

## Accepted Manuscript

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PII: S2210-6707(18)31316-7  
DOI: <https://doi.org/10.1016/j.scs.2018.12.028>  
Reference: SCS 1400

To appear in:

Received date: 2 July 2018  
Revised date: 5 December 2018  
Accepted date: 22 December 2018

Please cite this article as: Lovati M, Salvalai G, Fratus G, Maturi L, Albatici R, Moser D, New method for the early design of BIPV with electric storage: a case study in northern Italy, *Sustainable Cities and Society* (2018), <https://doi.org/10.1016/j.scs.2018.12.028>

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# New method for the early design of BIPV with electric storage: a case study in northern Italy

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## Highlights

- A new method for the techno-economic optimization of building integrated photovoltaic is presented.
- A large share of the electricity demand can be covered by photovoltaic systems in a profitable way with current prices and technologies.
- Installing photovoltaic modules on the façade can be economically advantageous even when there is still free area on the roof.

## 1 Abstract

This paper presents a new method for the planning of photovoltaic systems in the early architectural design. The method finds capacity and position of a photovoltaic system over the envelope of a building by means of optimization. The input consists in: geometry of the building, surrounding shadings, local weather, hourly electric demand, unitary costs of the system and benefits for the production of electricity (sold or self-consumed). In the input there are known values (e.g. PV installation costs [€/kWp] or present costs for the electricity [€/kWh]) and unknown ones (e.g. degradation rate [%/year], maintenance costs [€/kWp year] or discount rate [%/year]). The optimization is performed using the expected value out of a set of parametric scenarios generated by the unknown input values. The results show that, if capacity and position of the system are tailored on its aggregated electric demand, a large penetration of photovoltaic electricity is profitable at current prices without incentives or valorization from the grid. The optimization performed with an arbitrary set of electric storages shows how the presence of storage fosters a higher optimal capacity for the PV system. This method has the potential to hugely expand the installation of urban photovoltaic.

## 2 Introduction

### 2.1 Context

The energy integration of BIPV systems will become a key aspect related to the new ways buildings are conceived and their energy provision. In fact, EU policies are promoting and regulating the NZEB (nearly zero energy buildings) concept [1], [2] and RES (renewable energy sources) exploitation at local level [3], [4], with buildings thus becoming more than just passive stand-alone units using energy from the grid [5], [6]. To support energy transition, energy retrofit of building stock plays a key role and the applications of local renewable energy systems such as photovoltaics is crucial [7], [8]. They are becoming “Energy flexible Buildings” consuming, producing, storing and supplying energy, thus transforming the EU energy market, shifting from centralised, fossil-fuel based, national systems towards a decentralized, renewable, interconnected and variable system [9]. The effect of this can clearly be seen in the draft of the new RES directive where the legislator introduces the concept of self-consumers and collective self-consumers, stating that “there is a need for a definition of renewable self-consumers and a

regulatory framework which would empower self-consumers to generate, store, consume and sell electricity without facing disproportionate burdens” [10].

In particular, according to the IEA EBC Annex 67 project [11], the Energy Flexibility of a building is defined as the ability to manage its demand and generation according to local climate conditions, user needs, and energy network requirements. Energy Flexibility of buildings will thus allow for demand side management/load control and thereby demand response based on the requirements of the surrounding energy networks [12].

In this context, there is a sensible need to develop new methodologies, methods and tools to address BIPV design in an effective way considering the aforementioned aspects

In numerous past forecasts, BIPV has been viewed as a powerful market driver for the whole PV industry in reality it still represents a niche market in the PV sector [13]. Possible strategies to increase the prominence of BIPV installations are proposed in literature, and the lack or underdevelopment of PV system in buildings is seen as problematic. These strategies usually fall in to two approaches which are the development of better products [14]–[17] and the integration of BIPV into the design process [18]. Some researchers propose PV education as a promoter of the BIPV integration [19], [20], others propose design procedures based on performance and often taking into account multi-functional aspects of BIPV [21]–[25].

## 2.2 Main innovation.

In this paper the integration of BIPV into the design workflow is accomplished by means of optimization: a strategy that is currently missing in the design process [26]. The optimization plays the role of an initial shaping and dimensioning agent which can provide creative design constraints. The major software tools used in the photovoltaic community are devoted mainly to simulation [27], do not offer optimization of the capacity and position of the PV system on the building envelope in relation to its electric load. Optimization is realized in these tools, but only in terms of inverter sizing and wiring strategy [28] can perform optimization on the wiring strategy and number of inverters, but works on a capacity that is arbitrarily chosen; [29] can optimize the wiring strategy and automatically place modules on a roof or façade surface, but the placement serves only to fill the given surface and does not optimize capacity according to a particular scope; [30] considers optimization only in terms of inverter sizing; [31] regards utility scale PV system only; [32] can calculate and report numerous financial metrics concerning PV and can be used with external scripts to perform optimization, it could in theory serve the purpose shown in this paper but it would need a comprehensive set of scripts for pre and post processing. In the last few years some optimization experience have been made to find the optimal geometry of the PV system, nevertheless these calculations rely on a parametric model produced by the authors and are unique experiences rather than unified design processes. [17] is focused on the use of a really specific dynamic façade technology and requires specific modelling; [24] and [33] also focused specifically on the technology of solar shading and requires ad-hoc modelling. Furthermore often the optimization is intended at the maximization of the cumulative irradiation like in the cases of [34] or [35] and not at a techno-economic analysis. [36] is similar to [24] in the sense that considers the angle of PV with respect to the façade, it provides more technological variability in the architecture but still represent a parametric model made specifically for the study and evaluates only the annual cumulative production.

Techno economic assessment are present but, not being optimization, they are difficult to integrate in the design process. [37] evaluates the potential Urban PV surface over a city portion of two square Km; [38] evaluates the feasibility of a BIPV system over a large building setting a threshold of minimum irradiation; [39] Considers the profitability of a system built over the roof of a large building in the university campus. Furthermore most assessments focus on PT (Payback

Time), LCOE (Levelized Cost Of Electricity) or IRR(Internal Rate of Return) than on NPV (Net Present Value). This is an important aspect since all these metrics: IRR, LCOE and PT have their optimal value when the annual cumulative irradiation is highest and for IRR and PBT the self-consumption is 100%. If, for example, a building has 100 inhabitants and 90 are on holiday during August and we exclude valorization of feed-in PV electricity, the shortest PT will result in a system small enough to cover the demand of only 10 people. This happens because the slightest over-capacity reduces the yield of the system [kWh sold/kWp] and extends therefore the PT (or shrinks the IRR). This is just one example in which the rate of return, LCOE or the PT will lead to a system with negligible impact on the energy demand and minimal NPV. It is easy to see how diverse economic indicators, though providing interesting information for the designer, may lead to poor design choices when applied as a fitness function to the BIPV optimization.

The NPV is a measurement of profit calculated by subtracting the present values (PV) of cash outflows (including initial cost) from the present values of cash inflows over a period of time [40]. In other words, it is a measure of the value of the money invested in something.

The main innovation of the method presented in this paper is in the fact that the PV capacity and position on the building envelope is not an input but an output of the software. Optimization software are a strict minority within the building simulation tools [26], but the optimization technique fits for the architectural design workflow, especially for the BIPV system. A simulation procedure where the characteristics of the system are an input generates a trial and error workflow, while a productive architectural design workflow should be based on an act of constrained freedom, i.e. a process enhanced by creative constraints [41]. The use of technical or cultural constraints as a creative aid is apparent in contemporary architecture as well as vernacular one. For example, the designs of the Spanish architect Santiago Calatrava are deeply influenced by the mechanical performance of their bearing structures. Throughout history numerous cultures developed dwellings capable of making good use of the local conditions, these buildings could improve comfort by means of shape and properties of the building and by clever architectural devices [42]–[44]. Considering the disseminated nature of vernacular buildings, is unlikely that they were a product of deliberate design, they were instead produced by a long process of slow differential improvements based on imitation. In such a process many variations of a same archetype are evaluated and selected by performance, this pattern of evaluating variations of a subject is seen in any process of optimization [45]–[47]. Optimization can put in place a set of rules to improve the performance of an architectural system, which can in turn prove effective as a creative constrain. If the main features of the BIPV system are known before the development of the design concept they can concur in its formation, if the PV system is added in a later stage of the architectural workflow it acts like a mere unnecessary complication (Figure 1). In the future, the PV system should be considered among the design constrains as it already happens for other architectural systems such as windows or bearing structures.

Two examples of optimization of positions and capacity for BIPV have been found by the authors: [48] has stunning similarities to our paper, in fact in both works the capacities and position are chosen out of a set of points where the hourly irradiation is calculated using ray- tracing. The main difference lies in the fitness function used: [48] choses to evaluate the PV systems through a multi-objective optimization. One of the multiple fitness is self-sufficiency [%](equivalent of the parameter “self-production” found in Table 5). This represents the proportion of the total consumed electricity which is contemporaneously produced by the PV system or by a PV fed electric storage. This parameter, contrary to the NPV, does not have a maximum in the dimension of the capacity (it only increases with increasing capacity), the problem is constrained through another parameter which measures the balance between the grid and the PV system. The study proceeds in individuating a front of Pareto between self-sufficiency and balance with the grid

where increasing self-sufficiency leads to a less balanced system/grid. The study is an insight into one aspect of urban PV but not a design strategy because the designer is left with one degree of freedom and could very well chose to sacrifice self-sufficiency or grid balance. In the study the point of maximum curvature of the Pareto is chosen, but also others could be, because every point on a Pareto has, by definition, an identical fitness. Furthermore the curve would be disrupted by the use of ohmic-resistance to dissipate the excess production or smart inverter designed to work below the power of the load. Of course with these technologies part of the electricity would be wasted, that is precisely why there is the need for a fitness function that has a maximum with respect to capacity.

