A BiPV design optimization method

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Abstract:

This paper shows a method for the optimization of the design of a building integrated photovoltaic system minimizing costs over life-time, through the use of Radiance software, taking into account the constraints imposed by the architecture of the building and of the surroundings. It calculates the annual solar radiation in many spots of a surface (flat or complex) from a geometry defined by the user, calculates the power production from different PV module configurations, and finally the cash flow over the system lifetime.
The procedure was applied on a case study, specifically a geodesic dome with embedded triangular photovoltaics, two cities were considered(Izmir-Turkey and Bolzano-Italy) and two shading scenarios (i.e. shading-free and an hypothetical urban background).
The solar irradiation values (i.e. yearly insolation) on each triangular face were computed for all scenarios, ranging from ~300 to ~2100 kWh/m^2 y for Izmir and from ~250 to ~1600 kWh/m^2 y for Bolzano.
Cash flow over the BiPV system life-time is plotted for each configuration to evaluate the optimal insolation threshold, leading to the optimal configuration.
This work will be part of a complete model, which takes into account other parameters to achieve a multi-target optimization.

Keywords:

BiPV, optimization, simulations.

1.Introduction:

A Building Integrated Photovoltaics (BiPV) system consists of integrating photovoltaic modules into the building envelope, such as the roof or the façade. By simultaneously serving as building envelope material and power generator, BiPV systems can provide savings in materials and electricity costs, reduce use of fossil fuels and emission of ozone depleting gases, as well as add architectural interest to the building [1].
The aim of photovoltaic is to produce electricity, that is why the design of a PV plant is driven by the need to reduce the costs by maximizing the energy production (i.e. applying optimal tilt and azimuth angle, distance between arrays etc). On the other hand, considerations on building components are usually driven by a variety of issues ranging from statics to aesthetics. Architectural design competes with maximization of photovoltaic energy production.
Many software tools were developed in the last decade to help architects in the BiPV system design. An international survey carried out in the framework of IEA Task 41project [2][3] points out the need for software tools that can be used during the first stages of the design (conceptual design) putting a particular stress on the necessity for software to perform preliminary sizing. According to the state-of-the-art of digital tools for Solar Design given in IEA Task 41 [4], the most of the available software are more suited for detailed design than for a preliminary phase. Only few software are suitable for supporting architects in the preliminary design phase, and they should be improved to really support the development of architectural design aspects together with the PV sizing.
This paper shows a method to optimize the design of a BiPV system minimizing costs over life-time, but taking into account the constraints imposed by the architecture of the building and of the surroundings. It calculates the annual solar radiation in many spots of a surface (flat or complex) from a geometry defined

by the user, calculates the power production from different PV module configurations[1], and finally the cash flow. The method accounts costs and revenues, for a chosen life span of the BiPV. It does not force the designer to focus the building design around PV components only, but it helps to improve the BiPV design by providing suggestions.
The method described in this paper is a first step towards an integrated early design tool for architects and engineers.

2.Method:

Using free software

This method has as its core the Radiance[2][5] Software which is free and open source; to build the geometry and position numerous "virtual radiometers" over it, and to perform various programming tasks we used Grasshopper 3D, which runs on Rhino[3], and to help compile the radiance command we used Diva[4]; these are not open source software even tough, except Rhino, they are generally given for free for research purposes. It is possible to apply the same method using Radiance only: programming skills are required to automatize the compiling of the "virtual radiometers" making it less user friendly, and to perform the calculations of production and cash flow that are here presented in a mathematical form. The *.obj file could be created with various free CAD software (e.g. FreeCAD, SketchUp, DraftSight etc…).

