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Comparative Analysis of BIPV Solutions to Define Energy and Cost-Effectiveness in a Case Study

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Received: 8 June 2020; Accepted: 22 July 2020; Published: 25 July 2020

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Abstract: The built environment remains a strategic research and innovation domain in view of the goal of full decarbonization. The priority is the retrofitting of existing buildings as zero-emission to improve their energy efficiency with renewable energy technologies pulling the market with cost-effective strategies. From the first age of photovoltaics (PV) mainly integrated in solar roofs, we rapidly moved towards complete active building skins where all the architectural surfaces are photoactive (Building Integrated Photovoltaics - BIPV). This change of paradigm, where PV replaces a conventional building material, shifted the attention to relate construction choices with energy and cost effectiveness. However, systematic investigations which put into action a cross-disciplinary approach between construction, economic and energy related domains is still missing. This paper provides the detailed assessment of a real multifamily building, taking into account retrofit scenarios for making active the building skin, with the goal to identify the sensitive aspects of the energetic and economic effectiveness of BIPV design options. By assuming a real case study with monitored data, the analysis will consider a breakdown of the main individual parts composing the building envelope, by then combining alternative re-configurations in merged clusters with different energy and construction goals. Results will highlight the correlation between building skin construction strategies and the energy and cost parameters by identifying the cornerstones for enhancing efficiency. The outcomes, related to the total life cost, self-consumption/sufficiency, in combination with different building design options (façade, roof, balconies, surface orientations, etc.), provide a practical insight for researchers and professionals to identify renovation strategies by synergistically exploiting the solar active parts towards lower global costs and higher energy efficiency of the whole building system.

Keywords: BIPV; cost-effectiveness; life-cycle cost; building skin

1. Main Definitions

Typological cluster: functional element of the photovoltaic (PV) building skin.

Merged cluster: groups of different typological clusters.

Total cost of energy: actualized amount of costs incurred during the lifetime of the PV system. This includes the initial cost of investment to install the PV and/or battery system, the energy costs to pay during operation due to building energy consumption, the cost of maintenance of the system and the revenues obtained due to the self-consumption and sale of the PV energy produced.

Self-Sufficiency Rate (*SSR*): percentage of the energy demand covered by the energy produced with the BIPV system and used outright.

Self-Consumption Rate (*SCR*): energy produced with the BIPV system and used outright.

2. Introduction

In the last decade, the use of PV systems connected to the grid has undergone a considerable increase, due to both the incentive mechanisms and the progressive decrease in installation costs of over 10% per year [1]. Currently, however, the reduction in incentive tariffs in most EU countries and the increasing cost of electricity withdrawn from the grid, have led to identify the self-consumption of electricity production from PV systems as a real solution of economic gain for consumers in their role as prosumer (producer–consumer). The interest in self-consumption, defined as the ratio between the electric energy produced and directly consumed on site and the total energy produced by the PV system, instantaneous and/or deferred, is mainly due to the increase in profits, as it decreases the energy withdrawn from the grid and the relative costs as well as the PV energy injected. The exchange with the grid is, in fact, an economic loss for the end user, in addition to the reduction in problems created to the electricity grid [1,2].

The growing introduction of Nearly-Zero Energy Buildings (nZEBs) in the built environment, in view of the objectives set by EU directives and national regulations in previous years, also implies the need to intervene in the optimization of plants powered by renewable sources, such as photovoltaics, improving their design, integration, performance and maximizing the energy and cost-effectiveness as well as the producibility on-site. More and more buildings are designed as power generators with a PV cladding which, as an active building material, produces renewable energy. From the first age of solar roofs, we are moving towards a complete active building skin where all facades and building surfaces are photoactive, and PV becomes part of the aesthetics and building skin technology. This change of architectural paradigm also shifts the attention in terms of energy behavior, since energy is produced all day, from surfaces with various orientations and increasingly with variable operating conditions affected by the surrounding built environment.

The present work concerns an analysis on a pilot Swiss BIPV building, Palazzo Positivo located in Chiasso-Canton Ticino, which has been renovated according to Passivhaus and Minergie standards by transforming all the building skin into a new active PV cladding producing energy. By using the real production data derived from an annual monitoring of the building, we intend to define a method that permits the assessment of the energy and economic effectiveness of different BIPV skin possible for configurations (separating and recombining only some facades or roofs as active PV parts, in simulated scenarios) set as reference scenarios (we will call them merged clusters, *MC*) and highlight the limits/potentials of the optimization. Today, many pilot BIPV buildings are realized [3] but a deep critical technical-economic convenience on the role/effectiveness of each part of the building skin to become active is not yet known. Some methodologies in literature have recently defined the cost effectiveness by means of similar assumptions and based on a life cycling cost approach, but these methodologies are not verified in a real and monitored case study [4].

The paper is organized as follows. In Section 3, the state of the art is analyzed, highlighting both objectives and points of innovation of the project. Section 4 describes the solar system features. Section 5 illustrates the methodological framework, aimed to clarify the assumptions and methods of analysis for assessing the economic and energy benefits in relation to current and future possible scenarios. The development of the analysis and the results are summarized within Section 6. Section 7 concludes the work by describing the implications of the results.

3. State of the Art and Motivation

On 30 November, 2016, with the aim to promote the use of smart technology in buildings, the European Commission proposed an update to the Energy Performance of Buildings Directive to streamline existing rules and accelerate building renovation [5]. The Directive (2018/844/EU) amending the Energy Performance of Buildings Directive, revised, entered into force on 9 July, 2018. This revision introduces targeted amendments to the current Directive aimed at accelerating the cost-effective renovation of existing buildings, with the vision of a decarbonized building stock by 2050 and the mobilization of investments. The revision also supports smart technologies and technical building systems [6,7]. Solar installations, on-site and integrated, are an opportunity for increasing energy performance in buildings. In the new Energy Performance of building Directive, important provisions for solar in buildings have been considered [8]. In this framework, thus, BIPV is confirmed as a strategic approach for prosumers and small/medium-scale installations which should drive the energy transition in future decades. In the Commission Recommendation (EU) 2019/1019 of 7 June, 2019 on building modernization (Official Journal of the European Union, 21.06.2019), it is stated that the performance of technical building systems has a significant impact on overall building energy performance and should therefore be optimized.

The growing interest in the self-consumption of electricity production has generated in the last few decades the development of numerous research on the theme of optimization and maximization of Self-Sufficiency Rate (*SSR*) and Self-Consumption Rate (*SCR*) of photovoltaic systems, both in the residential and tertiary sectors. Even in absence of incentives, the self-consumption has numerous advantages: it contributes to the reduction in production peaks, helps to avoid overloads on the network and allows a better control of electricity purchase costs [9]. The *SSR*, however, is defined as the percentage of coverage of electricity production needs, which is similar to the *SCR* only in the case of an ideal nZEB building, with a perfect balance between photovoltaic generation and electrical requirements.

The methods investigated for the optimization of the value of self-consumption are different, although they can mainly be traced to two types: the use of storage systems (batteries) or the movement of active loads, defined as Demand Side Management (DSM). These strategies can be used separately or combined, leading to different results [8,10]. The aim is minimizing the dependence from the grid of currently connected PV systems, in order to maximize the consumption of locally-produced PV energy, reducing costs and avoiding peaks and grid instability.

In the first case (accumulation systems), optimization strategies are based on the storage of the surplus of electricity generated by the PV system and on its deferred use, avoiding the input into the grid. However, today, despite the increase in the percentage of self-consumption due to the use of batteries, the continued high costs of this system do not allow us to define it as a convenient tool [11–19]. Numerous studies focus on the optimization of self-consumption by inserting batteries. Some deal with the correlation between the increase in *SCR* and the size of the battery to be installed, others with its long-term management and with the technical–economic benefits that can be obtained. The study [20] illustrates the influence of battery storage size on PV self-consumption in a grid-connected residential building. It shows that self-consumption reaches a "plateau" at a certain value of storage size equal to the average amount of daily PV-consumption/production. Moreover, for all analyzed storage sizes, the achievable amount of energy self-consumption is considerable: by increasing the battery size in terms of energy from 0 to 32 kWh, the SSR increases by 36 percentage points in winter and 51 in summer [20]. In [15], a similar result is achieved for a case study in Germany, where the increase is 27 percentage points (from 38% to 65%) with a 7 kWh battery [21]. In the latter case, Truong et al. [15] analyze the technical and economic benefits of the Powerwall designed by Tesla on a residential building in Germany, estimating the conditions that lead storage to become economically viable. Additionally, [22] shows a strategy for maximizing the self-consumption, using a simulated Vanadium Redox Flow (VRF) battery (demonstrator), showing the possibility of reaching a value of self-consumption equal to 100%, from a value of 65%, through the local use of the energy produced, avoiding its injection into the grid, covering about 75% of total consumption. The same VFR battery technology is used in [23] with the aim of achieving system self-sufficiency thanks to its sizing capacity independent of nominal power. Always referring to residential buildings, the study conducted by Weniger et al. [13] leads to important results for the sizing of battery capacity. In fact, with a PV plant sized with 1 kWp/MWh, a single residential building can reach a self-consumption value equal to 30%. The addition of 1 kWh/MWh of the battery capacity increases the SCR and the SSR to almost 60%, while the further increase in accumulation does not lead to appreciable results, showing that the correct capacity value must be based on the daily requirement [13]. As in other studies, the case study is a nZEB multi-family residential building in which the goal is to reduce as much as possible the electricity injected or withdrawn from the grid, giving priority to self-consumption and storage of the energy surplus produced.

