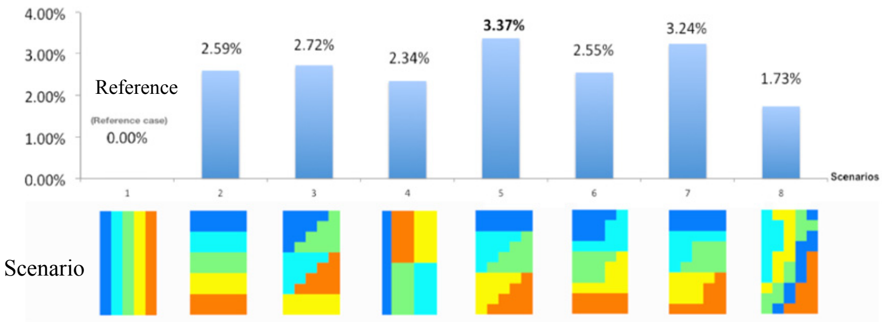

Fig. 7. Percentage gain in the yearly energy production by switching to different scenarios

The optimal string matching for this particular part of the façade, considered in its real conditions and urban environment exposure, is shown in Fig. 8. This configuration shows the yearly irradiation pattern calculated for the different BIPV modules.

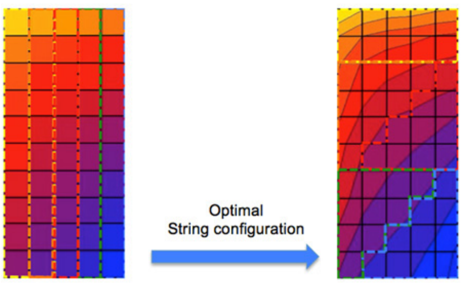

Fig. 8. Optimal string configuration for the selected south façade

In order to deeper understand the BIPV façades behaviour, 5 modules (module 1, 5, 28, 46, and 50, according to the Fig. 4 (a)) have been chosen to be further investigate. Two simulations have been done: with the surrounding conditions (urban integration); without any surrounding conditions. The difference in irradiation (ΔI [W/m2]) on an hourly basis during a year have been calculated. The obtained results are reported in a 8760-pixel heat-map for each of these simulations (see Fig. 9).

