EFFECT OF MODULE ORIENTATION AND BATTERIES ON PERFORMANCE OF BUILDING INTEGRATED PHOTOVOLTAIC SYSTEMS.

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ABSTRACT: This paper explains the working principle of the free and open source software “POW” (Photovoltaic Optimization Ware) and shows its application in three fictional examples. The examples show that the sheer annual cumulative irradiation cannot be the only parameter considered when installing a PV system in a building. Furthermore the installation of photovoltaic collectors in the facades of a building can be economically more profitable than on the roof provided that the price [€/kWp] is assumed equal on both the surfaces. This phenomena persists also when combined with a prominent electric storage system. The orientation of the modules in terms of Azimuth loses importance when batteries are installed, but the orientation of the PV module in terms of tilt keeps holding primary importance because it influences the seasonal production profile of the system.
Keywords: Building Integrated PV (BIPV), Building Integration, Economic Analysis, Software, Solar Architecture.

1 AIM OF THE TOOL

Photovoltaic Optimiztion Ware (POW) was developed within the H2020 4RinEU project and is intended to advice building designers about the correct PV and battery capacity to install and about which parts of the building envelope are the most useful for PV. The tool is especially significant in urban context or in case of PV installation in facades and other non-conventional surfaces. In urban context, shadows are common and affect the irradiation of parts of the envelope in different hours of the year. In projects where the roof cannot be used for electricity production the facades can still be profitable and sharply reduce the electricity demand of the building. In such cases PV is often ignored as not believed to be lucrative, this tool aims to increase the confidence in its use and to show how to make urban PV profitable. The ultimate aim is therefore to increase the prominence and capillarity of BIPV by including it in non conventional areas of the buildings and of the city. Another desirable effect is to increase the quality of installations in terms of fitness to the energy needs of the building. The workflow controlling this tool is explained in the paper, a free and open source software tool was generated from the method in order to promote replicability.

1.1 Innovative features

An innovative aspect of this method is the ability to support complex geometries because of both the input type and the procedure used to calculate the irradiation. The irradiation is based on the RADIANCE powered DAYSIM software [1], which calculates it by means of ray-tracing [2]. This Method presents some stochastic elements but proves much more versatile compared with purely geometric and deterministic methods. Aside of this, the main innovation presented by this method and tool is that the PV positions and capacity and battery capacity are not an input of the software but an output. Simulation tools, which greatly outnumber optimization tools in the field of building’s physics [3], are used to predict the behavior of a specific system. Simulation software, in case of PV, can accurately model the electricity production and in some cases offer an economic outlook of the system, nevertheless they require the position and capacity of the PV system as an input, therefore cannot fit into the design workflow. The optimization process, being similar to spontaneous processes in the architectural practice, could well integrate into the design workflow providing some basic rules for the design of BIPV systems in the early design stages [4].

2 APPROACH USED

The main task of the tool is to find, out of a complete cloud of points, the sub-system of those on which make sense to install a photovoltaic collector (see Figure 1). Together with this information, automatically comes the capacity of the PV system. Altough not examined in this paper, the tool can optimize the battery capacity in relation with the PV capacity. To find the most economically rewarding PV system the method should take into account all the relevant aspects that can influence its performance and the profitability. Not all the inputs required by the simulation are known as some are strongly dependent on factors such as developments in the global economic outline or the aging of the photovoltaic material. For this reason, some inputs are values and others are lists, the lists will transform the result in a probabilistic curve where more values are possible.

Figure 1: simplified scheme of the working of the POW tool, the battery capacity is represented in gray as it is not examined in the paper.

2.1 Inputs

The following table (see Table I) represents all the inputs required by POW Where:

Table I: inputs of the simulation.

deterministic	stochastic
Cloud of points Irradiation matrix Weather file Load vector Area of the modules **A** Efficiency of modules **η** N° of years for NPV **t** Price consumed el. $\mathbf{P_c}$ Price sold el. $\mathbf{P_s}$	PV degradation Load growth Price el. growth Price sold el. Growth Discount rate **i** Mantainance [€/kWp] $\mathbf{C_t}$

PV cost[€/kWp] $\mathbf{C_0}$

Battery cost[€/kWh] $\mathbf{C_b}$

The **cloud of points** is a file containing all the tridimensional positions and directions where the irradiations are calculated, the direction associate to each points represents the plane over which the irradiation falls. The **irradiation matrix** contains a vector of hourly irradiations for each point of the cloud of points. The **weather file** is an *.epw (Energy Plus Weather[5]). The **load vector** [W] represents the hourly consumption of electricity of the building under exam. The **N° of years for NPV** represents the time horizon after which the Net Present Value (NPV) is calculated. **Price consumed el.** And **price sold el.** Are the prices for the electricity bought or sold from-to the grid.