Numerous studies investigate the topic of Demand Side Management (DSM) as an alternative to storage to optimize the self-consumption value of a system. This strategy, however, is mostly convenient in the case of residential buildings. In fact, when office and commercial buildings are considered, where the load profiles follow fixed characteristics during the year, the mismatch of needs makes it more difficult to achieve feasibility [9]. In this case, as proposed by Martín-Chivelet et al. [9], optimization is carried out by simulating the differently oriented façade combinations that provide better output in terms of *SCR* and *SSR*. Sánchez et al. [11] also studied the performance of poorly oriented BIPV systems, but the study is not designed to evaluate the benefits in terms of self-consumption. As for batteries, even DSM cases in the literature are numerous for residential buildings. The concept of DSM concerns the temporary shift of energy demand by the user, due to the use of more energy-intensive equipment, such as dishwashers, washing machines and tumble driers. A large part of energy waste can in fact be charged to a non-virtuous behavior of users, which necessarily implies a lack of overlap between the needs profile and the production profile. Optimizing this profile, translating the load curves in an appropriate way, can therefore be a good way to increase self-consumption. Numerous references in the literature aim to improve self-consumption in residential buildings by combining the strategies previously exposed: DSM and storage [1,2,10,14,24,25].

Castillo-Cagigal et al. [26], define the concept of ADSM (Active Demand Side Management) as the automation control of user load management, potentially useful in the residential sector for the possibility of being combined with additional functions relating to the comfort and safety of the building. The interesting results of his study are the following: the discovery that the influence of storage systems in the energy balance has no linear growth based on its capacity but reaches an asymptotic level for high storage capacities.

The final assumption is, therefore, that the use of the ADSM strategy is the same as the use of a small electrical energy storage system and the combination of the two strategies significantly improves the direct use of photovoltaic production.

The investigations previously analyzed are mainly based on simulated PV production models created on the basis of real meteorological conditions. The only reference of real monitoring of both consumption and electrical production of a BIPV system is not aimed at optimizing the values of self-consumption and self-sufficiency. In [14], the power generation of the BIPV system and the building loads were investigated by monitoring the building to verify the worst array causing the reduction in generation performance and to verify the achievement of the purpose of zero-energy buildings.

From an economic perspective, the investigations previously analyzed show that the BIPV system and storage installation are becoming attractive investments due to decreasing trends in costs and feed-in tariffs, also in the case of energy efficient retrofitting.

Due to the assumption that, actually, electricity tariffs, PV system cost and system efficiency do not allow us to define BIPV solar energy technology, a cost-effective option is reported in some studies, as in the research of Radhi H. [27]. According to this, the only way such a system will be convenient is if the electricity tariff increases or if the total system cost drops drastically. However, as Scognamiglio A. specifies in her studies, in the case of the BIPV system, the economic evaluation is more complex because not only the direct costs of BIPV installation should be considered, but also the benefits deriving from PV energy production and the avoided costs of the traditional building materials [28].

Other studies focus on the evaluation of the cost-effectiveness of BIPV for the building skin, in addition to the energy performance [29,30]. In [29], Hammond, G. P. et al. study the performance of a domestic BIPV system utilizing energy analysis, environmental life-cycle assessment (LCA) and economic analysis. The results illustrate that the systems are unlikely to pay back their investment over the 25 year lifetime, even if the energy analysis determines that the system paid back its embodied energy in just 4.5 years. They also demonstrate the importance of government support to the future uptake of BIPV.

Bonomo et al. illustrate a new methodology for evaluating the cost-effectiveness of BIPV, based on a life-cycle costing approach, assessing the whole building envelope solution, taking into account the multi-functionality of the system and, therefore, all the advantages of BIPV [29].

The economic sustainability of BIPV technology is a crucial aspect of its feasibility and market success. So far, the main efforts towards cost-effectiveness have been focused, similarly to conventional PV, on minimizing the final installation price per kWp. When using PV, the economic analysis and the afford ability assessment are generally focused on the energy payback time and on the return of investment [31]. The present study will base the analysis of a BIPV solution on the following innovative aspects beyond the state of art:

- Multi-functionality. BIPV is considered as a building material, which replaces a conventional layer of the building skin, thus providing a cost saving due to the cost of the replaced building cladding;
- Unitary concept of BIPV and building envelope. The energy and economic assessments are conducted considering the BIPV system together with the whole building, as a unique system.
- Life-cycle costing. The balance of costs and benefits is extended to the entire life cycle of both PV and the building envelope.
- A project-based approach. The analysis is performed for a specific case study in which characteristics and peculiarities are known and provided by real data by avoiding uncertainties on simulated cost and energy parameters. Accordingly, the paper will focus the analysis on the energy performance and the cost effectiveness of the BIPV and BAPV systems installed in the case study building.

4. Description of the Case Study: Multi-Family Building with a Fully-Active Building Skin

The following investigation will be based on a reference case study of an 8-storey multi-family house built in 1965 and renovated in 2013, which has been equipped with an integrated photovoltaic system on all façades and roofs, in addition to a single-axis solar tracker. The building, which represented a pilot example in Switzerland for building renovation according to a plus-energy target and with a completely active skin, is located in Chiasso (Figure 1). The building energy demand index before retrofit was 291 kWh/m^2 y with a total energy yearly demand of 399.5 MWh.

After renovation, according to Passivhaus and Minergie protocols, the energy consumption was 56 kWh/m^2 y. Electrical loads in the current state were 77’366 kWh, which was at the base of the load profile considered in the following. Currently, the whole electricity production of the whole PV installations, consisting of about 16’381 kWh/y for the facades and 33’105 kWh/y for the roofing (roof and garage) and the tracker, was injected into the grid and was subjected to a *Feed in Tariff* (*FiT*) remuneration scheme. The *FiT* is an energy supply policy. Long-term (10–25 years) purchase agreements support the development of new renewable energy projects [32].

PV modules installed on the façade were installed as a cold ventilated system supported by a metallic structure with an air gap of 27 mm between the cladding and the thermal insulation layer behind. Façade modules were divided into glass–glass opaque amorphous silicon for about 35 kWp in all orientations; glass–glass opaque mono-crystalline Silicon for about 12 kWp in the south orientation; semi-transparent glass–glass modules for balconies for about 6 kWp in the east and west orientation. Details are displayed in Table 1.

The case study was used as the reference building to perform analysis and assess scenarios. The energy values, as explained in the following section, are real data taken from monitoring and grid meters.

Figure 1. East façade of Palazzo Positivo (source: SUPSI, University of Applied Sciences and Arts of Southern Switzerland).

Table 1. Definition of BIPV and BAPV (Building Applied Photovoltaics) system.

Application	Inclination	Orientation	Technology	Surface m^2	Nominal Power kWp	Final Yield kWh/kWp	Electric Production kWh/y
Facade S	90	20	aSi	160	12	229	2′521
Facade S	90	20	cSi	72	12	439	5′045
Facade E	90	−70	aSi	92	7	483	3′233
Facade W	90	110	aSi	26	2	351	666
Facade N	90	−160	aSi	235	14	189	2′803
Balcony E	90	−70	cSi	33	3	576	1′671
Balcony W	90	110	cSi	35	3	116	441
Total				**652**	**53**	**311**	**16′381**
Garage	10	20	cSi	70	15	660	9′699
Roof	10	20	cSi	48	10	1′216	12′155
Tracker	-	-	cSi	58	12	938	11′251
Total				**176**	**37**	**902**	**33′105**

5. Assumptions and Methodology

In this section, the necessary steps and key elements that permitted us to reach the results of the analysis are explained. The chapter is divided into three parts considering the energy aspect (5.1), method and aspect of analysis (5.2) and the assessment of the optimal scenario (5.3).