[49] explains in detail the working principle of the placement of modules on the different facades of a case study and analyzes the effect of this on a specific set of KPIs (Key Performance Indicators). This paper is a broader analysis and therefore does not seem to provide a clear design methodology. In the conclusions it seems to suggest that electric storage is a preferred option matching the load compared to the use of facade, nevertheless in terms of NPV the use of storage or façade PV (or even over-capacity of PV on the roof) is ultimately a matter of relative unitary costs for PV and batteries. A function similar to the NPV, but focused on co2, could be implemented considering the specific emissions generated for the production, transport and installation of a PV system and its lifetime electricity self-consumed. Storage and façade integration are not always competitive strategies: in presence of load variability over the day the storage discourages the installation of PV on east and west. In presence of seasonal variability tough (difference between winter and summer), an over-dimensioned electric storage would be required, and having part of the system with an higher tilt seems more sensible. In [49] the NPV is not among the serie of KPIs evaluated.

### 2.3 Aim

The method and tool presented in this paper were developed as a mean to increase the quality and quantity of BIPV (building integrated photovoltaics) installations by providing a correct system sizing in the early design stage including the use of electric storage. The tool informs designers on how much and where to install BIPV over the building envelope and shapes and sizes the system to increase its self-consumption. This in turn produces earnings over the life span of the system. The use of the tool is intended both for new construction or retrofit of existing buildings, it aims to improve the functionality of the PV system in relation to the building and increase the number of installations by showing the potential profitability of an optimal system. Furthermore, including the BIPV alongside other building components in the early stage of the architectural design, the tool gives relevance and necessity to the BIPV system. This effect is very welcome provided that the building in the future should aim to produce the energy it consumes. The need of producing energy should be added in the future to the existing needs such as shielding from the rain, maintaining a comfortable temperature etc. [18].

The paper presents the description of the modelling approach in section 3, the case study to which the model is applied is described in section 4. In section 5 we present the main results.

## 3 Modelling approach

The method presented in this paper is based on a ray-tracing procedure to calculate the incoming irradiation. The incoming solar irradiation is calculated using the free software DAYSIM [50] which is based on the reverse Ray-tracing simulation software RADIANCE [51]. This procedure has the advantage of working in the same manner both for simple and complex geometries. The ray-tracing technique is in fact a stochastic approach and the computational

effort, which depends on simulation parameters such as the number of rays traced from each measurement position, is less dependent by the complexity of the geometry compared to a deterministic geometrical approach. Thus, the Ray-tracing approach particularly fits for BIPV applications where there are effects of partial shading and reflections from nearby objects.

In order to apply the new proposed optimization algorithm for the BIPV system optimal calibration using the GitHub tool, the first stage is the complete definition of the thermodynamic performance of the building under consideration.

In fact, a detailed model of the thermo-dynamic behavior of the building is a key element given the importance of the form and size of the electric power demand as an input for our tool. Such a model can be achieved with different already existing tools, but in the case study presented in the next section, the TRNSys environment was used. Appliances and lighting demands are added to the electric consumption of the HVAC system to obtain the overall demand. The hourly electric consumption of the building is crucial in determining the optimal PV capacity: if a PV system is too small it has no impact on the demand profile (hence on the NPV), if it is too big most of the electricity produced is not self-consumed.

### 3.1 PV and battery model

In order to suggest an adequate capacity for PV and well performing areas where to place it, the tool needs a list of all potential PV positions (i.e. a cloud of points where a collector can potentially be installed).

Out of the whole number of potential positions (Figure 3) the tool will select some to be occupied by the PV modules, the chosen system is optimized for enhanced NPV. The quantity of PV modules selected indicates the capacity of the optimized system. It is possible to optimize the capacity of the electric storage as well. In this paper this is done with 3 different capacities of batteries to have an insight of the effect of the electric storage on the NPV of the system. A set of relevant inputs should be considered in order to obtain a remunerative PV system (Figure 4), some of these can only be estimated based on educated guess because they depend on future events and trends (e.g. socio-economic development or the physical aging of the photovoltaic material). These inputs are inserted in the tool as stochastic with a rectangular probability distribution function, and so they can assume various values within a limited domain. The presence of these values implies that the resulting NPV is not a forthright amount, but rather a probabilistic curve.

In the following table (Table 1), the inputs are divided in two groups: stochastic and deterministic. The inputs in the deterministic group are explained below.

The **cloud of points** (Figure 3) represents the positions where a PV module can potentially be installed, it consists of a series of coordinates and directions to describe a set of planes in the space. An hourly irradiation [ $\text{kW}/\text{m}^2$ ] is calculated over each position and direction of the cloud of points, this will form the **irradiation matrix**. The cloud of points works like a swarm of irradiation sensors laid upon the envelope of the 3D model. The irradiation matrix can be calculated over the cloud of points with various method and tools, in this paper the irradiation matrix is calculated using the RADIANCE [51] based tool DAYSIM[50]. In the future the input can be easily changed to use irradiation matrix produced with other software (e.g. new features of RADIANCE or the irradiance calculation method of the software BIMSolar under development in the European project PVsites[28]). The **weather file** used to retrieve the temperatures is in the format \*.epw (Energy Plus Weather[52]). The **load vector** is a file containing the hourly electric power demand [kW], the development of the load vector file for this case study was prepared using TRNSys [53] environment as explained in the section 4.2 . The **n° of years for NPV**

represents the time horizon chosen for the NPV calculation, in this case a length comparable with the life span of the system (25 years). The two prices for the electricity bought from or sold to the grid are respectively **price consumed el.** and **price sold el.**

Among the stochastic inputs are the **PV degradation** and the **load growth**, which respectively represent the decline of performance of the system and the increase, or decrease, of the electric demand over the 25 years of NPV. Also the price of electricity bought from the grid and sold to the grid are subject to changes over the NPV calculation period, these are expressed as linear variations of the initial prices and named respectively **price el. growth** and **price sold el. growth**. The **discount rate** and the **maintenance costs** are considered stable during the NPV calculation, but is generally unknown in the early stage of the design, and can therefore assume different values. The fitness function is the metric according to which each system is evaluated, it can be either maximized or minimized, each individual system generated in the optimization process is evaluated according to this metric and the optimal one will be defined as the one which outperforms the others. The formula in Equation 1 is used as a fitness function for the single-target optimization process implemented in the tool and described in this paper. The result of this formula should be maximized to improve the profitability of the BIPV system. The main quantities affecting the result of the formula are shown below.

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

*Equation 1: formula for the calculation of the NPV, this is the fitness function of the optimization*

**P<sub>c</sub>** and **P<sub>s</sub>**: prices of the consumed and sold electricity [€/kWh].

**c** and **s**: cumulative energy self-consumed or sold [kWh]: **c** refers to the electricity that is consumed contemporaneously to the production, whose cost has therefore been avoided. **c+s** is equal to the cumulative electricity production of the PV system.

**ω<sub>PV</sub>**: capacity of the PV system [kWp]

**C<sub>t</sub>**: unitary maintenance costs [€/kWp year]

**i**: discount rate (it is real so it does not need to be adjusted for inflation)

**C<sub>0</sub>**: Unitary cost for the purchase and installation of the PV system [€/kWp]

**ω<sub>b</sub>**: Capacity of the electric storage system [kWh]

**C<sub>b</sub>**: unitary cost of the electric storage [€/kWh]

**nb**: energy sent to the grid interested by the net billing incentive scheme [kWh]. Some countries give the possibility to re-use the electricity sent to the grid when needed, it is somehow as having an infinite electric battery[54]. In the formula this effect is considered as a feed in tariff.

**P<sub>nb</sub>** feed in tariff [€/kWh] limited to the quantity of energy **nb** (**Errore. L'origine riferimento non è stata trovata.**) that is consumed during the year and not contemporaneously covered by photovoltaic

$$nb = (d - c) \cdot \min\left(\frac{s}{(d - c)}; 1\right),$$

*Equation 2: quantity of energy that is self-consumed but non-contemporaneously over the year*

**d** :annual cumulative electric demand of the building.

Presently, the tool does not allow to insert a different **PV cost** for different facades within the building, in other words the unitary price [€/kWp] is the same for the PV on the roof and on the façades. This parity might seem like an advantage for the façade integrated PV because a premium due to aesthetics and technological integration might be expected, nevertheless the price of a comparable façade cladding should be removed from the PV system in facades to account for multi-functionality [55]. If for example a system added on the roof has a total cost (modules+ cables+ inverters+ mounting structure) of 1500 [€/kWp] it could be price-comparable to a façade integrated system of ca. 3000 [€/kWp]. This is due to the assumption that the façade BIPV substitutes another material for a ventilated façade and the structure should be built regardless of the choice of PV or another material. With a back-of-the-envelope calculation we can calculate the price per square meter of the 3000 [€/kWp] system: assuming an efficiency of 15%, the cost of the BIPV ventilated facade would be 450 [€/m<sup>2</sup>]. Subtracting a price of a ventilated façade system (mounting structure + cladding) of 225 €/m<sup>2</sup> the increase in price due to PV functionality would be 225 [€/m<sup>2</sup>], hence 1500 [€/kWp]. The real price of BIPV is a complicated matter due to the high level of customization of the single project and relative scarcity of industrial solutions, this paper does not include an adequate study about pricing, therefore the price of PV is considered as façade independent (i.e. purely the cost of PV, neglecting façade-specific structures or discounts due to replacements of other materials). The elements **c** and **s** of the Equation 1 are the components of the total electricity production whose annual energy is explained in Equation 3. This equation is a simple way for estimating PV production and might lack accuracy, nevertheless the objective of this system is not an accurate forecast of the production. The objective of the search is a preliminary estimate to find an adequate capacity and positioning of the system for the underlying building. An accurate calculation, using tools such as PVlib [56], should be carried out in later stages of the design to have a more reliable figure on the electricity produced. In such a calculation the ability in forecasting meteorological data is crucial [57]–[60], is therefore beyond the scope of an early design tool for optimizing the economic performance over the next 25 years.

$$c + s = A \cdot \eta \cdot PR \sum_{HOY=0}^{8760} \sum_{p=0}^n G_{HOY,p} \cdot c(T_{HOY,p}),$$

*Equation 3: PV production for a given year in absence of net-metering schemes.*

**c** and **s**: as in the NPV formula, are the consumed and sold energy[kWh].

**A**: area associated to each point of the system under evaluation [m<sup>2</sup>], is equivalent in this study to the area of one single module.