PV degradation refers to a loss of performance over the years by the photovoltaic system, it is expressed as a linear percentual degradation of the efficiency. All the **growth figures** are expressed in the form of a linear percentual growth of the initial value and represent variation of some parameters over the time of the NPV evaluation. **Discount rate** is help here?.

2.2 Fitness function

To evaluate the performance of the system, the optimization algorithm needs a fitness function, this is a value that change for every possible configuration of the system, in the single target (i.e. single value function) optimization implemented in POW the fitness function is represented by the NPV =

$$\sum_{t=0}^{n°yr}\left(\frac{c\cdot P_c + s\cdot P_s - \omega_{PV}\cdot C_t}{(1+i)^t}\right) - \omega_{PV}\cdot C_0 - \omega_b\cdot C_b.$$

Equation 1: formula for the calculation of NPV

c is the production of electricity which is consumed in place, it depends on the weather, the capacity $\boldsymbol{\omega_{PV}}$ of the configuration, the load vector, the load growth, the battery capacity $\boldsymbol{\omega_b}$ and on the PV degradation. **Pc** or **Ps** are the prices of the self-consumed or sold electricity, they change every year (dependence on **t**) according to the relative price growth. **s** is the production that is sold to the grid, it depends on the same variables as **c**. **Ct**,**i**,**C0** and **Cb** can be found in Table I. The PV cost C0 in the present version of POW is considered constant over the surface of the building. No difference is made in terms of cost [€/kWp] between PV in façade or on the roof. This aspect might be seen as an advantage for the PV on façade as it is expected to cost more due to premiums in aesthetics and mounting technology. In the façade integration PV is more likely to substitute another coating material compared to the roof integration, but it is not easy to establish which comparable coating solution should be subtracted from the price to establish the real price of PV.

The variables c and s are complementary parts of the power of the system described, in every hour of year (hoy), by the relation

$$c + s = A\cdot\eta\cdot PR\sum_{hoy=0}^{8760}\sum_{p=0}^{n} I_{hoy,p}\cdot c(T_p),$$

Equation 2: power of the system in every hour of the year

where **p** is one of a configuration of points {p_1, p_2, …, p_n}. $\mathbf{I_{hoy,p}}$ is the irradiation over the point p in a specific hoy, **c(Tp)** is a reduction coefficient due to temperature losses and calculated with the linear relation as described in [6]. **A** and **η** are described in Table I, PR is a static performance ratio except the temperature effect which is calculated. The temperatures in each point and hoy is described by the relation $\mathbf{T_p} = T_{ambient} + k\,\mathbf{I_{hoy,p}}$, where k is the Ross coefficient as in [7]. A strong influence on the magnitude of c over s is exerted by the capacity of the battery, this is presently modelled in POW as an ideal storage (with efficiency of 1 and no losses overtime) which follows the behavior shown in Figure 2.

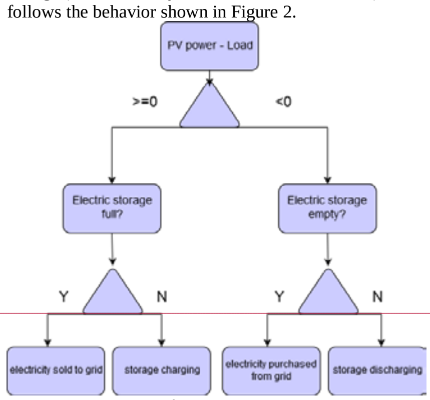

Figure 2: behaviour of the electric storage.