5.1. Building Energy Aspects

5.1.1. Load Profile

The building load profile is made up of space heating (*SH*), domestic hot water (*DHW*) and appliances. The *DHW* and *SH* is produced with a heat pump of 33 kW. In addition, a solar thermal plant of 46.5 m^2 installed on the roof produces yearly, according to design, 26′272.5 kWh of thermal energy (net income evaluated of 565 kWh/m^2). Because of the lack of hourly-based monitored consumption data, the load profile was calculated through the aggregated data given by the *Distribution System Operator* (*DSO*) and the energetic certification (Minergie® certificate). The hourly-based load profile was determined as explained in the following.

The thermal load for *SH* (*Qsh*) and for the *DHW* (*Qhw*) changed in electric load considering the hourly external temperature that influences the COP of the heat pump installed. The contribution of solar thermal was taken into account, as a *DHW* and *SH* thermal load share reduction (*Qsh* and *Qhw*). As reported on the energetic certification, the reduction corresponded to 74% for the *DHW* and 41% for the *SH*. The remaining 59% of the *SH* was produced with a heat pump during the 24 h of the day. The remaining 26% of *DHW* was produced with a heat pump every day for six hours, from 0 until 6 am. The thermal load profile *Qsh* and *Qhw* is shown in the Figure 2. Furthermore, a monthly correction factor of the heating produced with the heat pump according with the influence of the solar thermal seasonal production was individuated. The temperature of the hot water was assumed to be 58 °C and the indoor temperature was assumed to be 20 °C, from SIA 380/1. The supply heating temperature was assumed to be 30 °C.

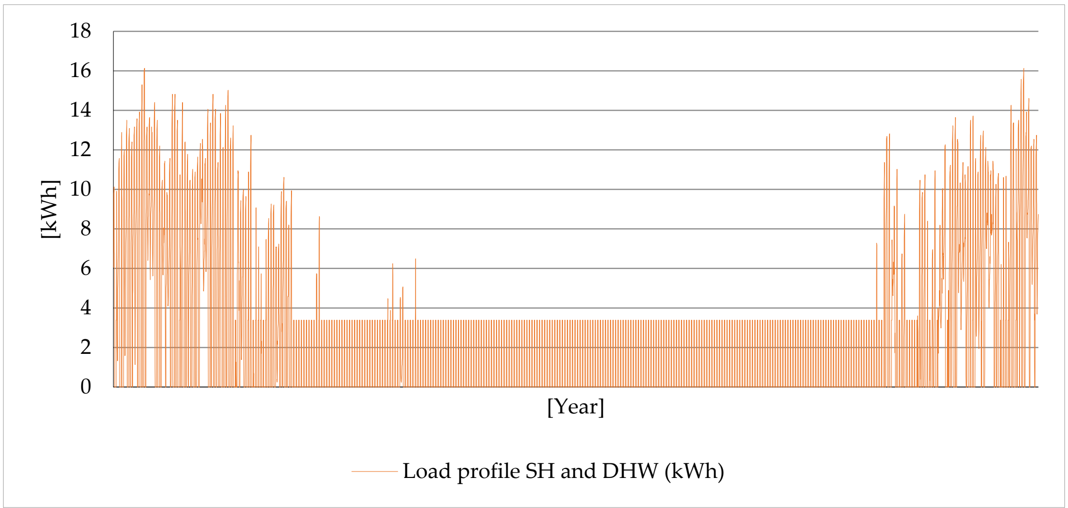

Figure 2. Space heating *SH*) and domestic hot water (*DHW*) energy demand.

The remaining electric consumptions (mechanical ventilation, lift, lighting and appliances) were merged, and an hourly load profile of a typical day was generated. The hourly load profile generated was obtained from the weighted hourly consumption of the 365 days of the year considering five typical profiles of five different families simulated with the software Load Profile Generator [33] Figure 3.

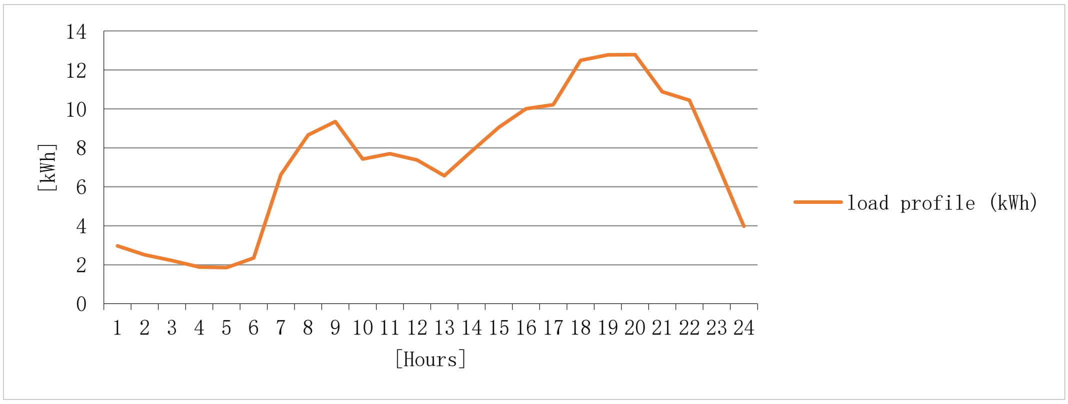

Figure 3. Mechanical ventilation, lift, lighting and appliances energy demand.

5.1.2. PV Production Profile

The PV production profile was obtained by monitoring the energy production of Palazzo Positivo, with sensors downstream of each string inverter (AC current). The sensors detected the hourly electric production of each inverter, the temperature of the environment and modules and the incident radiation. Figures 4 and 5 show the profile of PV production and electric consumption generated of the typical summer and winter day.

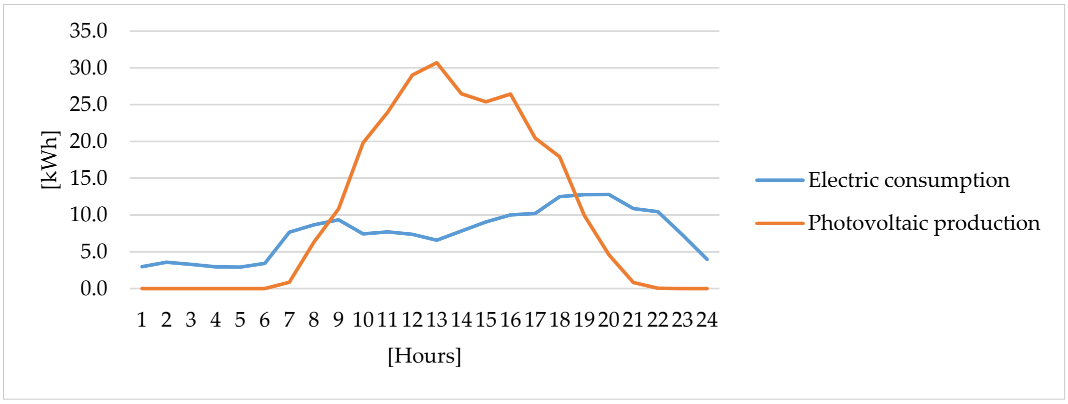

Figure 4. Typical summer day load profile.

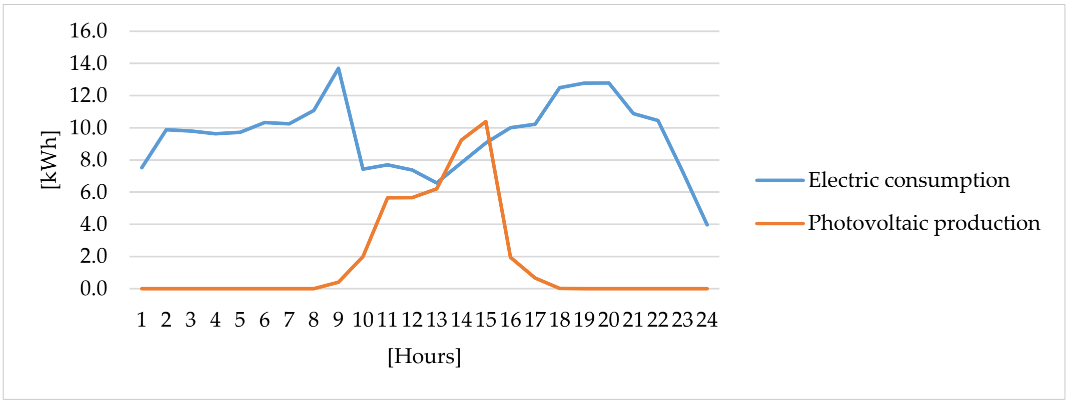

Figure 5. Typical winter day load profile.

5.2. Method and Steps of Analysis

As shown in Figure 6, this study was conducted in three steps: (i) step 1: breakdown and recomposition of the active building skin; (ii) step 2: economic analysis; (iii) step 3: comparison after the application of a storage system.