**η**: photovoltaic efficiency at module level

**PR**: performance ratio of the system (do not include the correction for the operating temperature)

**HOY**: hour of the year

**P**: position of a single module, at each position is associated hourly irradiation and temperature.

**n**: number of modules in the system under evaluation, this formula is used in an optimization process, therefore the number of modules forming the system (and their position) can change.

**G<sub>hoy,p</sub>**: point in time irradiation of a PV module [kW/m<sup>2</sup>] which depends on position and HOY.

**c(T<sub>HOY,p</sub>)**: coefficient for the correction of the efficiency due to the temperature of the module. This coefficient depends on the temperature on every point **T<sub>p</sub>** [°C] in every HOY. The



temperature  $T_p$  is found by the simplified relation  $T_p = T_{\text{ambient}} + k G_{\text{hoy},p}$  where  $T_{\text{ambient}}$  [°C] is the ambient temperature retrieved from the \*epw weather file and  $k$  [m<sup>2</sup>/kW] is the Ross coefficient described in [61], [62].

A model for the electric storage is incorporated in the tool given the impact on the ratio between  $c$  and  $s$  and their relevance on the revenues and avoided costs for electricity. The control strategy of the storage is explained in Figure 6, the efficiency of the storage is considered as 1 and there are no time dependent losses. Better models for the electric storage, both in terms of ideality and smart control strategies, need to be incorporated in the future.

### 3.2 Optimization algorithm

The optimization algorithm used is a simple direct search [63] iterated to improve its own solution: the initial condition is a system of 0 [kWp] capacity, a capacity is then found by the direct search and added on the chosen façade among the available ones (in this case roof or facade). The capacity added is the solution for this cycle of the direct search, but it will be the starting point for the next cycle. In other words, once the capacity is added, the direct search is repeated but with the new capacity as a starting point instead of the empty system. Making an analogy, the process is similar to the production of a painting (see Figure 7): each stroke is a simple action but is a step closer to the completion of the painting. If the difference between an empty painting and a photo being imitated is a fitness function, one stroke cannot find the minimum, but it can be a step closer to the minimum. The process can then be interpreted as painting a PV system on the surface of the building, where the parameters for each stroke are capacity and façade (e.g 62 kWp, roof).

## 4 Case study description

### 4.1 Main features and the design targets

The case study analysed in this paper is located in Rovereto sulla Secchia, a small municipality of Novi di Modena in Emilia Romagna region, in Northern Italy (Figure 8). The case study is modelled in a detailed way to produce consumption profiles which are needed as an input to the tool. In case of buildings at an earlier design stage, other means can be used to produce consumption profiles that do not require detailed simulations.

Rovereto sulla Secchia (44°50'27.35"N; 10°57'19.16"E) is one of the ten hamlets in which the municipality of Novi di Modena is divided, and it counts 3207 inhabitants on an area of 8.03 km<sup>2</sup>. The case study is a new school building designed on the area of an old one damaged by an earthquake in 2012. The "L" shaped site Figure 9 is a 10.550 m<sup>2</sup> area facing on three sides on public streets, on the other three borders the lot is facing private residential areas.

Considering the level of damages of the existing school, the municipality of Novi di Modena announced a competition for a new school campus, composed by multifunctional buildings. The idea of the public authority consists on giving to the community of students and the citizens a new recreational space in a short time. Three different blocks are clearly identifiable in the design proposal (Figure 10): the primary school bordering IV Novembre road, the administrative head at the intersection between the two streets and the first-grade secondary school on Forti road.

This study focuses on the first grade secondary school block. The main facades of the building are northeast and southwest. The classrooms characterized by large south-facing windows, receive direct sunlight during the most part of the day and require to be protected by a shading system to reduce the cooling load.

## 4.2 Thermal model of the building

The following thermal transmittance values (Table 2) were used for the determination of the energy demand curve of the case study building.

The TRNsys v.17 [53] software has been used for building thermal simulation. TRNsys is a graphically based software environment used to simulate the behavior of transient systems focused on assessing the performance of thermal and electrical energy systems. In the specific case the building simulation model has been used to derive the electrical energy loads [kW] of the building. The software allows the calculation on hourly basis of the electrical consumption to satisfy the heating and cooling demand. The geometry of the building is designed with TRNsys 3d (a sketch up plug in for TRNsys). The overall geometry of the modelled building is shown in Figure 12.

The model of the building has been divided into 10 thermal zones, each different from the others in use, features of the system and internal gains. The overall building envelope (opaque and transparent components) is defined using the “TRNbuild” tool: the program processes a file containing the building description and generates two files that will be used by the TYPE 56 component during the simulation in TRNsys. The following boundary condition (Table 3) are used to derive the electrical energy needs during the building operation.

The people inside the building contribute to the thermal behaviour of the building, the related gains are considered according to ISO 7730 activity levels. The following table sum up the use of the different zones:

Thermal zone	Heting/cooling schedule	Activity of the users
Classes	Winter 7AM - 6PM Summer 7AM - 6PM	Sedentary
Refectory	Winter 10 AM - 4 PM Summer 10 AM - 4 PM	Sedentary
Gym (*)	Winter 7AM - 6PM Summer 7AM - 6PM	Athletic
Kitchen	10 AM - 4 PM	Sedentary
Toilette	7AM - 6PM	Sedentary
Lobby and aisles	Winter 7AM - 6PM Summer 7AM - 6PM	Sedentary

The thermal building simulation output defines the heating and cooling end energy demand. To calculate the final energy consumption it is assumed that the building works with an electrical air-to-water heat pump system with a mean COP (coefficient of performance) equal respectively for winter and summer season to 3.0 and 3.5. To calculate the overall electrical energy demand the electrical energy consumption of the appliances has been considered as well.

### 4.3 Assumptions for the BIPV system

To perform the optimization, the following inputs (Table 4) were used. We do not consider the presence of net metering schemes and sold electricity is not valorized. This choice was made to focus on the economic viability of PV without the use of the grid as a storage option and to see which level of self-consumption can be achieved with this conservative assumption. Please note that the price of the electric storage is assumed as 0: this choice was made because the objective of the study is not to study the profitability of some specific batteries with the present prices, but the effect that storage have on the capacity and positioning of PV installed and to identify at which price storage can become economically viable. Furthermore, the maximum cost of stored electricity to be profitable can be found by evaluating the positive impact on the NPV of the PV system. In the paper four storage hypothesis are compared: NS (with NO storage), WS (With Storage: 87 kWh), 1/3WS (1/3 of the WS storage: 29 kWh) and 2/3WS (2/3 of the WS storage: 58 kWh) the quantity of PV installed is examined in relation to that.

The surfaces available for PV are the ones shown in Figure 13, each point represents an area A of 3.6 m<sup>2</sup>. Considering an efficiency of 15%, the potential capacity of the roof is ca. 95 kWp and of the façade is ca. 43 kWp, with an overall potential capacity of 138 kWp. The size of the battery for the WS storage hypothesis was taken to accommodate the maximum daily over-production over one year of the biggest possible system (138 kWp) with a resulting usable capacity of 87 kWh.

## 5 Results and discussion

Considering the climate condition, the building design technology and the intensity uses, the total electrical final energy consumption for the demo building described in section 4 is equal to 182 MWh corresponding to 52.87 kWh/m<sup>2</sup>y. The major share of energy is due for heating, 76% of the total; followed by electrical appliances + lights (18%) and cooling (6%).

Analyzing the irradiation over the two available surfaces (i.e. roof and south facade)(Figure 14), it is visible how, despite having a slightly lower annual cumulative irradiation, the façade presents a higher solar radiation during the heating season. This irradiation pattern shows a better matching to the monthly electric demand, this is the main reason why the load matching procedure was considered in the optimization. The load matching (LM) procedure is different from a mere capacity optimization (CO) because it enables the use of surfaces with a lower annual cumulative irradiation. This feature is computationally expensive, but can be used when the least irradiated surface (the façade in this case) presents a higher irradiation in some HOY.

The relation between NPV and capacity of the system is shown in Figure 15. It is visible how the NPV grows linearly for smaller capacities, then grows at a slower pace until eventually starts to shrink. This phenomena is mainly caused by the rate of self-consumption: while 100% of the electricity produced by a small system is instantaneously self-consumed, this percentage decreases to 83% at the peak NPV of the NS system. In the four charts of Figure 15 the WS and the NS systems are compared, the higher NPV of the WS system is due to a higher level of self-consumption. In these calculations the price for electricity fed into the grid is 0, which corresponds to a 100% curtailment (i.e. electricity is available from PV but nobody within the grid is willing to buy it).

The charts in Figure 15 also show that the highest NPV yielding capacity (i.e. the suggested capacity) is shifted on larger systems when the storage is added, the plateau "MP" in the curve in "a" (NS) is in fact on a capacity of ca. 62 kWp, while in "b" (WS) is located around 78 kWp. The larger capacity of the WS system, combined with the ability to store part of the excess solar electricity, can cover 42% of the cumulative electric consumption against a 32% brought by the NS system (both the values are calculated at the first year). The increase in optimal capacity is

another effect of a higher flexibility for self-consumption and gives reason to believe that the penetration of urban PV will increase thanks to a foreseen increase in storage capacity.