Required inputs:

The method, requires as inputs the followings [Table 1]:

Table 1

geometry	PV system	Energy price
Shape	Efficiency	Energy price
Location	Performance ratio	Energy price growth rate
Shading scenario	Degradation rate	
Materials	Initial price	
Constraints	Maintenance costs	

Generation of model:

Shape and constraints [Table 1] are the first inputs on which to perform a simulation.The information consists in all the places where it is possible to put a PV module, and contains all the important parameters for such a purpose: the area of every region eligible for PV integration, its orientation and tilt angle and, if the user is in an advance design development stage, potential constraints such as the presence of windows , the presence of vents or other regions that for some reasons cannot be covered. If the dimensions of the standard PV modules are already known, the former regions can be cropped with sizes multiple of the module´s dimensions.
In this case, we used a geodesic dome as a shape [Figure 1]: it is a polygonal structure which approximate the shape of a spherical cap by dividing it into triangular faces.

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[1] A configuration represents one single spatial arrangement for the PV modules related to the building
[2] **Radiance** is a suite of tools for performing *lighting simulation* originally written by Greg Ward
[3] **Rhino** is a commercial CAD software developed by Robert McNeel and associates.
[4] **Diva** is a plug in for Rhino for daylighting and energy modelling

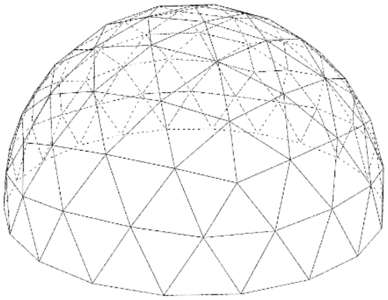

Figure 1: case study building

This type of building was chosen because every face is oriented in its own way, receiving a different annual irradiation; an equally complex pattern of irradiation can also occur on a flat surface surrounded by different shading objects. In this example triangular modules embedded in the faces of the dome were used. The dome under analysis has a radius of 5 meters and a frequency[5] of 4. For construction reasons the triangles in a geodesic dome are not perfectly equal. Integrating PV modules with different dimensions would lead to very complex PV system design and manufacturing, thus we decided to keep only one type of PV module, the area of which is equal to the area of the smallest geodesic triangle (i.e. an area of 0.76 m^2) [Figure 2] .

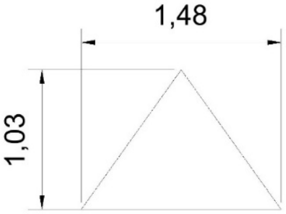

Figure 2: measures of the triangular PV module

The shading scenario is an input which allows the model to evaluate both the shadows cast by another object and also the reflections from a white, glazed or metallic surface nearby. In this example the simulation is performed in a simple urban environment [Figure 3]. Please note that there might be situations in which the building itself is part of the shading scenario

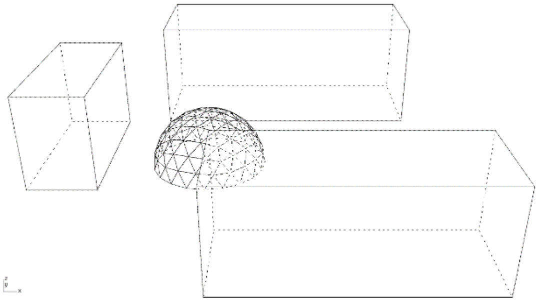

Figure 3: case study building in a urban background

The surrounding buildings can influence the behavior of light on the BiPVs under study. Thus, they must be associated with a material with properties such as color, reflectivity, specularity[6], roughness, light

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[5] The **frequency** represents the number of chords of a sphere (segments) used to connect the vertex of an icosahedron inscribed in the same sphere.

[6] **Specularity** is a property of materials in Radiance software, it represents the ratio of incident light that is reflected in a deterministic way without scattering

transmittance and light scattering. All the properties of materials are taken into account by the software Radiance.