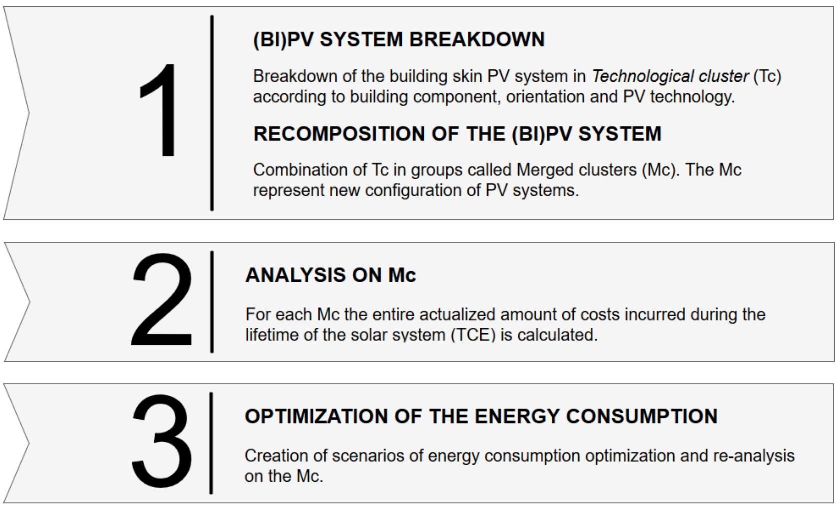

Figure 6. Work phases of the analysis.

5.2.1. Step 1: Breakdown and Recomposition of the Active Building Skin Façade Layout

The starting point of this step is a breakdown of the building envelope of Palazzo Positivo. Each main functional element of the PV building skin is isolated and identified as a group, called a *typological cluster* (*TC*), according to building component (façade, railing and roof), orientation (north, south, east, west) and PV technology (a-Si, c-Si). This permitted us to generate a mapping of the building envelope by BIPV functional parts useful for the analysis (Figure 7).

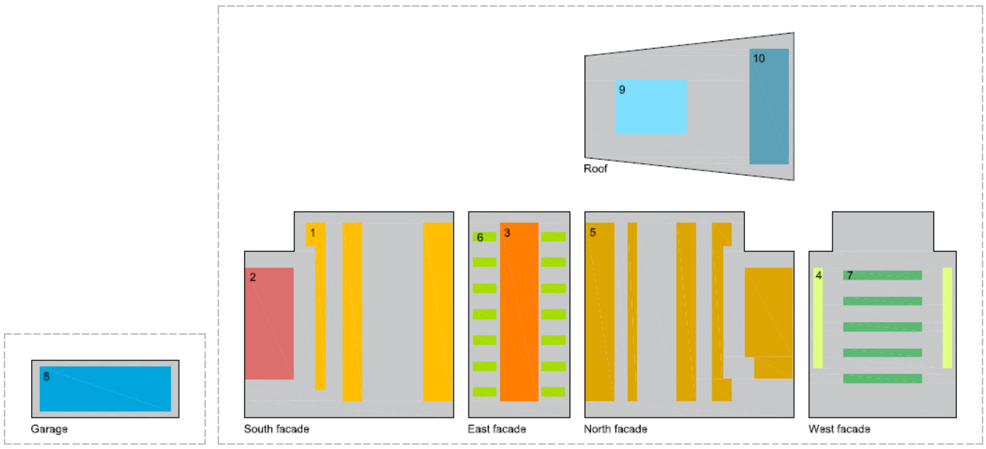

Figure 7. Schematic façade breakdown according with building component, orientation and PV technology. *TC1* S façade aSi, *TC2* S façade cSi, *TC3* E façade aSi, *TC4* W façade aSi, *TC5* N façade aSi, *TC6* E balcony cSi, *TC7* W balcony cSi, *TC8* Garage cSi, *TC9* Roof cSi, *TC10* Tracker cSi.

TCs were combined with each other in order to recompose groups of PV elements, called merged clusters (*MC*). *MCs* represented new configuration of PV systems thanks to a combination of different building skin parts, as shown in Table 2, so that it was possible to analyze a range of different solutions. *MC1* was a union of each *TC*; it represented the actual state (all PV plants). The retribution of the *MC1* did not represent the current state of the building (see *MC10*). *MC2* was composed of only façade BIPV systems without roofs, railing applications and without the north oriented facade. *MC3* stood for the BIPV solution with all four facades, namely *MC2* including the northern facade. *MC4* represented a combination of BIPV and roof BAPV systems; it was composed of BIPV modules on the four façades in addition to PV panels on the roof and the garage. *MC5* stood for a conventional rooftop PV installation. *MC6* was composed of only the PV modules with a final yield higher than 400 kWh/kWp (e.g., thus excluding some portions of facades non optimally exposed). *MC7* considered BIPV on facades (apart from a-Si part installed on the south façade and the north facade) and roofs apart from the railings and the tracker. *MC8* was the complete active skin excluding the garage, the tracker, the north facade and all the accessories such as balconies. All the *MCs* are reported in Table 2.

Table 2. *MC* definition. *MC1* represents the current building status. *MC9* is a passive reference building.

	Mc1	*Mc2*	*Mc3*	*Mc4*	*Mc5*	*Mc6*	*Mc7*	*Mc8*	*Mc9*	*Mc10*	*Mc11*
Tc1 aSi Facade S	x	x	x	x				x		x	x
Tc2 cSi Facade S	x	x	x	x		x	x	x		x	x
Tc3 aSi Facade E	x	x	x	x		x	x	x		x	x
Tc4 aSi Facade W	x	x	x	x			x	x		x	x
Tc5 aSi Facade N	x		x	x						x	
Tc6 cSi Balcony E	x					x				x	
Tc7 cSi Balcony W	x									x	
Tc8 Garage	x			x	x	x	x			x	
Tc9 Roof	x			x	x	x	x	x		x	x
Tc10 Tracker	x					x				x	

Furthermore, the other three *MC*s that considered special solutions were added in the analysis: *MC9*, *MC10* and *MC11*. *MC9* considered a solution without PV, namely the alternative solution of the building without any active surface where the electric energy was fully withdrawn from the grid. *MC10* and *MC11* corresponded to the *MC1* and *MC8* with the *Feed in Tariff* retribution rather than the self-consumption model. *MC10* represented the retribution and the solar configuration that represented the current state of the building.

5.2.2. Step 2: Life-Cycle Cost Analysis

The analysis consisted of the cost effectiveness in installing PV systems according to the *MC* previously defined. The main analysis parameters were total cost of energy, yearly average revenues, self-consumption rate, self-sufficiency rate and cost/extra cost of PV.

The *Total Cost of Energy* (*TCE*) in a certain period of time was the main parameter of this analysis and represented the entire actualized amount of costs incurred during the lifetime of the solar system [Swiss Francs-CHF]. *TCE* included the initial cost (investment) to install the solar and/or the battery system, the energy costs to pay during the operation due to building energy consumption, the cost of maintenance and the revenues obtained due to PV self-consumption. Within the *TCE*, both the building skin system (cladding and structures) and the *BOS* costs were included, with the cost to replace the inverter after 10 years. *TCE* did not consider the increase in the energy cost over years and possible subsidies on the investment. The Equation (1) expresses the *TCE* calculated as the present value of all the annuity costs and revenues.

$$TCE\ [CHF] = \sum_{t=1}^{y} \frac{(EC + MC)}{(1+i)^t} - \sum_{t=1}^{y} \frac{R * (1-dr)^t}{(1+i)^t} + EC_{BIPV} \tag{1}$$

where:

- *i:* discount rate, assumed 2%/year (BIPVBOOST, Competitiveness status of BIPV solutions in Europe, 2020);
- *EC:* yearly cost of running energy [CHF];
- *MC*: yearly cost of maintenance, assumed 10 CHF/kWpy [CHF];
- *y:* defined period of investment: 20 years [years];
- *t*: annuity
- *R*: yearly revenues calculated considering the gain due to the amount of energy self-consumed (kWh) and the energy injected into the grid (kWh) [CHF];
- *dr*: degradation rate of the PV, assumed 0.8%/year (Photovoltaic degradation rates—An analytical overview, D. C. Jordan, S. R. Kurtz, Journal article 2012);
- EC_{BIPV}: investment cost for BIPV systems. This was assumed as the extra cost to make a similar non-active façade active (in order to specify that, in most cases, the BIPV envelope is an active cladding installed in substitution of a similar non active system with the same substructures. Thus, the cost considered in this paper as the initial investment was defined as the extra cost compared to a traditional non-active system.). Included within the extra cost was the BOS (707 CHF/kWp) and the cost of the new inverter substituted after 10 years (312 CHF/kWp). This resulted from real examples analyzed from the Swiss market. For the BAPV element the extra-cost was assumed as the cost of the plant since it did not replace any building material [CHF].