The increase in expected peak NPV by virtue of 87 kWh of storage is 28 k€, thus for such a large storage to be profitable the cost per kWh (for 25 years) should fall below 320 € (see Table 5). Such a figure is still too low, although according to [64] it will likely be reached between 2027 and 2040 (if a life-span of 25 years is assumed). By design, such a large system would always be under-utilized (see section 4.3 in the last paragraph, about the sizing of the WS storage hypothesis), the optimal balance of PV/storage capacities is ultimately function of the relative prices of the two. Smaller storage system would be profitable with lower though still unrealistic prices as shown in Table 5. Analyzing the demand profile of the building (Figure 14) is visible how the electric demand is lower in summer. This prevents the full discharge of the battery in periods where the overproduction from PV is large and there is not enough demand to consume it. The electric storage should not be viewed simply as a physical support, it can be a service offered from a third party provider, this way a better use of the overcapacity can be envisioned. This approach would strongly mitigate the excess capacity of the battery in seasons where the demand is low, provided that there is enough “mixité” [65] in the low/medium voltage grid. If the storage is seen as a service and its capacity as a maximum guaranteed capacity, the maximum price that can be charged [€/kWh] can be obtained dividing the cumulative electricity exchanged by the difference in NPV with respect to the baseline storage hypothesis (NS). The cumulative energy provided by a WS storage in the first year is 9.3 MWh (Table 5), assuming a stable figure during its lifetime, the battery would provide ca 233 MWh. Considering the expected NPV gain of 28 k€ generated by the presence of the storage, the battery levelized cost of stored electricity LCOS could fall below 0.12 [€/kWh]. Table 5 clearly shows the need to include the optimization of the storage system as next step. It also shows that the smallest storage system considered in this study would be profitable at a final price of 576 Euros/usable capacity. This price is at close reach looking at learning curves of storage shown in [66] (year 2022 for residential Li-ion battery system price with a learning curve of 15%).

The NPV charts are not a defined values but they present an uncertainty due to the stochastic variables. In the four charts the expected value is shown within a range sweeping from 25 to 75 percentile. Observing the plateau in the ranges (Figure 15), a sliding toward higher capacities becomes visible when more optimistic scenarios are applied (LP < MP < HP). The dimensioning of the PV system can be done with a conservative or an optimistic mindset, the actual NPV of the system is maximized when the real scenario reflects the expectations. If a designer decides to install the capacity (WS) suggested by the pessimistic scenario (i.e. LP = 65.3 kWp), the system is under-dimensioned in the case the optimistic scenario happens: it should have had the optimistic capacity (i.e. HP = 89.6 kWp).

Figure 16 shows that of the 78 kWp of the median scenario (WS), ca. 18 are to be installed on the façade despite not having used up all the potential on the roof. In the bar chart the roof capacity remain unaffected by the scenario used while the façade capacity is strongly variable. This happens because the order of profitability of the positions does not change with the scenario, what changes is the number of positions that are being occupied by PV modules. The optimization algorithm adds the modules in the same order, but while the pessimistic NPV is peaking, the median and optimistic NPV figure is still growing. The use of the pessimistic or optimistic NPV as a fitness function, in spite of the median, has a negligible effect on the optimal configuration, in this sense the order of profitability of the PV positions is not influenced by the scenario.

Aside from the scenario, the capacity installed is affected by the use of load-matching. Figure 17 shows the best performing (WS) NPV capacities obtained by merely optimizing the capacity and

by performing load matching. In a pure capacity optimization (CO) the façade will not be used until the roof potential is completely covered because the façade has a lower annual cumulative irradiation. Figure 17 shows that the overall capacity installed is higher for the optimal system where load matching (LM) is used (78 kWp against 75) although the roof capacity is ca. 15 kWp lower.

The LM configuration presents a slightly higher self-consumed cumulative energy over the life time (+3.3%), which would lead to an annual increase in revenues of 470-520 [€/year] over a baseline of 14'033-15'669[€/year] (at 0.2 €/kWh). Nevertheless the installation of an higher capacity carries an increased initial cost and higher risks in case of high maintenance costs or high discount rates. Despite this, the expected difference in NPV between the LM configuration and the CO is slightly positive as shown in Figure 18. The expected gain between the two peaks in expected NPV, regardless of their capacity, is 1684 [€] equal to an NPV improvement of ca. 1.6% on the CO configuration.

The chart in Figure 18 was produced comparing the NPV of the LM and CO configurations for every scenario, note that LM does not guarantee a monetary gain as there are chances (26.8%) that LM produces a loss. This effect is partially due to the higher overall capacity of the LM configuration, there are in fact variables (i.e. initial cost, maintenance costs, discount rate) that put high capacities to disadvantage. Analyzing a single scenario the probability would collapse in a single value. For example using a degradation of 0.5, load growth of 1% (annual linear), a stable cost of electricity, no discount rate and a maintenance of 27 [€/kWp year], the NPV gain associated with LM would be equal to ca 4500€.

If The NPVs are compared for each capacity (Figure 19), the expected NPV gain of simply moving part of the modules from the roof to the façade can be measured. At the capacity of the peak CO (ca. 75 kWp) the expected NPV improvement for LM is small (1412 €), it is nevertheless interesting because it has been obtained without increase in the initial investment. If the NPV gain is spread to each kWp moved from roof to façade (ca 15 kWp) the expected gain is ca 97 €/kWp, which is ca. 5.4% of the initial cost. The highest gains provided by the LM are on systems of ca. 100 kWp with an expected gain above 5200 [€] equal to ca. 5.6% in NPV improvement. Given the current economics these capacities are slightly over-dimensioned, but are still hugely profitable and can nevertheless be chosen for environmental reasons. The chart in Figure 19 shows a higher gain from load matching in case of optimistic scenarios, in terms of percentage of the NPV though the trend is the opposite. The reason for this is that the peak of NPV gain due to LM is independent from the scenario, while the peak of the sheer NPV tends to slide right for the optimistic ones. For example the NPV of a 100 kWp system, in a pessimistic scenario, increases of about 13% thanks to LM.

## 6 Conclusions

The research described in this paper showed the possibility of integrating BIPV in the early architectural design by means of an optimization strategy and stressed on the advantages brought by it. This approach is currently missing in the professional practice and in scientific literature, as pointed out in the section 2.2. The study was based on the development of a Python tool that suggests which parts of the building envelope should be covered with PV to maximize the Net Present Value (NPV) of the investment. KPIs such as LCOE or IRR are very interesting for

assessment purposes, but did not work when used as a fitness function for a BIPV system in an economic regime of self-consumption. The main reason for this is that on a building, where the irradiation is uneven, the minimum LCOE is available only in the very spot where the annual cumulative irradiation is the highest, therefore minimizing LCOE would suggest a rather small system. The same drawback holds true when IRR is maximized or PT is minimized. Furthermore, IRR and PT are best when the self-consumption is 100% (as the revenues/cost ratio depends on rate of self-consumption), and would suggest an insignificant system whenever there is a seasonal drop in the electric demand. Fitness functions based on IRR and LCOE are feasible but require some further constraints: for example self-consumption can be maximized while requiring a specific IRR, LCOE can be minimized but requiring a minimum self-production. These different functions will be examined in future works.

The method is developed with the goal to support conceptual/preliminary design with a technical-economic optimization. However the current workflow of for the modelling, simulation and analysis and the need to know in detail some information such as the hourly electric consumption are still fragmented, specialist and likely time-consuming. This could represent a limit in early design. The idea is presented in this paper as a concept and the advantages of this approach are shown and discussed, nevertheless future work should be devoted to the integration of this method as a plug-in in a dynamic simulation software, possibly BIM based.

The method in this paper can be applied both on new construction or retrofit of existing buildings. The optimization was repeated with four possible hypothetical storage capacities: from the absence of electric storage (NS), to the presence of ca. 87 kWh of storage (WS). The NPV optimal system turned out to be ambitious in terms of demand coverage. the NS (no storage) optimal system can in fact cover (i.e. self produce) 32.3% of the annual cumulative demand of the building in the first year of installation (Table 5). Unsurprisingly higher percentages of demand are self-produced when electric storage is installed (up to 42% for the highest storage). This higher coverage from PV is not due uniquely to the higher flexibility provided by the storage, but also to higher installation of PV capacity when the storage is present. An interesting aspect is in fact the synergetic effect of PV and storage on each other: The presence of storage pushes higher the NPV optimal capacity of PV (from 62 to 78 kWp, see Table 5), and keeps the self-consumption stable around 83%.

Part of the input data necessary to run the optimization is stochastic, therefore the process gives the NPV as a probabilistic curve and not as a forthright amount. It is clear that the proposed forecasts strongly depend on the stochastic variable defined at the beginning of the design process (see the gray band in Figure 15). The designer has the possibility to choose between a pessimistic and an optimistic scenario, even if the median one is more resilient to varying scenarios. The plateau of the pessimistic and optimistic curves are shifted in terms of capacities compared to the expected one (e.g. from 50 to 73 kWp in the NS case, see Figure 15).

Besides, the designer can choose a mere capacity optimization or a load matching procedure, the latter more computationally expensive but interesting when the least irradiated surfaces have higher irradiation in some particular period of the year. Considering the installation of the PV modules, it has been highlighted that their position on the building envelope can be different from the usual and expected ones, thanks to the load matching LM procedure. Using the LM, an improvement of NPV is possible without variation of installed capacity (see Figure 19) therefore without affecting the investment costs, but just moving the PV modules on the envelope. The entity of the NPV improvement is usually very small (5.6% gain for a system of 100 kWp in the expected scenario, see Figure 19), but it can become important for ambitious systems in pessimistic scenarios (+13% for a 100 kWp system under pessimistic scenario).