Generation of the environment

To estimate the levels of irradiation within complex geometries it is essential to consider, in addition to direct and diffuse sky radiation, shadows cast by objects and their reflected sunlight. This is done through the use of the software Radiance, which works with a coupling of Monte Carlo and deterministic ray tracing to achieve a reasonably accurate estimation of the annual cumulative radiation over the various surfaces with a limited computational effort. The radiation source is described as a sky vault divided into 145 patches, each with a similar solid angle and associated with an annual cumulative radiance [Wh·(sr·year)$^{-1}$·m^{-2}] value. This sky description is a variation of the original model proposed by Tregenza [6]. The distribution of radiance follows "*continuous mathematical expressions that change smoothly from the horizon to the zenith and with angular distance from the sun"* [7]. Information to build such a model are: latitude and longitude of the location, a period of time over which the cumulative radiation is calculated, a weather file to retrieve direct and diffuse radiation. The Radiance software calculates the position of the sun from latitude and longitude and based on the information retrieved from the weather file (*.epw), it assigns a value of cumulative radiance [Wh·(sr·year)$^{-1}$·m^{-2}] to each sky patch. In the example shown in this paper, the annual weather files were retrieved from Meteonorm[7] [8] for Izmir and Bolzano.

Generation of virtual radiometers

Radiance requires as an input a grid of points where to measure the irradiation values according to a given vector direction. These points are like virtual radiometers, which measure radiation in each given position and direction. The radiometers are described by six digits where the first three represent their position related to an Euclidean spatial reference system, and the other three represent a vector normal to the measuring surface. For example to measure the horizontal radiation of the point having coordinates x, y, and z the radiometer should be identified as "*x y z 0 0 1*".

Calculating the energy output and the cash flow of the BiPV

The energy output depends on the location, and on the shape of the building under study, but also on the positions where we decided to put our solar modules.
In order to evaluate the best PV modules positioning on the geodesic, a threshold [Wh/m^2 yr] for the minimum insolation was set, below which the installation of PV module is not suitable from an economic point of view. The higher the threshold the more are the positions which will be discarded.
By running the simulations, we obtain the annual insolation [Wh/year·m^2] for each measuring point (i.e. for every virtual radiometer). In order to estimate the "year 0" power production, we used this simple formula [Equation 1]:

$$E_{thr} = A_{min} \cdot \eta \cdot PR \cdot \sum_{n=1}^{n_{threshold}} H_n$$

Equation 1

Where:
E$_{thr}$ is the energy output [kWh] for one year
n$_{threshold}$ is the number of triangles having an incident cumulative irradiation higher than the identified threshold [Wh/m^2 yr] e.g. if our threshold is 1000 kWh/m^2 yr, n$_{threshold}$ will be the number of triangles with an incident solar irradiation higher than1000 kWh/m^2 yr

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[7] **Meteonorm** is a software and a database which allows the user to view weather data from many places on earth, and print it in different formats, in our case we used epw.

$\mathbf{A_{min}}$ is the area of the smaller triangle in the dome [Figure 2]
$\boldsymbol{\eta}$ is the module efficiency
PR is a performance ratio accounting for several losses that can be decided by the user
$\mathbf{H_n}$ is the cumulative insolation of the nth triangle [kWh/m^2 yr]

The cumulative energy output and the related cash flow over a chosen time-span are then calculated given an annual degradation rate with the formula (Equation 2):

$$B_{yr} = \left(\sum_{n=0}^{yr} E_{thr} \cdot Cp(n) \cdot \, P_E(n) - \, m_{thr} \right) - P_0$$

Equation 2

Where:
$\mathbf{B_{yr}}$ is the cash flow on a specific year: for example B_5 will be the cashflow after 5 years from the installation;
Cp(n) is a coefficient of performance which decreases each year: $Cp(n) = \, 1 - [{}^{k \cdot n}/_{100}]$, where **k** (degradation rate) is a value chosen by the user;
$\mathbf{P_E(n)}$ is the energy price [€/kWh] on the nth year which is made by an initial energy price [€/kWh] given by the user, and a growth rate formula, also given by the user;
$\mathbf{m_{thr}}$ is the yearly maintenance cost which depends only on the installed capacity, OPEX: operating expenditure: $m_{thr} = P_0 \cdot m_{input}\%$ where m_{input} is a value chosen by the user;
$\mathbf{P_0}$ is the initial price of the whole plant, CAPEX: capital expenditure (based on a price/kW$_{peak}$ chosen by the user);
$\mathbf{E_{thr}}$ is the annual energy output [kWh].