The revenue of the PV system was considered as a benefit. The remaining energy taken from the grid and the extra cost of the BIPV system were considered as negative factors. According to the electric society, the energy consumed outright cost 0.19 CHF/kWh, energy injected into the grid cost 0.07 CHF/kWh. In the *MC9*, the solution without PV, the energy withdrawn from the grid cost, as an assumption, 0.19 CHF/kWh. Considering the *MC10* and *MC11* with a *Feed in Tariff* retribution, the energy injected into the grid cost 0.28 CHF/kWh (Age SA retribution during the year 2013). The prices referred to the year 2013, when the PV system was installed.

The cost of the a-Si cladding module installed on the façade of Palazzo Positivo was 110 CHF/m^2. As also mentioned by P. Bonomo et al. [34], if we considered the cost of a conventional laminated glass cladding 80 CHF/m^2 we could define 30 CHF/m^2 as the extra cost for our active BIPV glazed cladding. Other costs and extra costs are showed in Table 3, for all the claddings used in the case study. The costs were actualized in 2020 for the analysis (t = 1). Analyses were extended to each *MC* considering a period of calculation of about 20 years.

Table 3. Extra cost of BIPV systems.

Material	Cost CHF/m^2	Extra Cost CHF/m^2
a-Si cladding facade	110	30
c-Si cladding facade	170	90
a-Si cladding railing	180	100
Non active glass cladding	80	80
PV module roof	448	448
Solar tracker roof	1041	1041

5.2.3. Step 3: Comparison Analysis after the Application of a Storage System

Along with the analysis explained above, Scenario 2 considered the introduction of a storage system, in order to analyze the ratio cost/benefit of a different alternative of technology implementation in the building. The general goal of optimization is to introduce batteries to increase self-consumption and reduce the *TCE* through storage.

In Scenario 1, the current load profile was compared with Scenario 2's modified load profile with electrical storage implementation.

5.3. Assessment of Optimal Scenarios

In the following section, the two scenarios that characterized the analysis of the study are explained. The difference between Scenario 1 and Scenario 2 is the introduction of batteries that permit the storage of electric energy during the day. This variation affects the value of the parameter *TCE*, explained on Section 5.2.2.

5.3.1. Scenario 1: Current Load Profile

In this scenario, the current load profile of the building was used. A total of 26% of the *DHW* and 59% of the *SH* were generated from the heat pump. *DHW* was produced during the night, from 0 until 6 am. Thus, Scenario 1 represented the current solution implemented in the building.

5.3.2. Scenario 2: Electrical Storage Implementation

In this scenario, a strategy of maximizing self-sufficiency and self-consumption was pursued by considering the presence of batteries. A complementary strategy to optimize the energy demand of the building did not consider the shift of the electric loads during the hours of PV production. Due to the shortage of hourly values of the whole electric loads, it was decided to show only the current configuration with the storage implementation solution.

The proposed approach for the evaluation was aimed at

- optimal sizing of the battery capacity, on the basis of the output values of the self-sufficiency and self-consumption and of the values electricity input and output from the grid;
- cost-benefit analysis of different battery capacities and choice of the optimal size;
- comparison of the optimized scenario with Scenario 1 in terms of *SSR*, *SCR* and cost-effectiveness analysis.

The first step involved the optimal sizing of the battery capacity (kWh) according to the total annual electrical loads of the building (Equation (2)). The battery capacity (*Cbat*) was then established as a percentage of the electrical load, varying from a value of 10% up to a maximum of 100%.

$$C_{bat} = R_i * E_{load} \tag{2}$$

where:

- R_i and E_{load} stand for capacity rate and daily energy consumption (kWh), respectively. Further input values that we considered are the following:
    - charging/discharging efficiency of the battery equal to 0.95,
    - Depth of Discharge (DOD) equal to 0.80.

    From an economic point of view, the cost-benefit analysis was conducted considering the following assumption:

    - use of Lithium-Ion Batteries;
    - fixed cost of about 339 USD/kWh (ca. 387 CHF-August 2018), plus about 33% of the cost for labor, without considering the cost of the inverters (forecast for 2020) [35];
    - life cycle of 13.6 years [34] was rounded off to 14 years for convenience;
    - annual operation and maintenance of the battery system 1.5% of the investment cost [19].

However, these data are constantly evolving. The future trend is in fact a drastic reduction in the installation costs of the batteries (equal to about half the cost for 2030) and an increase in the life cycle of the batteries (equal to about 1/3 more than the current life cycle for 2030). [35]

In order to consider the effects of the battery, the *TCE,* after 20 years, is slightly adapted from the previous one, mentioned in Section 5.2.2 In this case, the *cost of running energy* and the revenues included in *TCE* were split into during the battery lifetime (assumed 14 years, with storage) and after the battery lifetime (for the remaining 6 years, without storage). The Equation (3) expresses the *TCE* calculated as the present value of all the annuity costs and revenues.

$$TCE\ [CHF] = \sum_{t=1}^{14} \frac{(EC_1 + OM)}{(1+i)^t} + \sum_{t=15}^{20} \frac{(EC_2)}{(1+i)^t} + \sum_{t=1}^{20} \frac{MC}{(1+i)^t} - R_{ATT} + EC_{BIPV} + BC \tag{3}$$

where the new parameters represent:

- i: discount rate, assumed 2%/year;
- EC_1: yearly cost of running energy with battery, considering a constant annuity [CHF];
- EC_2: yearly cost of running energy after battery, considering a constant annuity [CHF];
- MC: yearly cost of maintenance for PV plant, assumed 10 CHF/kWpy [CHF];
- EC_{BIPV}: investment cost for BIPV systems. It was assumed as the extra cost to make a similar non-active façade active (rainscreen façade in glass). For the BAPV element, the extra-cost was assumed as the cost of the plant since it did not replace any building material. Included within the extra cost was the BOS (707 CHF/kWp) and the cost of the new inverter substituted after 10 years (312 CHF/kWp) [CHF];
- OM: annual operation and maintenance on batteries as 1.5% of the investment cost;
- R_{ATT} stands for revenues actualized, calculated considering the amount of energy consumed outright and not taken from the grid and the energy injected into the grid and expressed by Equation (4).

$$R_{ATT}[\text{CHF}] = \sum_{t=1}^{14} \frac{R_B * (1-dr)^t}{(1+i)^t} + \sum_{t=15}^{20} \frac{R_{NB} * (1-dr)^t}{(1+i)^t} \quad (4)$$

where:

- dr: degradation rate of the PV, assumed 0.8%/year;
- t: annuity;
- R_B: yearly revenues of battery and PV during the battery lifetime (with storage) [CHF];
- R_{NB}: yearly revenues of PV after the battery lifetime (without storage) [CHF].

6. Analysis and Results

In this section the results concerning the technical-economic assessment, according to the assumptions and reference scenarios described in the previous chapters, are presented and discussed. The goal was to bring to light how the different *MC*s affected the energy and cost-effectiveness of the whole building in different ways. To make the results more clear, the discussion and results were grouped in the thematic analysis as follows:

- energy and cost effectiveness,
- comparison between BAPV and BIPV scenarios,
- business model alternative to self-consumption: *FiT*,
- electrical storage implementation: Scenario 2.

As abovementioned, the outcomes were the results of the method actualized for a specific case study. In Table 4, an overview of the analysis after 20 years, considering Scenario 1, is shown.

Table 4. Main factors after a 20 year analysis. The highlighted merged clusters (*MC*s) are the solutions with the lowest total cost of energy (*TCE*) after 20 years.

Merged Cluster (*MC*)	PV Production kWh/y	EC_{BIPV} CHF	*SCR* %	*SSR* %	Final Yiel kWh/kWp	*TCE* in 20 Years CHF
MC1	49’486	233’713	54	35	554	304’734
MC2	11’465	47’492	100	15	369	224’370
MC3	14’268	69’608	100	18	311	232’180
MC4	36’122	147’877	66	31	512	244’207
MC5	21’853	78’269	81	23	885	212’936
MC6	43’054	184’458	59	33	745	263’955
MC7	30’798	108’702	72	29	687	215’038
MC8	23’619	79’180	84	26	575	203’600
MC9	0	0	0	0	0	240’359
MC10	49’486	233’713	0	0	554	279’109
MC11	23’619	79’180	0	0	575	226’234

It is worthy to note the position of *MC9* (building without PV) and the current status of *MC1*.

6.1. Energy and Cost Effectiveness

The quantification of the energy effectiveness of each *MC* is represented within this paragraph by the *SSR*, namely the amount of energy produced with a renewable source and self-consumed compared with the global amount of energy needed during the year for the building. This value is directly related to the PV energy production value.