This work represents a stepping stone into a broader research endeavor, improvements in the algorithm can be made both in terms of accuracy and computational speed. Furthermore, to integrate technologies such as semi-transparent PV and static PV shadings, the integration of dynamic building simulation is needed. The tool presents synergies in research fields like urban renewable energy assessment, building data collection and analysis, renewables business models, micro grids control strategies and solar resource forecast. For example it would be interesting to apply real-time operation and control (based on weather and price forecasts) on an optimized BIPV system, or assess the impact of adding the EV demand on the optimal capacity of PV. This paper is based on a single case study, but more generalized results are expected as the tool is being applied to an ever growing portfolio of examples.

## Acknowledgements

This work is part of the research activities of the project **EnergyMatching**, funded by the European Union's **Horizon 2020** research and innovation programme under **grant agreement No 768766**.

The authors wish to thank **Giulia Merli** and **Maria Paola Persico** for the help and support that they provided during the simulation of the electric demand of the building using TRNsys.

Special thanks to **Jennifer Adami** for the design of the workflow diagrams.

## References

- [1] I. Sartori, A. Napolitano, and K. Voss, "Net zero energy buildings: A consistent definition framework," *Energy Build.*, vol. 48, pp. 220–232, 2012.
- [2] M. M. Sesana and G. Salvalai, "Overview on life cycle methodologies and economic feasibility for nZEBs," *Build. Environ.*, vol. 67, pp. 211–216, 2013.
- [3] European Parliament & Council, "Directive 2010/31/EU on the Energy Performance of Buildings (EPBD)." 19-May-2010.
- [4] European Parliament and European Council, "Directive 2009/28/CE on renewable energy sources (RES)." 23-Apr-2009.
- [5] M. Mandalaki, S. Papantoniou, and T. Tsoutsos, "Assessment of energy production from photovoltaic modules integrated in typical shading devices," *Sustain. Cities Soc.*, vol. 10, pp. 222–231, Feb. 2014.
- [6] G. Bizzarri, M. Gillott, and V. Belpoliti, "The potential of semitransparent photovoltaic devices for architectural integration: the development of device performance and improvement of the indoor environmental quality and comfort through case-study application," *Sustain. Cities Soc.*, vol. 1, no. 3, pp. 178–185, 2011.
- [7] E. Saretta, P. Caputo, and F. Frontini, "A review study about energy renovation of building facades with BIPV in urban environment," *Sustain. Cities Soc.*, 2018.
- [8] S. Paiho, I. P. Seppä, and C. Jimenez, "An energetic analysis of a multifunctional façade system for energy efficient retrofitting of residential buildings in cold climates of Finland and Russia," *Sustain. Cities Soc.*, vol. 15, pp. 75–85, 2015.
- [9] I. Vigna, R. Perneti, W. Pasut, and R. Lollini, "New domain for promoting energy efficiency: Energy Flexible Building Cluster," *Sustain. Cities Soc.*, vol. 38, pp. 526–533, Apr. 2018.
- [10] E. U. Commission and others, *Directive of the European Parliament and of the council on the promotion of the use of energy from renewable sources (recast)*. Brussels, 2016.
- [11] S. Ø. Jensen *et al.*, "IEA EBC Annex 67 Energy Flexible Buildings," *Energy Build.*, vol. 155, pp. 25–34, Nov. 2017.

- [12] K. O. Aduda, T. Labeodan, W. Zeiler, G. Boxem, and Y. Zhao, "Demand side flexibility: Potentials and building performance implications," *Sustain. Cities Soc.*, vol. 22, pp. 146–163, Apr. 2016.
- [13] R. J. Yang, "Overcoming technical barriers and risks in the application of building integrated photovoltaics (BIPV): hardware and software strategies," *Autom. Constr.*, vol. 51, pp. 92–102, 2015.
- [14] P. Heinstein, C. Ballif, and L.-E. Perret-Aebi, "Building Integrated Photovoltaics (BIPV): Review, Potentials, Barriers and Myths," *Green*, vol. 3, no. 2, pp. 125–156, 2013.
- [15] R. Valckenborg, W. van der Wall, W. Folkerts, J. Hensen, and A. de Vries, "ZIGZAG STRUCTURE IN FAÇADE OPTIMIZES PV YIELD WHILE AESTHETICS ARE PRESERVED."
- [16] J. Escarré *et al.*, "When PV modules are becoming real building elements: White solar module, a revolution for BIPV," in *2015 IEEE 42nd Photovoltaic Specialist Conference (PVSC)*, 2015, pp. 1–2.
- [17] P. Jayathissa, M. Luzzatto, J. Schmidli, J. Hofer, Z. Nagy, and A. Schlueter, "Optimising building net energy demand with dynamic BIPV shading," *Appl. Energy*, vol. 202, no. Supplement C, pp. 726–735, Sep. 2017.
- [18] H. Kaan and T. Reijenga, "Photovoltaics in an architectural context," *Prog. Photovolt. Res. Appl.*, vol. 12, no. 6, pp. 395–408, 2004.
- [19] L. Broman, "On the didactics of renewable energy education — drawing on twenty years experience," *Renew. Energy*, vol. 5, no. 5, pp. 1398–1405, Aug. 1994.
- [20] R. Ciriminna, F. Meneguzzo, M. Pecoraino, and M. Pagliaro, "Rethinking solar energy education on the dawn of the solar economy," *Renew. Sustain. Energy Rev.*, vol. 63, pp. 13–18, Sep. 2016.
- [21] L. Sun, L. Lu, and H. Yang, "Optimum design of shading-type building-integrated photovoltaic claddings with different surface azimuth angles," *Appl. Energy*, vol. 90, no. 1, pp. 233–240, Feb. 2012.
- [22] C. K. Wee, P. Janssen, and A. Schlueter, "Performance Driven Design Optimisation with Scientific Workflow System," in *International Conference on Green Buildings and Optimization Design (GBOD 2012)*, 2012.
- [23] M. D. Bazilian and D. Prasad, "Modelling of a photovoltaic heat recovery system and its role in a design decision support tool for building professionals," *Renew. Energy*, vol. 27, no. 1, pp. 57–68, Sep. 2002.
- [24] M. Lovati, J. Adami, G. De Michele, L. Maturi, and D. Moser, "A MULTI CRITERIA OPTIMIZATION TOOL FOR BIPV OVERHANGS," presented at the EU PVSEC, Hamburg, Germany, 2016.
- [25] A. Chatzipanagi, F. Frontini, and A. Virtuani, "BIPV-temp: A demonstrative Building Integrated Photovoltaic installation," *Appl. Energy*, vol. 173, no. Supplement C, pp. 1–12, Jul. 2016.
- [26] S. Attia, M. Hamdy, W. O'Brien, and S. Carlucci, "Assessing gaps and needs for integrating building performance optimization tools in net zero energy buildings design," *Energy Build.*, vol. 60, pp. 110–124, May 2013.
- [27] W. M. P. U. Wijeratne, R. J. Yang, E. Too, and R. Wakefield, "Design and development of distributed solar PV systems: Do the current tools work?," *Sustain. Cities Soc.*, Nov. 2018.
- [28] "PVsites." [Online]. Available: <http://www.pvsites.eu/software/>.
- [29] "Valentin Software." [Online]. Available: <https://www.valentin-software.com/en/products/photovoltaics/57/pvsol-premium>. [Accessed: 03-Sep-2018].
- [30] "PVSyst general features." [Online]. Available: <http://www.pvsyst.com/en/software/functionalities>. [Accessed: 03-Sep-2018].
- [31] "SolarGis." [Online]. Available: <https://solargis.info/pvplanner/#tl=Google:hybrid&bm=satellite&c=16.972741,22.5>. [Accessed: 03-Sep-2018].
- [32] N. Blair *et al.*, "System advisor model, sam 2014.1. 14: General description," National Renewable Energy Laboratory (NREL), Golden, CO., 2014.