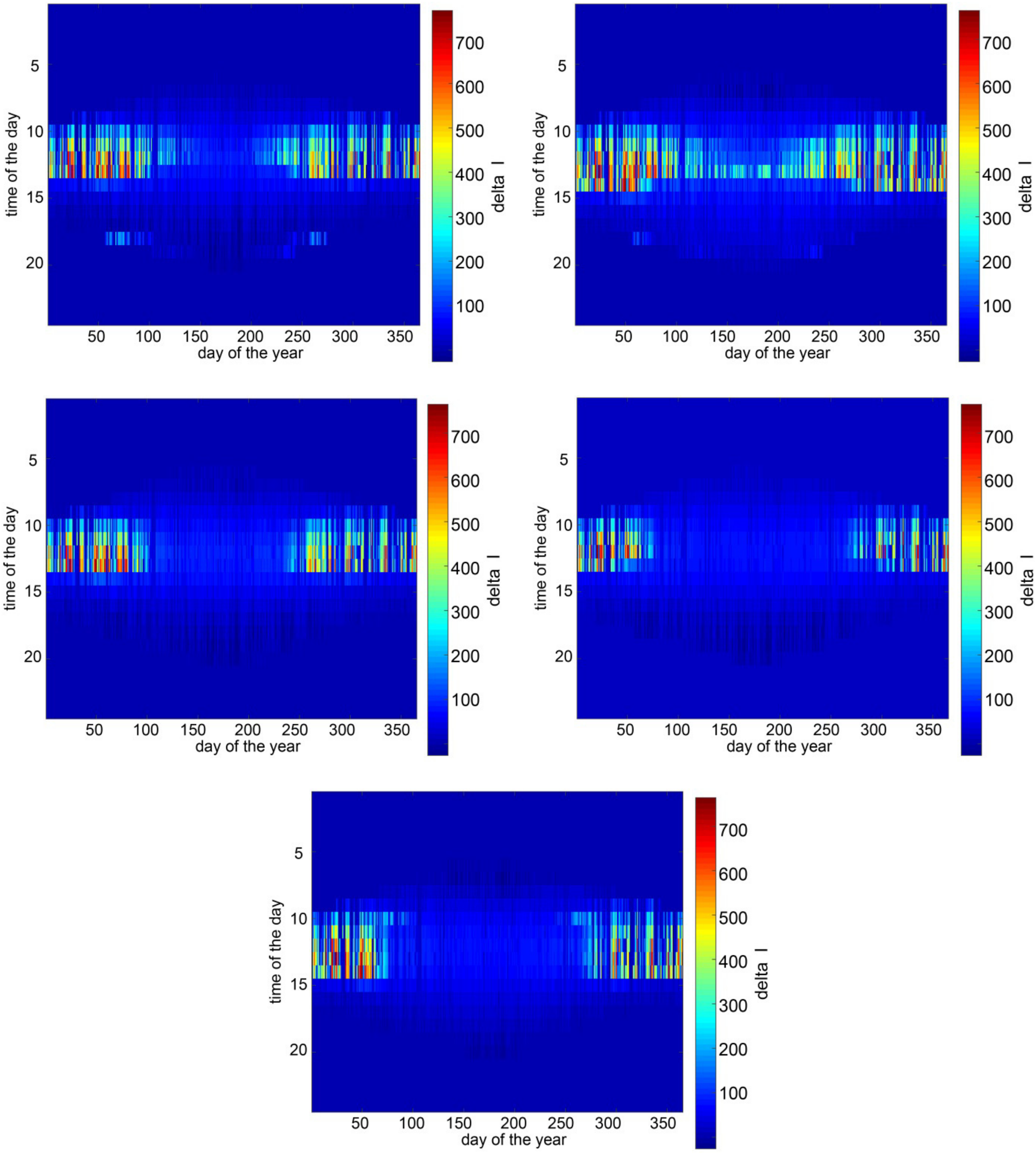

Fig. 9. Heat map of modules (1, 5, 28, 46, and 50 respectively from left to right) irradiation differences between the real case (located in urban environment) and the theoretical case (without dense environment)

From these results, we could identify differences in received irradiation on the left and right sides of the heat-maps, which corresponds to winter times, where the sun's elevation in the sky is lower, and therefore leads to higher impacts of the urban environments. The middle of the maps corresponds to summertime, and as the sun's elevation in the sky is higher, we can identify lower impacts of surroundings (see middle of the maps). The two most affected modules are the 1 and 5 as they are located in the bottom of the facades. Additionally, we can also identify urban impacts during summer on the module 5 due to its location in the bottom right of the façade, which is the part of the façade with the highest exposure to shading effects, as shown in the fig.8.

4. Conclusion

The paper presented a methodology for simulating different BIPV string configurations under complex urban scenario. The simulations proved to be very effective to understand the behavior of the BIPV system and the energy harvesting of the facades in different scenarios. Complex shadow paths on BIPV façade can have a strong impact on the energy output of the photovoltaic system if not well designed. The difference between the optimal scenario and the current one has been proven to be more than 3% for this case of study. This design strategy to enhance the performance of any BIPV system proves the importance of connecting the PV string based on an accurate shading analysis, with a careful consideration to the irradiation received by each module of the facade. The SMO model is applicable on every type of BIPV façade with an effectiveness of the optimal string configuration different from an environment to another, from a less complex urban exposition to a more complex one. In addition, it doesn't only enhance the yearly output of the system but also allows a longer lifetime for the system since it avoids mismatch losses by gathering modules within a defined range of irradiation under the same MPPT.

Acknowledgements

The authors would like to show their sincere gratitude and appreciation to the whole ISAAC team for their support and contribution.

References

[1] Directive 2010/31/EU of the European Parliament and of the council of May 2012 on The Energy performance of buildings – Published 19 May 2012; Article 2, Article 9.

[2] Carpenter S. Learning from experiences with advanced houses of the world. CADDET Analysis Series 14, Centre for the Analysis and Dissemination of Demonstrated Energy Technologies, Sittard, The Netherlands; 1995.

[3] Peippo K, Lund PD, Vartiainen E. Multivariate optimization of design trade-offs for solar low energy buildings. Energy and Buildings 1999; 29 pp.189-205.

[4] Solar Edge, Technical Note – Bypass Diode Effects in Shaded Conditions - published August 2010, pp. 1-2

[5] Díaz-Dorado E.,Suárez-García A., Carrillo C., and Cidrás j. Influence of the shadows in photovoltaic systems with different configurations of bypass diodes, International Symposium on Power Electronics Electrical Drives, Automation and Motion, SPEEDAM 2010

[6] Frontini, F. and Friesen T. and von Ballmoos C. and Di Gregorio S., Palazzo Positivo: renovation of a residential building in Switzerland with BIPV facades. In proceeding of 29th European PVSEC , 2014, Amsterdam.

[7]Meteonorm Handbook part II: Theory. July 2015. Accessed November 201: http://meteonorm.com/i

[8] Reinhart C F, Herkel S, "The simulation of annual daylight illuminance distributions- A state of the art comparison of six RADIANCE based methods." Energy & Buildings, 32:2 pp. 167-187, 2000.

[9] Walkenhorst O, Luther J, Reinhart C F, Timmer J, "Dynamic annual daylight simulations based on one-hour and one-minute means of irradiance data." Solar Energy, 72:5 pp. 385-395, 2002.

[10] Reinhart C F, Breton P-F, "Experimental Validation of Autodesk® 3ds Max® Design 2009 and Daysim3.0". Leukos 6:1 2009