However, as emerging from Figure 8, a high value of *SSR* itself did not entail a low value of *TCE* during the solar system lifetime (in this study 20 years; the lifetime value was an approximated value based on the average performance guarantee on 80% of nominal power under standard test conditions of some examples of PV modules of different brands and different technologies. The lifetime of a PV system could be longer). The *MC1*, representing the current state of the solar system installed on the building was the solution with the higher *SSR*. However, in terms of *TCE*, it did not represent the most affordable solution.

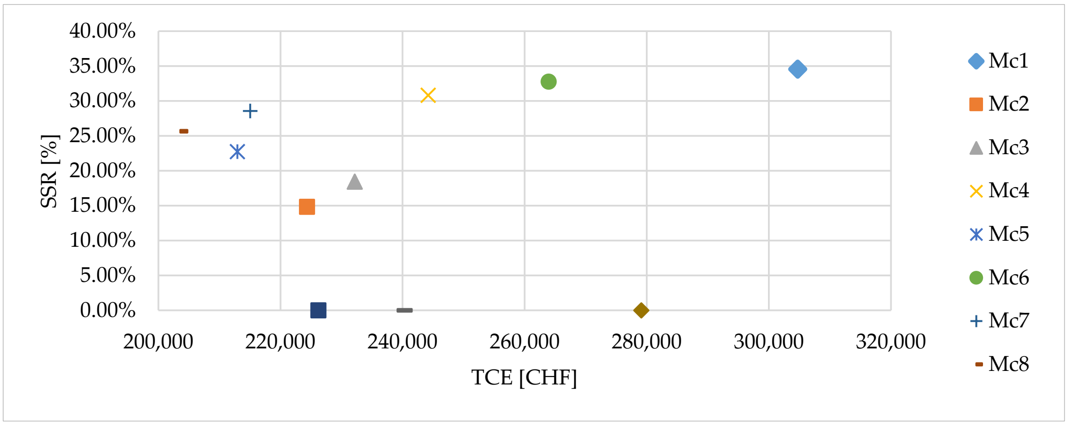

Figure 8. Correlation between self-sufficiency rate (*SSR*) and *TCE* of each *MC*.

Figure 8 represents a comparison between the *SSR* and the total cost in 20 years. Solar solutions without accessories (mainly tracker and balconies), with a high final yield and self-consumption rate were the most effective from an economic point of view, such as *MC7*, *MC8* and *MC5*.

For the *MC9*, *MC10* and *MC11*, the *SSR* was zero because of the total injection of the energy produced into the grid.

6.2. Comparison between BAPV and BIPV Scenarios

Three different *MCs* were compared in order to evaluate the effectiveness of building integrated/added PV systems. The analysis on BAPV (*MC5*) and BIPV (*MC3*) systems showed typical aspects. The BAPV systems had a high value of PV energy production, corresponding with high yearly average revenues and *SSR*, which, despite the extra cost of the system (modules, cables, structures, etc.), was high. Namely, the extra cost used in the calculation corresponded to the entire PV plant cost, since in a BAPV system no building system was replaced. On the other hand, the BIPV system, *MC3*, had a restrained energy production due to the non-optimal exposition, but a lower initial extra-cost as indicated in Table 5.

Table 5. Comparison between BIPV and BAPV.

Merged Cluster (*MC*)	Final Yield kWh/kWp	Extra Cost Norm. (CHF/kWp)	*TCE* (CHF)
MC3 BIPV	311	1’517	232’180
MC5 BAPV	885	3’169	212’936
MC8 BIPV + BAPV	575	1’931	203’560

The most affordable solution in terms of *TCE* was represented by the *MC8*, the solution combining BAPV on the roof and BIPV on facades where the *TCE* was significantly lower. Within this analysis, the *MC5* (only BAPV) was more affordable than other BIPV or mixed BIPV/BAPV solutions.

6.3. Business Model Alternative to Self-Consumption: FiT

The *MC9*, the solution without any PV on the building, was not convenient, according with the *TCE*, in comparison with more than half of the *MC* due to the high price of the energy purchased from the grid. However, in comparison with the current configuration, both in self-consumption (*MC1*) and *FiT* (*MC10*), the *TCE* of the *MC9* was about 20% and 15% lower, respectively.

The MC with *Feed in Tariff* (*MC10* and *MC11*), showed different results. Only *MC11* showed a low value of *TCE*, which represents a good convenience of this business model (Table 6). The energetic benefit in terms of *SSR* was not calculated because the energy produced with PV was all injected into the grid. In spite of the low value of *TCE*, it is necessary to underline that the *FiT* for the energy injected into the grid was considered 0.28 CHF/kW, as paid by the electric society in 2013 for the building, according to Swiss *FiT* skills. Nowadays, it is important to remark that the subsidies are no longer available in most EU countries. Self-consumption also shows feasible scenarios in a non-subsidized situation.

Table 6. *FiT* models.

Merged Cluster (*MC*)	*TCE* CHF
MC9	240’359
MC10	279’109
MC11	226’234

6.4. Electrical Storage Implementation: Scenario 2

In this paragraph, the scenario concerning the storage implementation is discussed. Within the first part, we will provide an insight on the correlation between the batteries’ capacity and the effect on building self-consumption and self-sufficiency, along with the main assumptions adopted for this scenario, with the goal to also define an optimal size of storage.

6.4.1. Battery Implementation. Preliminary Assumptions and Results for *MC1*

The values of both *SCR* and *SSR* and of electric injected and withdrawn energy from the grid were calculated and the output values of the various capacity scenarios were compared, with the goal to assess the effectiveness of battery implementation, as shown in Figures 9 and 10 (for the *MC1*).

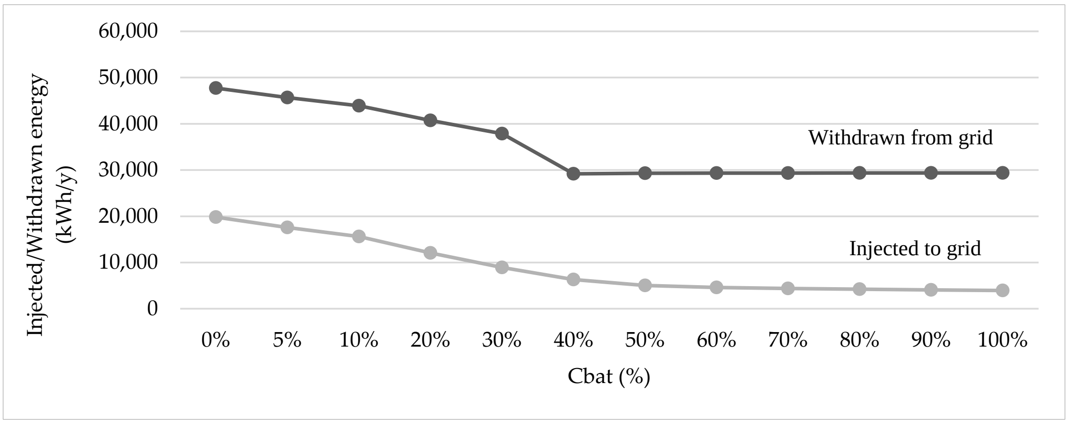

Figure 9. Comparison between various storage capacity and the injected and withdrawn energy from the grid (*MC1*).

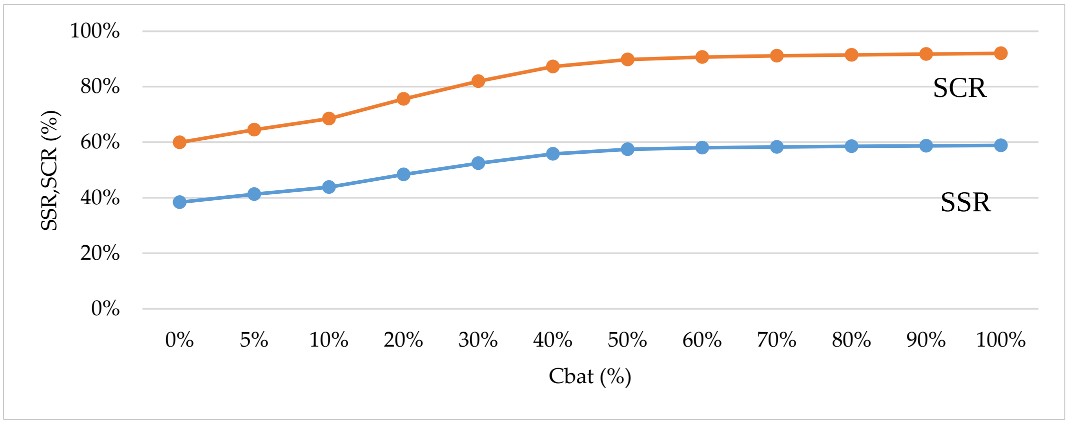

Figure 10. Comparison of the various storage capacity and the *SSR* and self-consumption rate (*SCR*) values (*MC1*).