- [33] F. Frasca, M. Lovati, C. Cornaro, D. Moser, and A. M. Siani, "Use of photovoltaic modules as static solar shadings: Retrofit of a paleontological site in Rome.," presented at the 12th Conference on Advanced Building Skins, Bern, Switzerland, 2017.
- [34] G. Lobaccaro, F. Fiorito, G. Maserà, D. Prasad, and others, "Urban solar district: a case study of geometric optimization of solar façades for a residential building in Milan," in *50th Annual Conference, Australian Solar Energy Society (Australian Solar Council)*, 2012, pp. 1–10.
- [35] G. Lobaccaro, F. Frontini, G. Maserà, and T. Poli, "SolarPW: A new solar design tool to exploit solar potential in existing urban areas," *Energy Procedia*, vol. 30, pp. 1173–1183, 2012.
- [36] T. Hwang, S. Kang, and J. T. Kim, "Optimization of the building integrated photovoltaic system in office buildings—Focus on the orientation, inclined angle and installed area," *Energy Build.*, vol. 46, pp. 92–104, Mar. 2012.
- [37] K. Fath, J. Stengel, W. Sprenger, H. R. Wilson, F. Schultmann, and T. E. Kuhn, "A method for predicting the economic potential of (building-integrated) photovoltaics in urban areas based on hourly Radiance simulations," *Sol. Energy*, vol. 116, pp. 357–370, Jun. 2015.
- [38] A. G. Imenes and J. Kanters, "3D solar maps for the evaluation of building integrated photovoltaics in future city districts: A norwegian case study," in *2016 IEEE 43rd Photovoltaic Specialists Conference (PVSC)*, 2016, pp. 3141–3146.
- [39] D. L. Talavera, E. Muñoz-Cerón, J. de la Casa, M. J. Ortega, and G. Almonacid, "Energy and economic analysis for large-scale integration of small photovoltaic systems in buildings: The case of a public location in Southern Spain," *Renew. Sustain. Energy Rev.*, vol. 15, no. 9, pp. 4310–4319, Dec. 2011.
- [40] D. Kurt, "Net Present Value - NPV," *Investopedia*, 24-Nov-2003. .
- [41] B. Rodriguez, *The power of creative constraints*. 2017.
- [42] B. Rudofsky, *Architecture without architects: a short introduction to non-pedigreed architecture*. UNM Press, 1964.
- [43] H. Al-Hinai, W. J. Batty, and S. D. Probert, "Vernacular architecture of Oman: Features that enhance thermal comfort achieved within buildings," *Appl. Energy*, vol. 44, no. 3, pp. 233–258, Jan. 1993.
- [44] T. Tassiopoulou, P. C. Grindley, and S. D. Probert, "Thermal behaviour of an eighteenth-century Athenian dwelling," *Appl. Energy*, vol. 53, no. 4, pp. 383–398, Apr. 1996.
- [45] J. Horn, N. Nafpliotis, and D. E. Goldberg, "A niched Pareto genetic algorithm for multiobjective optimization," in *Evolutionary Computation, 1994. IEEE World Congress on Computational Intelligence., Proceedings of the First IEEE Conference on*, 1994, pp. 82–87.
- [46] S. Kirkpatrick, C. D. Gelatt, M. P. Vecchi, and others, "Optimization by simulated annealing," *science*, vol. 220, no. 4598, pp. 671–680, 1983.
- [47] M. Dorigo, M. Birattari, and T. Stutzle, "Ant colony optimization," *IEEE Comput. Intell. Mag.*, vol. 1, no. 4, pp. 28–39, 2006.
- [48] S. Freitas, C. Reinhart, and M. C. Brito, "Minimizing storage needs for large scale photovoltaics in the urban environment," *Sol. Energy*, vol. 159, pp. 375–389, Jan. 2018.
- [49] C. Waibel, G. Mavromatidis, A. Bollinger, R. Evins, and J. Carmeliet, "Sensitivity analysis on optimal placement of façade based photovoltaics."
- [50] C. F. Reinhart and S. Herkel, "The simulation of annual daylight illuminance distributions — a state-of-the-art comparison of six RADIANCE-based methods," *Energy Build.*, vol. 32, no. 2, pp. 167–187, Jul. 2000.
- [51] G. Ward, "RADIANCE reference manual," *IEA SHC Task*, vol. 12, 1996.
- [52] D. B. Crawley *et al.*, "EnergyPlus: creating a new-generation building energy simulation program," *Energy Build.*, vol. 33, no. 4, pp. 319–331, 2001.
- [53] University of Wisconsin--Madison. Solar Energy Laboratory, *TRNSYS, a transient simulation program*. Madison, Wis. : The Laboratory, 1975., 1975.
- [54] "Net metering," *Wikipedia*. 20-Feb-2018.
- [55] G. Verbene *et al.*, "BIPV Products for Facades and Roofs: a Market Analysis," 2014.
- [56] R. W. Andrews, J. S. Stein, C. Hansen, and D. Riley, "Introduction to the open source PV LIB for python Photovoltaic system modelling package," in *Photovoltaic Specialist Conference (PVSC), 2014 IEEE 40th*, 2014, pp. 0170–0174.

- [57] D. J. Gagne, A. McGovern, S. E. Haupt, and J. K. Williams, "Evaluation of statistical learning configurations for gridded solar irradiance forecasting," *Sol. Energy*, vol. 150, pp. 383–393, 2017.
- [58] E. Lorenz, T. Scheidsteiger, J. Hurka, D. Heinemann, and C. Kurz, "Regional PV power prediction for improved grid integration," *Prog. Photovolt. Res. Appl.*, vol. 19, no. 7, pp. 757–771, 2011.
- [59] M. Pierro *et al.*, "Multi-Model Ensemble for day ahead prediction of photovoltaic power generation," *Sol. Energy*, vol. 134, pp. 132–146, 2016.
- [60] M. Pierro *et al.*, "Deterministic and Stochastic Approaches for Day-Ahead Solar Power Forecasting," *J. Sol. Energy Eng.*, vol. 139, no. 2, p. 021010, 2017.
- [61] E. Skoplaki and J. A. Palyvos, "Operating temperature of photovoltaic modules: A survey of pertinent correlations," *Renew. Energy*, vol. 34, no. 1, pp. 23–29, Jan. 2009.
- [62] L. Maturi, G. Belluardo, D. Moser, and M. Del Buono, "BiPV System Performance and Efficiency Drops: Overview on PV Module Temperature Conditions of Different Module Types," *Energy Procedia*, vol. 48, pp. 1311–1319, 2014.
- [63] R. Hooke and T. A. Jeeves, "Direct Search Solution of Numerical and Statistical Problems," *J. ACM JACM*, vol. 8, no. 2, pp. 212–229, 1961.
- [64] O. Schmidt, A. Hawkes, A. Gambhir, and I. Staffell, "The future cost of electrical energy storage based on experience rates," *Nat. Energy*, vol. 2, no. 8, p. 17110, Aug. 2017.
- [65] R. E. Best, F. Flager, and M. D. Lepech, "Modeling and optimization of building mix and energy supply technology for urban districts," *Appl. Energy*, vol. 159, pp. 161–177, Dec. 2015.
- [66] Eero Vartiainen, Gaëtan Masson, and Christian Breyer, "PV LCOE in Europe 2014-30," 2015.

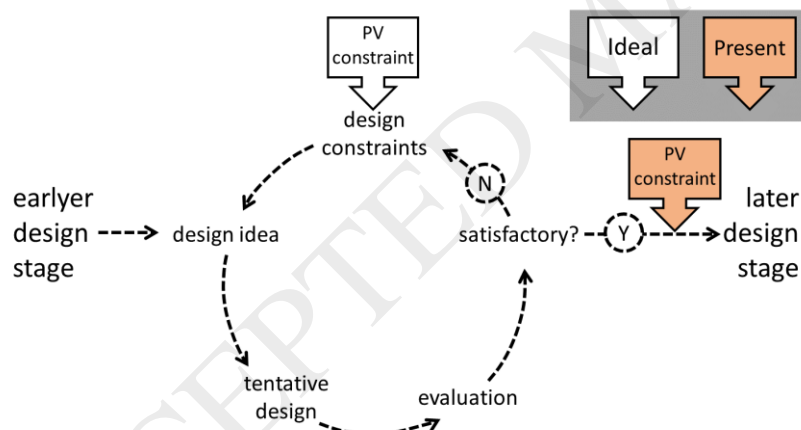


Figure 1: present and desired position of BIPV design within one step of the architectural workflow

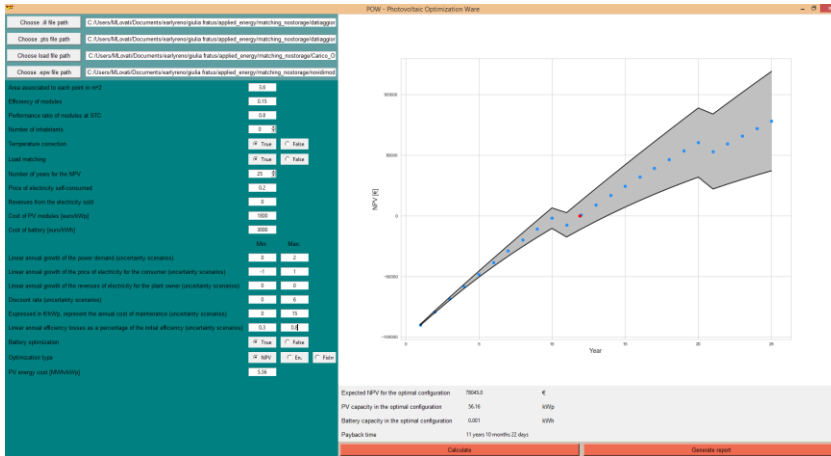


Figure 2: screenshot of the interface of the tool, all the inputs are reported on the left, on the right the NPV along the whole lifetime of the investment is reported for the optimal configuration.

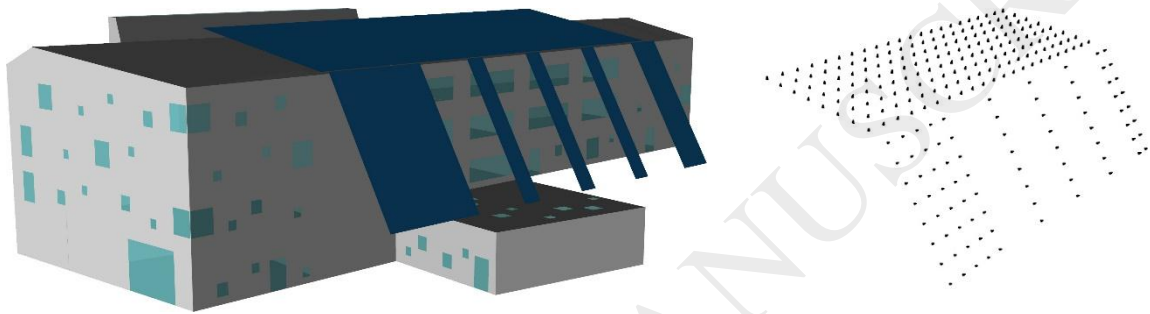


Figure 3: cloud of point of the building model

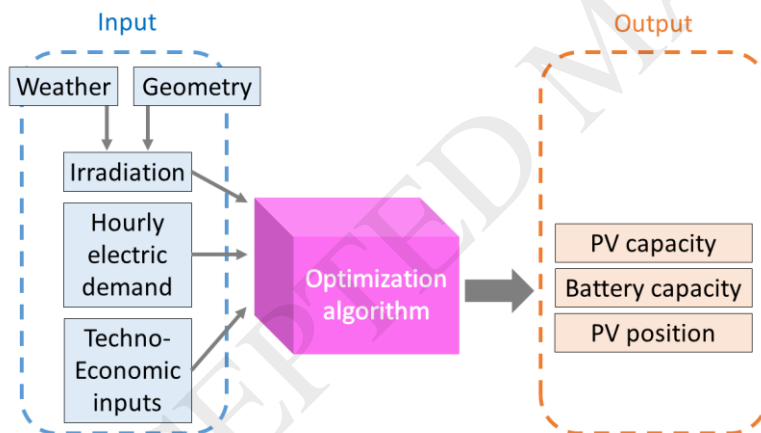


Figure 4: schematic view of the workflow of the tool, among the techno-economic inputs are the costs for the components of the system and the prices for the electricity.



