

## Article

# Pathway to Zero-Emission Buildings: Energy and Economic Comparison of Different Demand Coverage by RES for a New Office Building

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**Abstract:** In recent years, energy efficiency and the decarbonization of the building sector have become key goals in Europe. However, substantial efforts are still needed to support the increase in on-site energy generation from renewable energy sources (RES) and to phase-out the use of fossil fuels. Moreover, this challenge must be backed by financial mechanisms provided by Member States. In this context, the aim of this work is to investigate different RES generation layouts for a reference office building in Italy and to determine whether it can achieve the goal of a net zero energy building (net ZEB) or a positive energy building (PEB). Different layouts are analyzed from both energy and economic perspectives through dynamic energy simulation, considering different financial schemes, such as “net metering” (SSP) and “premium tariff” (RID). The results show that the energy performance improves due to the size and the characteristics of the PV system. However, the avoided operating costs due to RID increase linearly, while the economic benefits provided by the SSP scheme encourage an appropriate design of the renewable energy system, avoiding oversizing for economic profitability.

**Keywords:** zero-emission buildings; zero energy buildings; positive energy buildings; net metering scheme; premium tariff; renewable energy sources; building energy modeling; investment costs



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## 1. Introduction

In 2022, the building sector accounted for 30% of the world’s total energy consumption, and it was responsible for 26% of its emissions, with 8% coming from direct sources like natural gas for heating and cooking and 18% coming from electricity use [1]. From 2010 to 2022, global building energy consumption grew by 1.1% annually, reaching 133 EJ. China saw the highest growth at 4.8% per year, followed by India at 1.9%. In contrast, energy use in buildings remained stable in the United States, while it decreased in the European Union (EU) and Japan by 1.3% and 1.1% per year, respectively, due to improvements in energy efficiency [1].

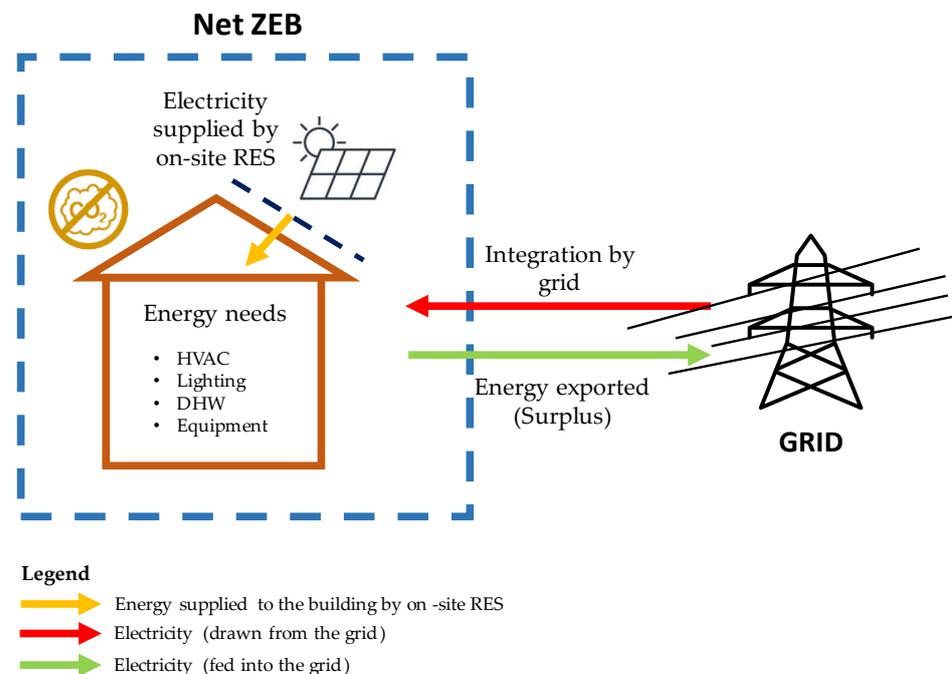
Building energy regulations are crucial for improving energy efficiency and sustainability in the building sector, and their global implementation has expanded significantly in recent years. By 2023, 81 countries had adopted mandatory codes for residential buildings and 77 for non-residential buildings, with an additional 17 codes under development. Despite this progress, only a few codes have been revised to promote net zero emission performance [1]. Looking at the European Union regulatory framework, there is an increasing focus on energy efficiency and sustainability, and new challenges have been offered with the updating of the last EU directives. Specifically, the key target of the Energy Performance of Buildings Directive (EPBD) [2] is the decarbonization of the EU building stock by 2050 and the general increase in its renovation rate, with particular attention to the worst-performing buildings. To support the decarbonization objective, the revised EPBD promotes measures such as:

- The introduction of minimum energy performance standards for non-residential buildings;
- An enhanced target for new constructions to meet zero-emission buildings;
- The increasing adoption of solar technologies in all new buildings and in existing buildings where it is technically and economically feasible to make them solar-ready;
- A gradual phase-out of fossil-fuel-powered boilers, beginning with the end of subsidies for such boilers starting from 1 January 2025;
- The continued expansion of recharging points for electric vehicles in buildings.