In Figure 9 the correlation between the storage capacity and the resulting energy injected into the grid and withdrawn is reported. The graph of the *SSR* and *SCR* (Figure 10) shows a non-linearity between the storage capacity and the *SCR* and *SSR*, resulting, instead, in an asymptotic trend towards a limit value as the storage capacity increases. In fact, when a capacity of about 50% of the load profile was reached, further capacity of storage led to negligible increases in the values of *SSR* and *SCR*. Oversized batteries, in fact, could not be fully charged or discharged. As storage capacity increased, the *SCR* varied from a minimum of 54% to a maximum of 90%, while the *SSR* varied from a minimum of 35% to a maximum of 58% (Table 7).

Table 7. Energy taken and injected into the grid at different capacity of the battery for the *MC1*.

Cbat %	*SSR* %	*SCR* %	From Grid kWh/y	To Grid kWh/y
0	35	54	50'638	22'758
10	41	63	46'428	18'099
20	45	71	42'982	14'288
30	50	78	39'937	10'921
40	54	84	37'239	7'937
50	56	87	35'670	6'206
60	57	89	35'082	5'561
70	57	89	34'845	5'305
80	57	90	34'678	5'127
90	58	90	34'526	4'965
100	58	90	34'401	4'833

This means that, for this size of PV system which included all building skin surfaces, the energy produced can be consumed almost totally, with the use of optimal accumulation systems, while self-sufficiency can reach a maximum percentage of about 58%.

Even the values of injection and withdrawal from the grid had an asymptotic profile towards a minimum limit, remaining almost unchanged from the achievement of 50% of storage capacity.

From this point of view, the capacity of the battery which optimized the values of *SSR*, *SCR*, energy input and energy taken from the grid is considered equal to 50% of the total daily electrical load, as already found in other studies in the literature [1,9,10,12,13,18,19,21]. In addition, in this case, the optimization method of the battery capacity took into account the *TCE* value, also becoming a cost-optimal sizing. For each scenario, in fact, Step 2 was developed to compare the different MCs according to the main parameters: PV energy production, final yield, *PbP* and *TCE* after specific years. The final yield stood for the ratio between the energy produced and the nominal power of the PV system (kWh/kWp).

The total costs over 20 years included

- initial investment costs for the PV plant,
- battery installation costs,
- PV revenues for 20 years,
- storage revenues for 14 years.

The results of the analysis are reported in Table 8 that shows the comparative values of *SSR*, *SCR* and *TCE*, considering the period of 20 years calculated for the *MC1*.

Table 8. Different factors at different capacity of the battery for MC1.

Cbat %	*SSR* %	*SCR* %	*TCE* 20 Years CHF
0	35	54	304′734
10	41	63	297′971
20	45	71	294′787
30	50	78	293′473
40	54	84	293′779
50	56	87	299′370
60	57	89	309′547
70	57	89	321′365
80	57	90	333′510
90	58	90	345′725
100	58	90	358′066

In conclusion, the optimal sizing of the battery, from an economic point of view (*TCE*) and for the *MC1*, would be assuming $Cbat = 0.3\ E_{load}$, as Figure 11 shows.

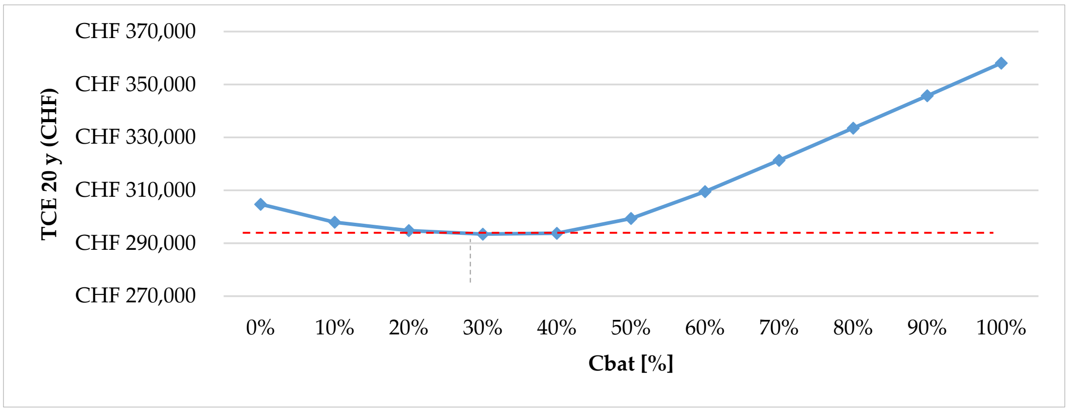

Figure 11. Comparison of the various storage capacity and the *TCE* in 20 years for MC1.

6.4.2. Results of Battery Implementation in the Various Construction Typologies

Within Figure 12 is shown the value of the *TCE* of the *MC* at the change of the capacity of the battery (*Cbat*). The optimal sizing of the battery changed according to the *MC*.

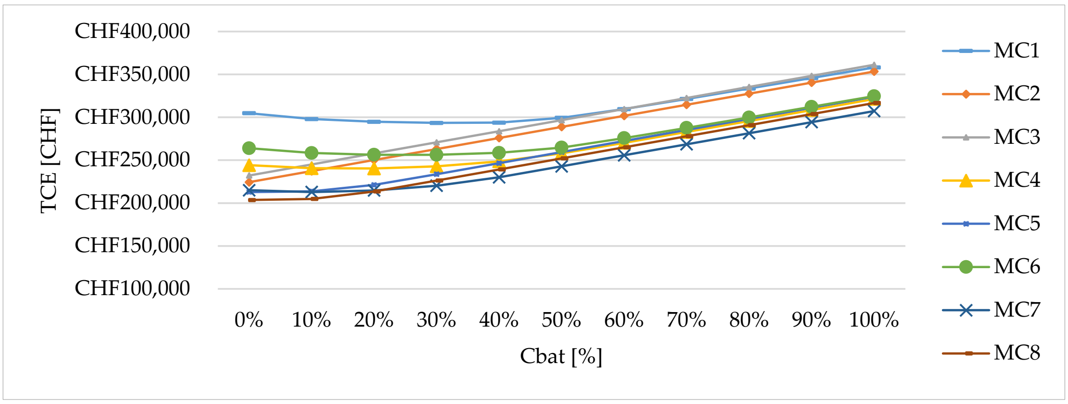

Figure 12. Comparison between the capacity of the storage system and the *TCE* for the *MC*.

The analysis showed that for half of the cases analyzed, a storage system, with a capacity included between 10% and 30%, will be affordable by 2020 (*MC1*, *MC4*, *MC6*, *MC7*). These *MCs* represented the configurations with higher PV production. Within these cases, an improvement of the *SCR* permitted the self-consumption of a higher amount of energy in comparison with the *MC* where the energy production was low. As possible to notice from Figure 13, the *MC1*, *MC4*, *MC6* and *MC7* showed a low *SCR* at low capacity of the storage system, while, considering the high PV production, the *SSR* was the highest compared with the other analyzed *MC*. However, the installation of a storage system, also for the *MC* where batteries reduce the *TCE*, entailed low benefits considering the reduction in *TCE* in 20 years. A further reduction in the batteries' cost would permit the considerable reduction in the *TCE*. Although in these conditions and for this case study a storage system is not recommended, in a few years the batteries could be a solution that permits the reduction in the costs of a PV system.

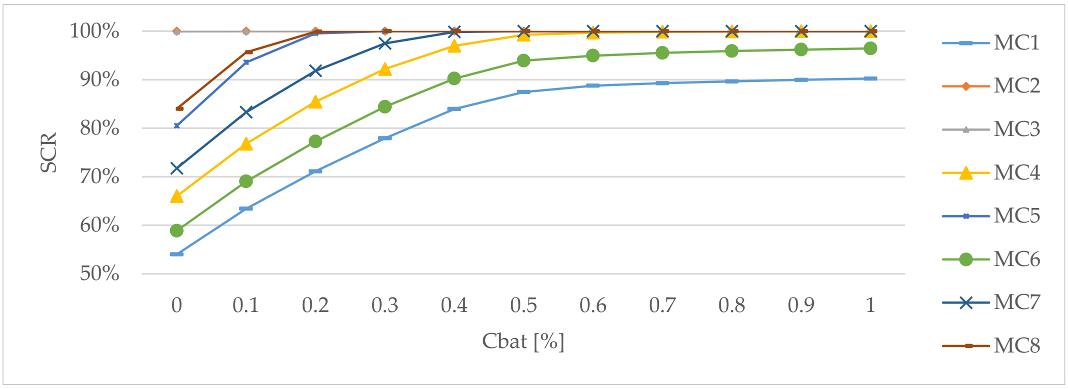

Figure 13. Comparison between the capacity of the storage system and the *SCR* for the *MC*.