Figure 5: format of the inputs and outputs of the tool, the tool requires Radiance and a Python interpreter in order to work, the OBJ can be produced with any CAD software

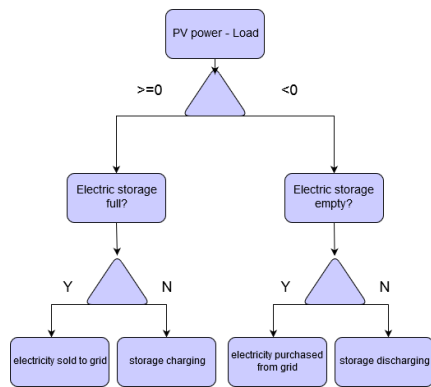


Figure 6: control strategy of the battery



Figure 7: Application of the optimization algorithm described in the paper for imitating an image using strokes of color. If the difference between an empty painting and a photo being imitated is used as a fitness function, one stroke cannot find the minimum, but it can be a step closer to the minimum.



Figure 8: Rovereto sulla Secchia in northern Italy

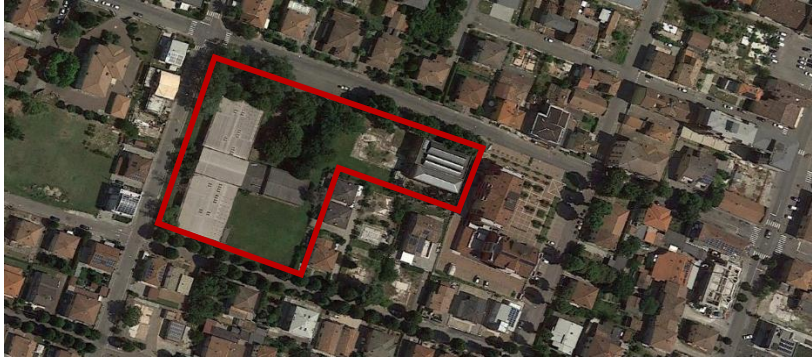


Figure 9: satellite view of the project site with existing buildings.



Figure 10: Masterplan of the project

Figure 10: Masterplan of the project

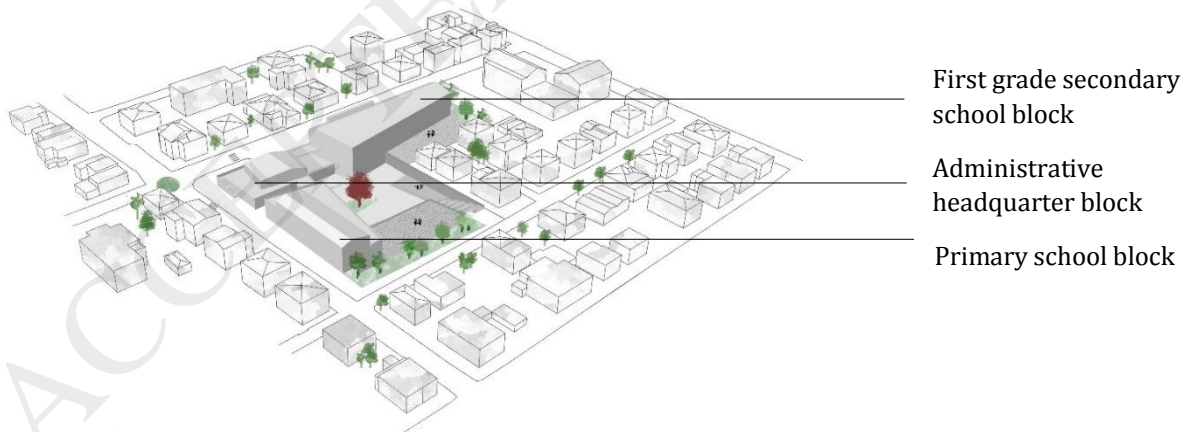


Figure 11: Buildings and their functions.

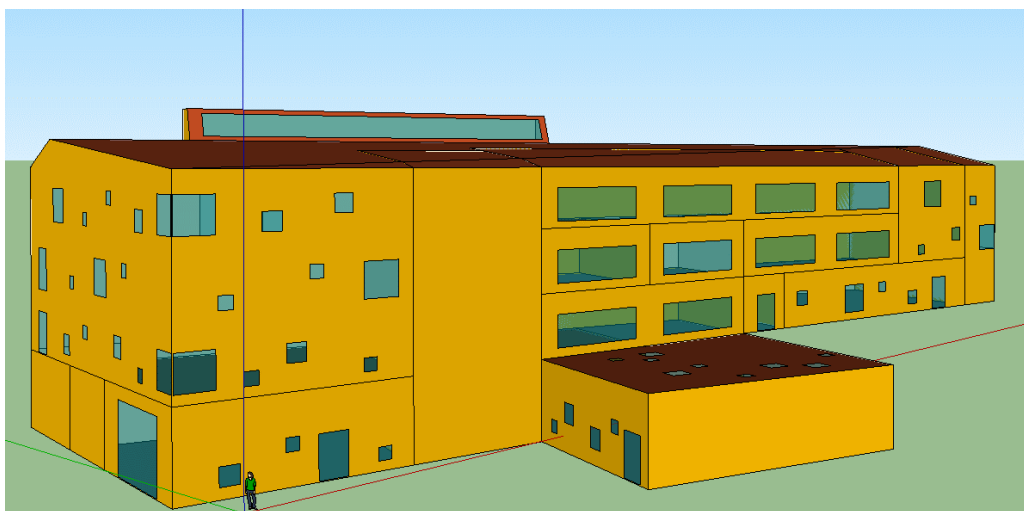


Figure 12: View of the whole building model

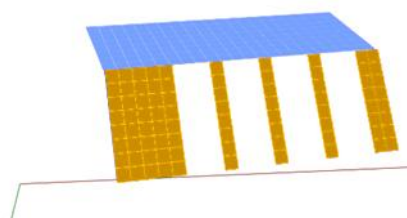


Figure 13: 3D of the cloud of points, there are 176 points on the roof and 80 on the façade, each point is shown as the area it represents (squares with an area of 3.6 m<sup>2</sup>).

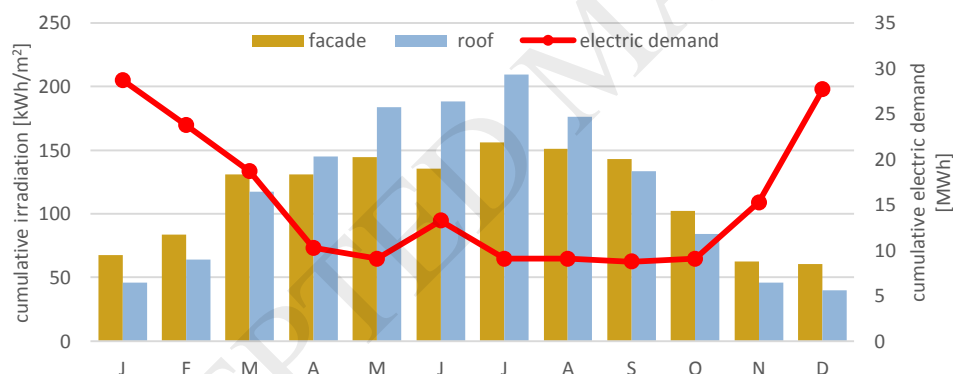
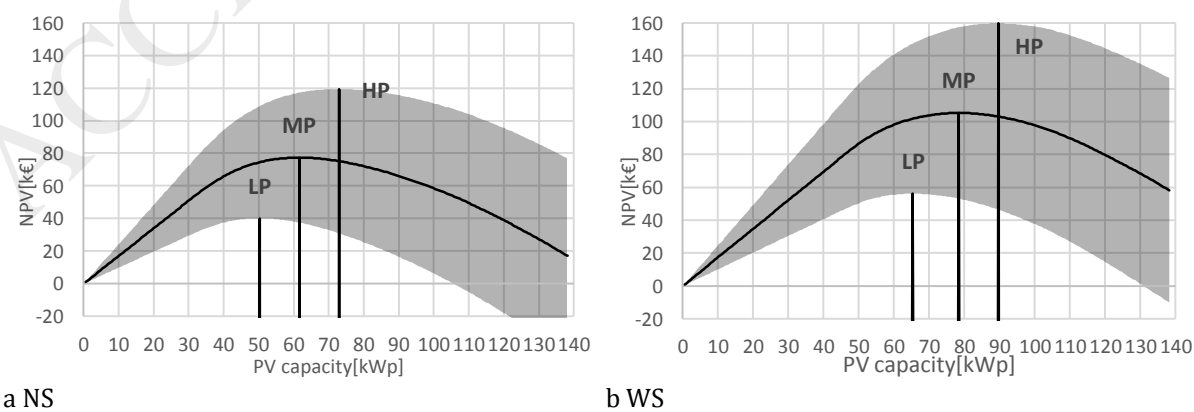
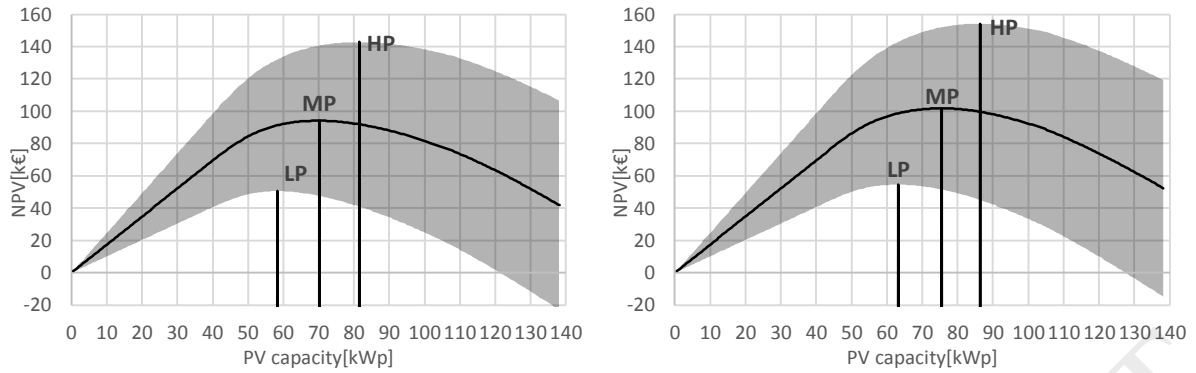