2.3 Optimization algorithm

The optimization algorithm is the procedure followed to obtain a well-performing, if not the best performing, configuration of the system. Presently POW allows for the use of a simple embedded algorithm, hence called One-By-One (OBO) , or a single target genetic algorithm, hence called single target genetic (STG), based on the DEAP [8] library for Python. The main difference between the two optimization algorithms is that OBO has an additional (incremental) behavior and solves the problem one point at a time while STG directly finds the configuration in a single run. Facing the problem of deciding the best combination of points to occupy with PV collectors from the cloud of points, OBO simply starts with an empty system (0 kWp) and adds only one solar collector (the available one yielding the best NPV). After having added the first collector, it restarts again but with this collector instead of the empty system form before, and so on. The difference between the first and the second run lies in the load profile, in fact the electricity production of the collector indents the original demand profile of the building, this fact will at length dramatically reduce the level of self-consumed electricity produced by the system. Faced with the same problem STG would instead try various combination of points measuring the NPV of each complete system and be driven, generation by generation, towards a combination characterized by a high NPV. In both the algorithm the points are divided in groups according to their orientation (façade or roof-pitch) and each group is sorted from the most irradiated to the least, this is done because the orientation influences the hour of the year in which the collector produces electricity. Thanks to this organization of the points, OBO only has to select among the most irradiated modules of each group deciding which group can yield the highest NPV. STG also has a reduced number of combination as should only find one percentage of utilization for each group instead of including every possible arrangement of points. If the battery is not part of the optimization, OBO really has an

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edge over STG as it can reach the best solution with a far smaller number of simulations. On the "Tower" building in the results session, which has 7 groups of 10 points each, OBO would have to perform (in the worst case) 7 simulations for each of the 70 points totaling at worst 490 simulations. On the same building STG would have to perform a good 10% of 10^7 simulations to have a good chance of finding the best combination. OBO is tough incapable of handling the optimization of a battery alongside the PV system, this because the battery has a sort of retro-active effect on the system. OBO can in fact install collectors in less irradiated groups in reason of a better contemporaneity between production and consumption. Whenever a battery is added, the production profile becomes less important compared to the sheer energy production rejecting the previous point selection criteria based on contemporaneity. In these situations OBO would have to run an entire optimization cycle for each battery capacity increasing the number of simulations by the grain of the battery capacity parameter. In the former "Tower" building example the number of simulations would climb up to 490×10 if to the battery capacity parameter is applied a grain of 10. On the other hand STG could give an excellent result with 70 simulations only (10% of 70 points × 10 batteries) provided that the points are divided in one group only, which, considering the battery, should not impair the result. The OBO algorithm has the advantage that saves the best PV module at each iteration, in this way the output is a list of positions for the PV collectors. If the whole list up to a chosen point is taken, it represents the best possible system of that specific capacity. Being that a collector area is assigned to every point, the number of points in a configuration is directly linked to the capacity of the system. This aspects of the OBO algorithm allows for the production of charts such as (Figure 6).

2.4 Assumptions for the examples

In the paper, three imaginary examples are examined in which the tool is used to find the best configuration of modules on the building skin to achieve a hign NPV. In all the cases the OBO algorithm was used. The three examples will hence be called "Tower"(Figure 3), "Roof" (Figure 4) and "Block" (Figure 5).

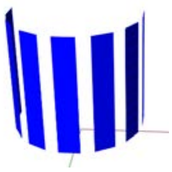

Figure 3: all possible PV positions for "Tower".

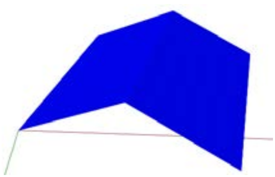

Figure 4: all possible PV positions for "Roof".

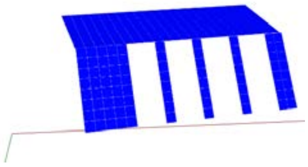

Figure 5: all possible PV positions for "Block".

Despite different geometries and weather files, all the examples share the following set of inputs (Table II), these are imaginary inputs and do not represent real countries or systems.

Table II: common inputs for all the examples

Efficiency of modules η	0.15
PR (except temperature)	0.82
N° of years for NPV **t**	25
Price consumed el. $\mathbf{P_c}$	0.2 €/kWh
Price sold el. $\mathbf{P_s}$	0 €/kWh*
PV cost $\mathbf{C_0}$	1800 €/kWp
PV degradation	[0.3,0.8]
Load growth	[0,2]
Price el. growth	[-1,-0.5,0,0.5,1]
Price sold el. Growth	[-1,-0.75,-0.5,-0.25,0]
Discount rate **i**	[0,1,2,3,4,5]
Mantainance $\mathbf{C_t}$	[18,36] €/kWp yr

*Can vary for the "Tower" building, see Table III

In the case of the "Tower" building, more scenarios have been tried to show how the positions in which is possible to install PV rank differently. In the case of the "Tower" building the aim is not to find the best NPV producing system, but rather show how the modules rank differently by varying the scenario.