The final output of the method is the BiPV system cash flow, as a function of threshold and year. The threshold is correlated with the number of modules installed, therefore with the peak power capacity. The last year of the series is the most important for the purpose of this paper because it shows how much we have earned or lost at the end of life whereas all the other years only show intermediate positions.

3.Results and discussion:

The simulation input

In our case study we used the following input:

- shape: a geodesic dome with a radius of 5m and a frequency of 4;
- locations: Izmir and Bolzano;
- shading scenario: two different scenario, an empty one and a simple urban background [Figure 3];
- materials: generic plaster (reflectivity 0.35);
- constraints: the PV module must be a standard one, because of this the smallest triangle determines the size appearing in the dome thus fitting on every triangle;
- cell efficiency: 10%;
- performance ratio: 80%;
- photovoltaic price: 3000 €/kWpeak;
- maintenance costs: 2% of the initial price;
- degradation rate: 1% /year, which is a typical value for CIGS [9];

- initial price: 0.15 [€/kWh] for Turkey and 0.23[€/kWh] for Italy according to Eurostat values [10];
- price growth rate: 2 % for Turkey and 1.8% for Italy in the next 20 years[11][12].

One radiometer is associated to every face of the geodesic dome, therefore a solar radiation value. Figure 6 shows the irradiation values on each triangular surface for the four case studies (i.e. Izmir and Bolzano, with and without shading scenario). In the scenes without shading scenario, the cumulative irradiation reaches 2070 kWh/m^2 yr in Izmir [Figure 6a] and 1640 kWh/m^2 yr in Bolzano [Figure 6c]. By adding the shading scenario, the irradiation values fall respectively to 1950 kWh/m^2 yr [Figure 6b] and 1470 kWh/m^2 yr [Figure 6d]. For the city of Bolzano the difference between the irradiation of a blank scene (i.e. without shading scenario) and the one with surrounding buildings is higher: this is due to the fact that it has higher latitude, and so the apparent sun path is lower causing the structures nearby to cast a longer shadow on the geodesic dome.

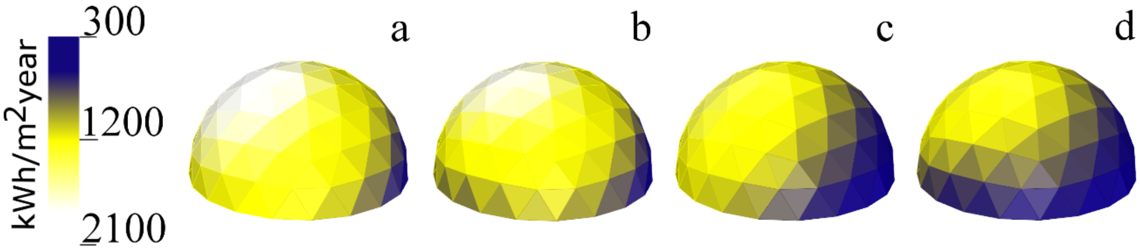

Figure 4: Yearly insolation: a) Izmir blank, b) Izmir with background, c) Bolzano blank, d) Bolzano with background

The different parts of a building (especially if they present complex shapes and many shading elements) are exposed to diverse levels of irradiation. Thus, some parts are more suitable than others for PV integration. Once the most irradiated areas are covered with PV modules, any additional power has to be installed in a less favorable position. This phenomena is particularly visible in a geodesic dome because of its shape. In Figure 7 the yearly production of the whole BiPV system and the yearly average normalized production are plotted for different threshold values. As expected, the overall energy production grows in a logarithmic way because for every PV module added in a less favorable position, the additional energy generation is decreasing. In fact, the average normalized energy production is decreasing linearly with the decreasing threshold.