Figure 14: monthly irradiation on roof and facade of the building and monthly electric demand. The façade is less irradiated overall but it presents a better irradiation in the winter months.





c 1/3WS d 2/3WS  
 Figure 15: NPV in relation to the installed capacity, the grey area represent the possibilities between 25 and 75 percentile. a) no storage (NS) b) with storage (WS) c) 1/3 of WS capacity (1/3WS) d) 2/3 of WS capacity (2/3WS).

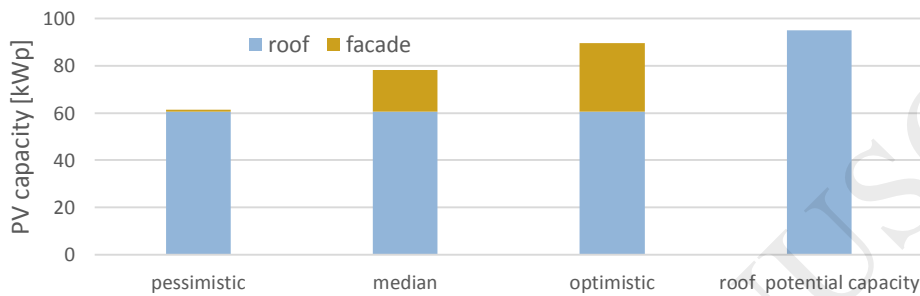


Figure 16: capacities that maximize the NPV for scenario WS at point LP, MP and HP. The roof potential capacity is reported to show that the facade is occupied although there is still unoccupied space on the roof

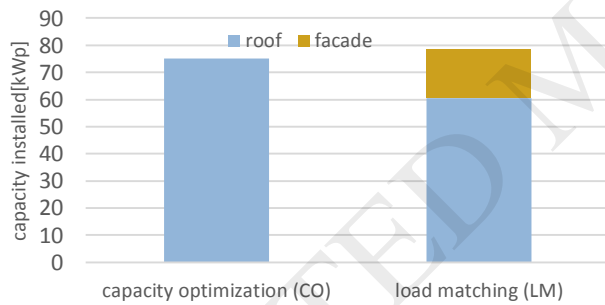


Figure 17: best NPV capacities with or without using load matching in storage hypothesis WS.

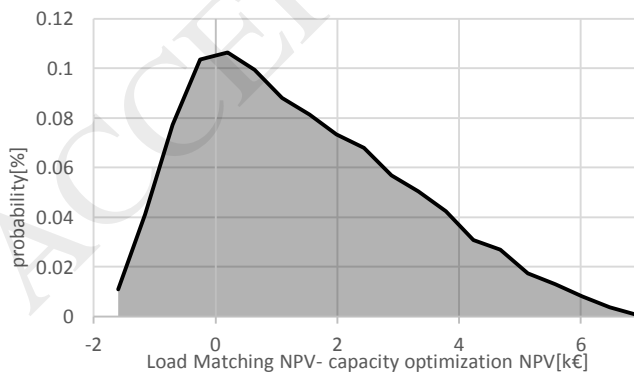


Figure 18: probability of the NPV difference between the load matching (LM) configuration and the capacity optimization (CO) configuration for the WS storage hypothesis

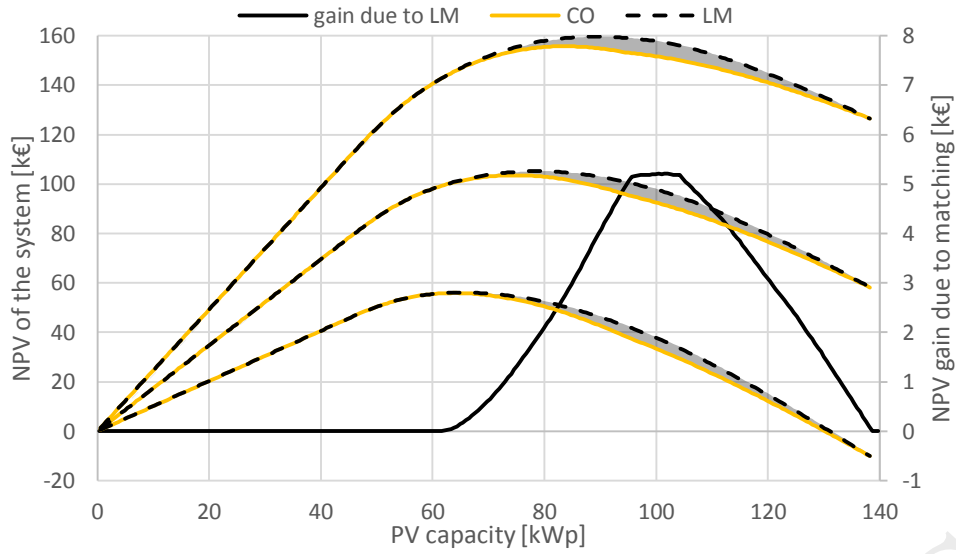


Figure 19: expected NPV gain generated by load matching for each capacity in WS hypothesis: the colored areas for the capacities show the difference in expected NPV, the gain due to LM is represented for the expected case.

Table 1: input for the optimization

deterministic	stochastic
Cloud of points	
Irradiation matrix	
Weather file	
Load vector	PV degradation
Area of the modules $A$	Load growth
Efficiency of modules $\eta$	Price el. growth
N° of years for NPV $t$	Price sold el. growth
Price consumed el. $P_c$	Discount rate $i$
Price sold el. $P_s$	Maintenance [€/kWp]
Price net metered $P_{nb}$	$C_t$
PV cost[€/kWp] $C_0$	
Battery cost[€/kWh] $C_b$	

Table 2: Thermal transmittance values of the element of the envelope

Building components	Thermal transmittance value [W/m <sup>2</sup> K]
Vertical wall	0.171
Roof	0.126
Basement	0.257
Windows with frame	1.40



Partition wall | 0.80

Table 3: boundary conditions for the TRNsys simulation

Climate condition	Novi di Modena climate (Typical Meteorological Year)
Heating season	15 <sup>th</sup> October -15 <sup>th</sup> April
Heating set point (temperature)	20°C
Cooling season	1 <sup>st</sup> June – 30 <sup>th</sup> June
Cooling set point (temperature/Humidity)	26°C/55%
Appliances	Printer= 50 W; Computer= 250 W; Artificial lighting = 5 W/m <sup>2</sup> .

Table 4: input used for the optimization, the procedure was repeated with diverse electric storages.

	WS	NS
Efficiency of modules $\eta$	15%	
PR (at STC)	0.8	
N° of years for NPV t	25	
Price consumed el. P <sub>c</sub> [€/kWh]	0.2	
Price sold el. P <sub>s</sub> [€/kWh]	0	
PV cost C <sub>0</sub> [€/kWp]	1800	
PV degradation %	0.3-0.8	
Load growth*	0-2	
Price el. Growth*	-1-+1	
Price sold el. Growth*	0	
Discount rate i	0-6	
Maintenance C <sub>t</sub> [€/year·kWp]	18-36	
battery cost [€/kWh]	0	n.d.
battery installed [kWh]	29,58,87	0

\*linear growth expressed as a percentage of the value of the first year

Table 5: dimensions correlated with the electric storage capacity, the table shows data for the peak NPV cases at each storage level

	no storage (NS)	29 kWh (1/3WS)	58 kWh (2/3WS)	87 kWh (WS)
Optimal capacity [kWp]	61.6	70.2	75.6	78.3
Self-production (year 0) [%]	32.3	37.7	40.6	42.0
Self-consumption (year 0) [%]	83.3	82.4	82.4	82.4
NPV (25 year) [k€]	77.3	94.1	101.8	105.2
Stored energy (year 0) [MWh]	--	5.4	8.0	9.3

Cost of stored energy [€/kWh]	--	0.1239	0.1219	0.1200
Profitability threshold price* [€/kWh <sub>capacity</sub> ]	--	576.3	419.8	319.5

*\*the profitability threshold price is a lifetime price, if the battery must be changed once, then the threshold price for profit with that capacity can be half of the reported (e.g. 576.3€ -> 288.15€ +288.15€) or divided considering a learning curve (e.g. 376.3€ + 200€).*

ACCEPTED MANUSCRIPT