Table III: different scenarios for the "Tower" building

	Internal load	battery	Price sold el. **Ps**
I	low (1 mWh/yr)	no	0
II	low (1 mWh/yr)	10 kWh	0
III	medium (7 mWh/yr)	no	0.05

3 RESULTS

3.1 Position rank for the PV system "Tower"

The first example is not a real optimization, it only deals with the order in which the potential positions are ranked. As visible form Figure 3 the building has the capacity to host 70 PV modules (7 groups with 10 modules each, totaling ca. 15 kWp). A customer who wants to install 14 modules (a power of 3 kWp) needs to know which of the potential positions should be occupied, therefore needs the positions to be ranked. The easiest way of ranking the positions is by irradiation (Figure 6), but it is not always the most profitable one.

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52	26	4	0	5	25	50
53	29	7	1	6	27	51
56	34	11	2	9	32	54
57	35	12	3	10	33	55
60	39	15	8	14	37	58
61	41	19	13	17	40	59
64	44	22	16	21	42	62
65	45	24	18	23	43	63
68	47	30	20	28	46	66
69	49	38	31	36	48	67

Figure 6: position ranking by irradiation

If the building is in the situation of *case I* from Table III, the best way of disposing 3 kWp is in fact in a horizontal array covering all the allowed groups of the building(see Figure 7).

3	2	5	0	1	4	12
8	6	10	11	9	7	13
14	17	22	21	19	16	26
15	25	24	23	20	18	27
34	36	38	28	31	30	40
35	37	39	29	33	32	41
53	44	43	47	46	51	54
52	49	42	48	45	50	55
64	67	61	58	56	65	69
63	66	59	60	57	62	68

Figure 7: position ranking by profitability case I

If the building is in the situation of *case II*, the most irradiated position gain importance compared to *case I* because they allow to charge the battery during the central hours of the day. This ranking shows a distinct preference for the east facing modules(see Figure 8). This happens because after noon the battery is charged and the electricity production is not rewarding. On the other hand, in the morning it has already discharged encouraging a “demand matching” behaviour. This ranking could change if the charge/discharge algorithm of the battery is modified. The overall performance of the system will probably benefit from a “smarter” storage system.

45	41	2	0	10	7	12
46	42	6	1	9	8	11
40	39	47	3	13	14	44
49	51	48	4	16	15	50
27	21	32	5	18	17	23
28	26	38	22	33	19	24
53	52	25	31	37	29	30
54	55	20	34	43	35	36
68	57	60	65	63	59	56
69	67	61	66	64	62	58

Figure 8: position ranking by profitability case II

If a higher electricity demand and a minimum valorization for the electricity sold to the grid is applied, such as in case III, the ranking pattern (Figure 9) becomes much more similar to the simple irradiation ranking of Figure 6. Installing a system of 3 kWp only one module differs between the ranking in Figure 6 and that in Figure 9.

50	15	4	0	5	20	51
53	22	7	1	6	25	52
56	29	9	2	8	33	54
57	30	11	3	10	34	55
60	36	14	13	12	37	58
61	41	19	16	17	40	59
64	43	24	18	23	42	62
65	45	27	21	28	44	63
68	47	32	26	31	46	66
69	49	39	35	38	48	67

Figure 9: position ranking by profitability case III

3.2 optimized PV system “Roof”

The “Roof” example is composed by two surfaces lighted by two different annual cumulative irradiations (see Figure 11) and has no possibility for installing battery. The electricity demand in the example is imaginary; its annual cumulative value is of 36 mWh. The optimization, regarding PV capacity and positions only, is carried out using the OBO algorithm with median NPV as fitness function. The algorithm adds the PV collector one by one, and at every iteration it adds the one that better increases the total NPV of the system (see Figure 6). When OBO reached the plateau it proceeds by installing the least damaging one (right side of the plateau in Figure 6). Despite being based on the median NPV each simulation produces a probabilistic curve of NPVs because the simulation is based on stochastic variables (Table III). In the grey area in Figure 6 are represented all the possibilities between 25 and 75 percentile, in the picture is visible that the plateau shifts toward highest capacities from the pessimistic scenario (lower bound of the grey area) to the optimistic one (upper bound). In this sense, the suggested capacity is 16 kWp and lies in the range (13,18) kWp. The thickness of the grey area is mainly due to the variability in the discount rate, when the optimization is run with a fixed discount rate the deviation of probability greatly reduces.