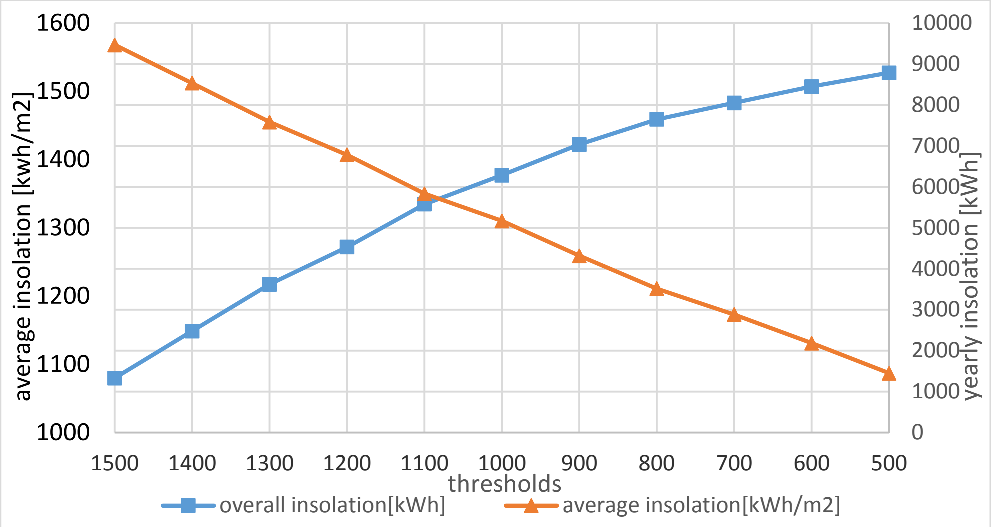

Figure 5:average or yearly production versus threshold for the case study building.

Despite the phenomena shown in the chart, examining the cash flow over 20 years, we see that the most positive cash flow is not for the highest threshold (i.e. the lowest installed capacity), but for an intermediate one: For Izmir it lies at 1600 kWh/m^2 year, corresponding to a capacity of 3,7 kW$_{peak}$ [Figure

8] for the blank scenario and to a capacity 1,3 kW_{peak} [Figure 9] for the scenario with shading because in the latter a lower number of modules are above that threshold. In Bolzano the optimal threshold is 1000 kWh/m^2 yr corresponding to a capacity of 5,9 kW_{peak} [Figure 10] in the blank scene, and it is 1100 kWh/m^2 yr corresponding to a capacity of 2,8 kW_{peak} in the urban set.
The method allows the user to understand which is the best PV system dimension yielding the highest earnings and it can also be used for other applications, such as PV ground mounted systems.
According to the optimal identified threshold for each case study, the corresponding dome configurations are shown in Figure 12, where the blue part represents the positioning of the PV modules. Depending on other constraints, the user can decide, if they want an higher production or a lower initial investment, to drift away from the peak of the curves shown in figures 8 to 11.