The "energy" comparison in terms of *SSR* and *SCR* (Figures 13 and 14) showed that, except for the *MC2* and *MC3*, where the *SCR* was already 100%, in all cases, the battery increased the values of self-sufficiency by about 30% at least, and the values of *SSR* by about 15%, averagely. The maximum percentage increase was in *MC6*, by about 38%, in terms of *SCR*, and by about 21% in terms of *SSR*. In *MC2*, *MC3*, *MC4*, *MC5*, *MC7* and *MC8*, the *SCR* reached the value of 100%.

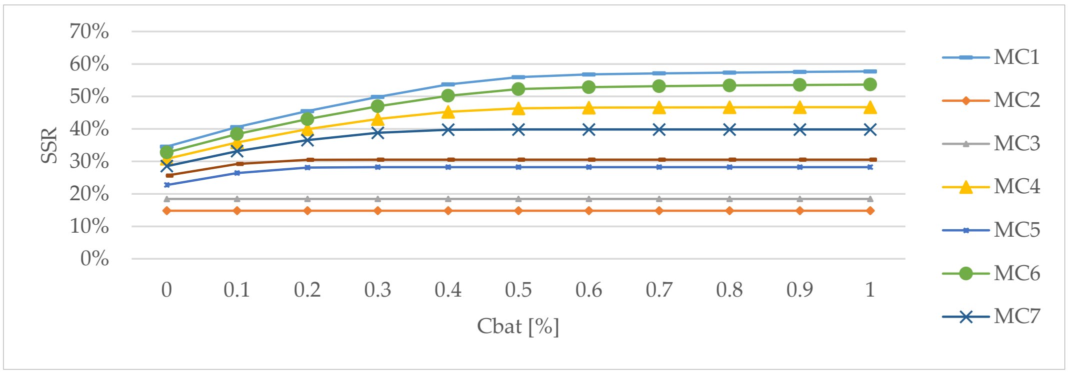

Figure 14. Comparison between the capacity of the storage system and the *SSR* for the *MC*.

7. Conclusions

The paper presented and discussed the results of a comparative analysis on a multifamily building, focusing on alternative scenarios for energy and economic effectiveness of building skin retrofit with PV parts. By assuming real monitored data for the case study, we analyzed and compared, in a life-cycle standpoint, the main construction and energy related design strategies affecting cost and energy effectiveness of the whole building. The main parameters relevant for BIPV skin design, including both construction aspects (orientation, surface typology) and energy strategies (such as self-consumption/sufficiency, storage and combination with BAPV) were highlighted and discussed in dedicated scenarios. This analysis permitted us to define both approaches and conclusions that are scalable for other case studies to correlate in detail the construction/architectural choices, typical of the architectural stage, with the energy and cost results which are crucial in order to establish the intervention feasibility for BIPV systems.

In Scenario 1 (current building load profile without storage) the following conclusions emerged:

- Comparison between BAPV and BIPV: the most affordable solution in term of *TCE* is represented by the *MC8*, the solution combining BAPV on the roof and BIPV on facades, where the high value of final yield in roof is combined with the low extra cost in façade.
- Affordable values of *TCE* can also be reached with only BIPV or BAPV (*MC2* and *MC5*, respectively). It shows, once again, that cost effectiveness is reached through a balanced combination of final yield, investment cost, *SSR*, *SCR* and revenues.
- Energy and cost-effectiveness: The most effective solar solutions from energetic and economic perspective are represented by building skin configurations in which the accessories (mainly trackers and balconies) are not used. This can be explained due to the high investment cost and the low irradiation.
- The cost-effectiveness is higher by about 25% in BAPV solutions *MC5*, *MC7* and *MC8* (on the rooftop and garage) due to the lower investment cost in comparison with the building state of the art (*MC10*). However, it has to be noticed that self-sufficiency is very low due to the limited rooftop area so that the scenario is not relevant from a nearly-zero energy building perspective.
- The solution without any PV surface in the building skin (*MC9*), even though it does not correspond to the target of nearly-zero energy building with on-site energy production, is about 15% more convenient than *MC10* (state of the art) but not convenient in comparison with most of the optimized solutions. This marks the need for optimizing building skin design with costs and building energy needs.
- Solutions with only BIPV surfaces on the façade (*MC2* and *MC3*) are average solutions in terms of cost effectiveness. Although the final yield of these solutions is low, the investment cost (EC_{BIPV}) of the PV installation is also low, therefore supporting their cost convenience.

- Business models with *FiT*: if compared with the self-consumption business model, subsidies with *FiT*, that are no longer available in most EU countries, would support a more convenient scheme (*MC1* vs *MC10*).

In Scenario 2 (including storage) the main conclusions are

- Optimal storage size: a correct sizing of the battery capacity can make significant increases to the values of self-consumption and self-sufficiency, as well as minimizing the values of power flows between the household and the grid.
- However, an excessive increase in the battery capacity corresponds to insignificant increases in both self-consumption and self-sufficiency, and reductions in the values of energy injected and withdrawn from the public grid reaching for both horizontally asymptotic values. In addition, an oversized battery, where a large part of its capacity would remain unused, leads exclusively to an inconvenient increase in installation costs, without energy benefits, as we have seen in the figure that shows the comparison between the capacity of the storage system and the *TCE* for the *MC*.
- Oversized solar systems benefit from the installation of a storage system with a capacity included between 10% and 30%. The installation of a battery permits a considerable increase in the amount of electricity self-consumed reducing the *TCE* (*MC1*, *MC4*, *MC6* and *MC7*). However, the benefits induced by a storage system are not worthwhile within a retrofitting effort. A further reduction in the batteries' cost would permit a considerable reduction in the *TCE*. Although in these conditions and for this case study a storage system is not recommended, in a few years the batteries could be a solution that permits the reduction in the costs of a PV system. No further links with the building construction in comparison with those found within Scenario 1 have been found.

This study provides a practical reference for researchers and professionals in finding the technical approaches and strategies supporting appropriate business models or at least a clearer value proposition project-related to BIPV systems. Outcomes permitted us to show, in a real case study, how BIPV design choices related to the building skin (including different building design options, surface orientations, technologies, price levels, etc.) are closely related to the specific building typology and energy system (HVAC, load profile, etc.) by directly affecting the total life cost, self-consumption/sufficiency and cost-effectiveness. It emerged as the two major components in view of the full decarbonization of the built environment are closely related. Retrofitting existing buildings to increase the energy efficiency is not independent from a transition to energy positive buildings producing electricity, covering their heating and cooling needs and contributing to the grid stability with sustainable, renewable energy technologies as part of the building skin design.

Further development will permit the extension of this methodology to other BIPV case studies, in order to perform a sensitivity analysis of the main parameters that influence the integration of solar systems in building skin and finding other patterns of the main technical approaches supporting appropriate value proposition BIPV systems.

Author Contributions: Conceptualization, P.C., L.C. and P.B.; Methodology, P.C., L.C. and P.B.; Validation, P.C. and L.C.; Formal Analysis, P.C., L.C. and P.B.; Investigation, P.C., L.C. and P.B.; Resources, P.B., F.F. and P.D.B.; Data Curation, P.C., L.C., P.B., F.F. and P.D.B.; Writing—Original Draft Preparation, P.C., L.C. and P.B.; Writing—Review & Editing, P.C., L.C., P.B., F.F. and P.D.B.; Supervision, P.B., F.F. and P.D.B.; Project Administration, P.B. and F.F. All authors have read and agreed to the published version of the manuscript.

Funding: This research did not receive any specific grant from funding agencies in the public, commercial or not-for-profit sectors.

Acknowledgments: We would like to thank Vasco Medici, Lorenzo Nespoli, Gianluca Corbellini and Marco Belliardi for supporting part of the methodology and analysis on storage systems.

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

BIPV	Building Integrated Photovoltaics	
BAPV	Building Attached Photovoltaics	
PV	Photovoltaics	
BOS	Balance of the system	
DHW	Domestic hot water	
SH	Space heating	
TC	Typological Cluster	
MC	Merged Cluster	
FiT	Feed-in Tariff	
DSM	Demand Side management	
DSO	Distribution System Operator	
ADSM	Active Demand Side Management	
SCR	Self-Consumption Rate	[%]
SSR	Self-Sufficiency Rate	[%]
TCE	Total Cost of Energy	[CHF]
EC	Running energy cost during lifetime	[CHF]
EC_{BiPV}	Extra Cost of BIPV in comparison to non-active skin	[CHF]
PbP	Payback Period	[year]
Cbat	Battery capacity	[%]

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