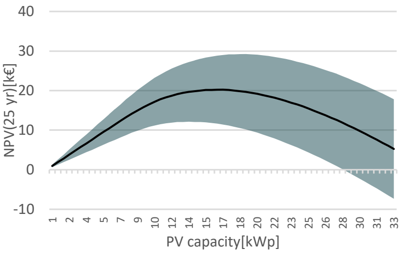

Figure 10: NPV vs installed capacity, the median value shows a plateau just above 16 kWp, the grey area represents all the possibilities between 25 and 75 percentile.

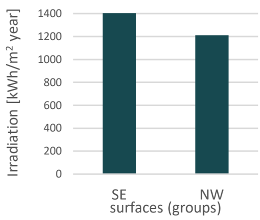

Figure 11: difference in irradiation between the South-East side of the roof and the North-West one.

For reasons of higher self-consumption, the tool suggests the installation of part of the capacity on the NW side of the roof (Figure 12) even if the SE part can host much higher capacities than the one required. In the optimistic scenario (i.e. a combination of stochastic variables that is favourable to PV) a higher PV capacity is suggested, the proportions of capacities between the two surfaces cannot be known unless the optimization is launched using the optimistic NPV as a fitness function. The same goes for the pessimistic NPV.

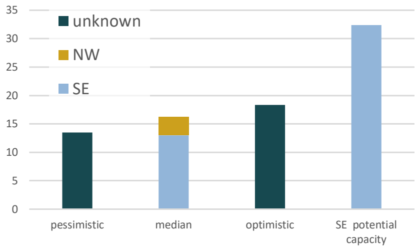

Figure 12: capacity to install as suggested by the optimization process.

3.3 optimized PV system "Block"

The third example is represented by a building featuring a tilted roof (20° tilt)and an inclined façade(70° tilt), both the surfaces are oriented south (9.6° East of South). Also in this case the irradiation is uneven (Figure 9), but less sharply than in the "Roof" example, this building is equipped with a battery of capacity180 kWh, the battery does not influence the initial cost of the system (i.e. the battery cost is assumed equal to 0). The electric load (totaling 182.4 mWh annually) is higher in winter as it covers the heating demand. The result of the optimization shows that, if given the possibility, the software suggests to install a significant portion of the capacity (ca 27% of the total) on the façade of the building (see Figure 10). If the optimization is run without the possibility of using groups (i.e. installing the capacity on the most irradiated spots first), a higher capacity is installed on the roof but no modules are installed on the façade. This is because the potential capacity on the roof exceeds the capacity required by the building+storage system (on an annual basis), the façade in this case is not even considered.

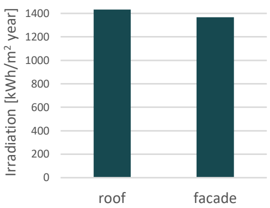

Figure 13: also in the Block building there are difference in terms of cumulative irradiation.

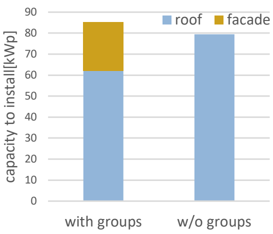

Figure 14: median (expected) output of two different optimizations, one allowing groups, the other simply installing on the most irradiated first.

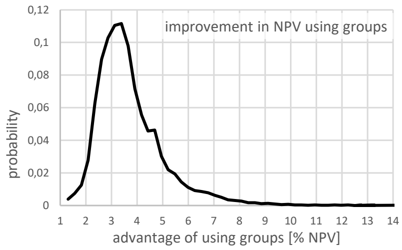

Figure 15: probability of improvement from the optimization w/o groups to the one with groups as % of NPV. Each combination of stochastic variables has a different % (all positive). the average is 3.86%.