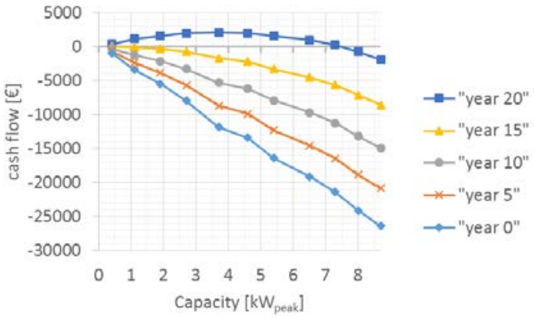

Figure 6: cash flow over 20 year for Izmir blank

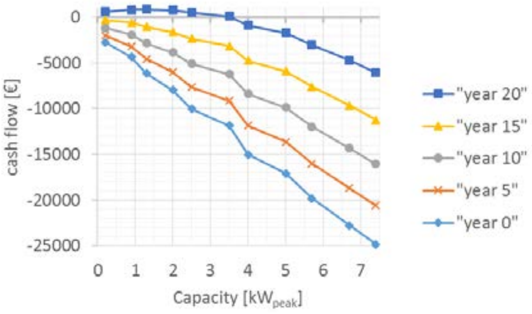

Figure 7: cash flow over 20 year for Izmir with background

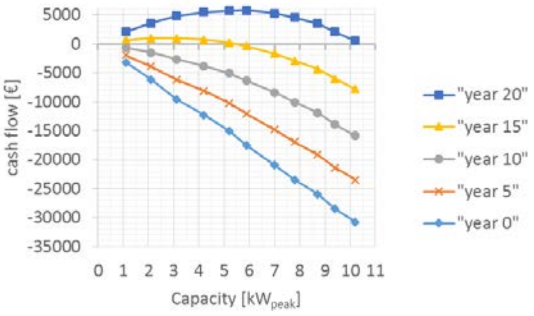

Figure 8: cash flow over 20 year for Bolzano blank

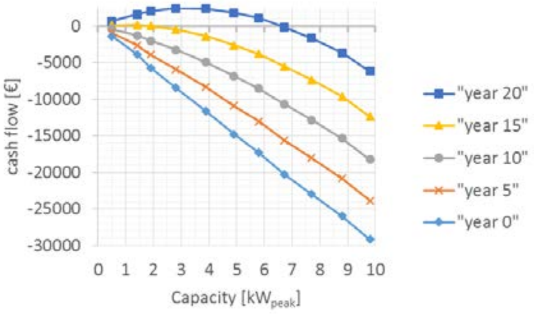

Figure 9: cash flow over 20 year for Bolzano with background

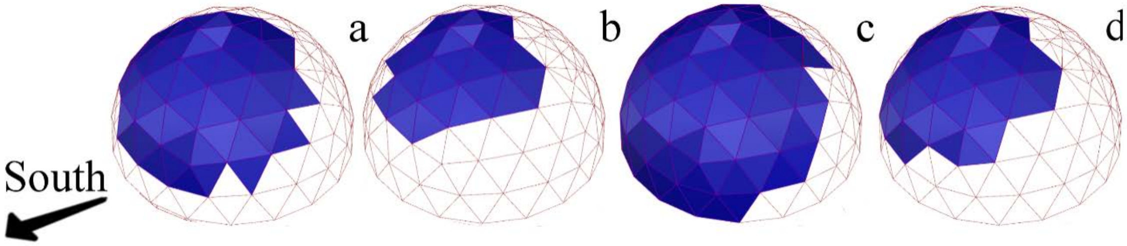

Figure 10 Configurations: a) Izmir blank, b) Izmir with background, c) Bolzano blank, d) Bolzano with background.

The case study brought as example shows that, despite a higher level of solar irradiation, the highest net income after 20 years for Izmir corresponds to a lower peak capacity respect to Bolzano (3.7 against 5.9 kW_{peak}), but also that despite a capacity of nearly 60% of the one for Bolzano, the yearly production of electricity from Izmir is around 85% of the other (5400 and 6200 kWh). One interesting aspect that emerges from the charts in Figures 8 to 11 is a shifting rightward of the peak of the cash flow over the years: for example in Bolzano it starts with a linear decreasing curve, having therefore as a highest point the left extreme (1,1 kW_{peak}), but after 15 years it is shifted on an higher capacity point (3,1 kW_{peak}) to finally reach the last peak (5,9 kW_{peak}). This right shifting of the peak shows that the number of years on which the cash flow is measured, i.e. the considered life-time of the system, affects in a positive way the number of modules that is convenient to install.

4. Conclusion:

This method is suitable for BiPV because it optimizes a system regarding cost and production but considering architectural aspects; it is simple and flexible, and it can be applied on different software, also exclusively free ones.

Because this method is meant to be used in the early design phase, the economics and energy calculations are very simplified and they do not provide detailed information. It will be possible to implement the method adding the effects of temperature on the overall efficiency or lifetime and to improve the electrical part including the wiring strategy and the electronics for a more precise estimation of the performance ratio and of the initial price. Moreover many input we used, such as degradation rate, price growth for the electricity and maintenance costs are still blurry due to the relative youth of most of all the installations. In future studies, this method could be integrated in an early design BIM (Building Information Model) which takes into account BiPV and is able to analyze the impact of the PV modules in terms of thermal behaviour, daylight, energy production and life cycle assessment, this will ultimately have an impact on the energy balance of the BiPV system as a whole.

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