The façade tough, enjoying higher irradiations in winter when the daily demand is higher, proves more profitable than the roof. The optimization run with the use of groups increases the overall hosting capacity of the system (see Figure 10), and leads to an increased NPV (see Figure 11). The curve in Figure 11 represents the % of NPV improvement when optimizing using groups compared to an optimization without groups, is visible that the % earning changes for each combination of stochastic variables and that in every combination considered the variation is positive. The average of the possible variation of NPV is +3.86%.

4 DISCUSSION AND CONCLUSION

The use of POW for the optimization of the PV system on different surface of buildings led to the first results. A better understanding of the energy phenomena of the PV system in relation to the building have been acquired, hopefully more case studies will uncover new things. Various improvements of the software and areas of development are noticeable from the first results. The changes in rankings of the Tower building shows that a ranking of positions in an energy system cannot be merely related to the irradiation, but the load and the electric storage should as well be taken into account. Figure 8 shows how the behavior of the storage (Figure 2) affects the result of the ranking. The current behavior of the electric storage praises East facing points even though they are slightly worst in terms of pure load matching in the absence of storage (see Figure 7). An improvement in the possibilities of the battery behavior would be much beneficial to the results of the simulation. The uncertainty in the load might be taken into account to increase the confidence and the reliability of the point rankings, this uncertainty should not be merely in terms of scale (wich is already accounted for with different load growth) but also in terms of daily or seasonal shape of the curve. The effect of such uncertainty, which can at times advantage production in different sets of hoy, should give value to resilient configurations. An interesting experiment would be to run the optimization at larger scales. There the electric demand is better known and shows higher predictability. Furthermore, the absence of valorization for the electricity sold to the grid is a more realistic assumption when analyzing a large system. Such a system cannot in fact afford significant excess of production in specific hoy. The launch of the tool at higher complexity scales requires some preliminary effort in simplification of the model (i.e. some form of clustering of the irradiation points) to reduce runtime. With the present technology of the tool, a proportional fraction of a city scale aggregate demand curve can be applied to a single building according to the size of its electric demand, this might improve the overall performance and hosting capacity of the grid if applied consistently. The "Roof" example shows how the most remunerative configuration involves the allocation of part of the total capacity on the least irradiated surface, it shows nonetheless that in a different scenario the suggested capacity to install is different (see Figure 12). In order to know which proportion of the two capacities should be installed in a pessimistic or optimistic scenario the whole optimization should be launched setting different fitness function from the "median NPV". Aside from the discount rate, which is known to have a profound impact on the profitability of an investment, other aspects can vary to determine the overall NPV of a scenario. The combination of variables in a "pessimistic NPV" could vary based on the building geometry, weather file, capacity/load ratio or other aspects of the model (initial or depending on the configuration). A pessimistic NPV does not correspond to a precise combination of stochastic variables, but simply to an ever-changing unlucky set of variables that produces an NPV lower than the 75% of the possibilities. An interesting information would be the effect of "unlucky" scenarios on the proportions between the capacities in different facades. As a rule of thumb, a reduction of the least irradiated surface can be expected as effect of a higher maintenance cost, but the scale of the reduction is difficult to determine in advance. The notion that least irradiated surfaces tend to be excluded in presence of batteries cannot be accepted in case of different tilt angles, this angle influence in fact the seasonal production curve of a system and may benefit from the presence of storage systems. In the "Block" building the façade enjoys a lower annual cumulative irradiation compared with the roof and the building is equipped with an important battery (ca. 30% of the cumulative daily demand), despite these factors 27% of the total installed capacity is installed on the façade. The façade integrated modules, although annually less irradiated, get more irradiation in the cold months when the electric demand is higher. In this situation the presence of a battery is synergic and boosts the façade modules as it allows them to store their premium winter production. The "Block" building is a lucky example because it is equipped with an inclined façade. If the façade was vertical, at the latitude of Northern Italy, its irradiation would have been inferior to that of the roof year round, therefore there would have been no energetic or economic advantage in façade integration. It is good news that façade integration can make sense from the economic point of view also if part of the roof area is still available, it might tough be necessary to install the modules in a non planar fashion. Non planar PV system exist [9], but they are now installed with angles for maximizing the annual cumulative production. It makes sense, from the energy and economic point of view, to install them more vertically, in a fashion similar to that of traditional wooden claddings.

5 AKNOWLEDGEMENTS

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