In particular, Member States should ensure that all new public buildings are zero-emission buildings (ZEB) from 1 January 2028 and all new other buildings are ZEBs from 1 January 2030, defining a zero-emission building as:

“a building with a very high energy performance [...] requiring zero or a very low amount of energy, producing zero on-site carbon emissions from fossil fuels and producing zero or a very low amount of operational greenhouse gas emissions”.

Figure 1 shows a schematic diagram of a net zero emission building with the components of the building's energy system and balance. The net ZEB is energy-neutral on an annual basis. Imported and exported energy contribute to the final energy balance that is equal to or less than zero.



**Figure 1.** Schematic diagram of a net zero emission building.

To reduce their greenhouse gas (GHG) emissions by at least 55% from 1990 levels by 2030 and to achieve a climate neutrality by 2050, the Energy Efficiency Directive (EED) [3] has made it mandatory to renovate each year at least 3% of the total floor area of heated and/or cooled buildings that are owned by public bodies to be transformed into at least nearly zero energy buildings or zero-emission buildings. Despite the ongoing process of decarbonization, substantial efforts are still needed regarding the building stock. It is responsible for 40% of the final energy consumption in the EU and represents 36% of its energy-related GHG emissions, while 75% of buildings are still energy-inefficient. Natural gas is the main energy source for space heating, accounting for approximately 39% of the energy used for residential space heating, followed by oil at 11% and coal at 3% [2]. Nevertheless, non-residential buildings make up approximately 25% of the total energy consumption in Europe's building stock, with an average energy consumption of 280 kWh/m<sup>2</sup> year, which is at least 40% higher than the energy consumption of residential buildings [4].

To tackle these challenges, the EU is also encouraging energy-efficient building retrofits by adopting various actions. The first one involves reducing the overall dependence on fossil fuels and imports by achieving the goals of the REPowerEU plan; the second one involves the development of the Heat Pump Action Plan to eliminate obstacles and speed up its widespread adoption. The shift from “nearly zero energy buildings” (nZEBs) to “zero-emission buildings” (ZEBs) is a challenging process, made more complex by the lack of a universally accepted definition for the intended purpose [5–7]. In fact, the numerical indexes used to assess building energy performance are not uniform or comparable across Member States, as different methodologies are employed to achieve them [5,7–10].

Pending the transposition of the new European Directives, since 2015, Italian legislation has issued an obligation for new constructions and for all buildings undergoing major renovations to comply with the minimum requirements in line with the nZEB objective. At the end of 2020, Italy’s total nZEB stock comprised about 8000 units, 96% of which were homes and 4% were non-residential buildings; at the end of 2021, the stock was estimated at around 15,000 units [11]. However, in the same year, the total final consumption (TFC) in the building sector represented around 40% of the TFC in Italy, of which residential buildings contributed for 68% and were almost double the consumption of service-sector buildings. The main sources of energy in buildings were natural gas (51%) and electricity (27%), followed by bioenergy and waste (both 14%). Moreover, Italy produces a very small amount of fossil fuels, so it imported 80% of its TES (Total Energy Supply), mostly oil and gas [11]. Consequently, the energy generated on site by renewable energy sources (RES) plays a crucial role and, along with building end-use electrification and the integration of energy storage, represents a key strategy for building decarbonization [12]. For new buildings, the Italian regulation [13,14] has established a coverage with RES equal to 60% of the domestic hot water (DHW) consumption and 60% of the sum of the consumption for DHW and winter and summer air conditioning services, which increases to 65% for new public buildings. At the same time, it promotes the use of energy from RES through several incentives and financial mechanisms. The Energy Services Operator (Gestore dei Servizi Energetici, GSE) oversees managing and paying the incentives on the electricity produced by RES or by the share of the energy produced and reintroduced into the grid. One of them, the so-called “scambio sul posto” (net metering), provides that electricity consumers and producers from renewable plants can benefit from net billing [15,16]. This is based on a specific form of self-consumption, since it allows for the compensation of electricity produced and fed into the grid at a given time with the electricity withdrawn and consumed at different times [15]. This incentive cannot be combined with another Italian financial scheme, the “Ritiro Dedicato” (or premium tariff) [16,17], which is a simplified purchase/resale arrangement that allows RES electricity producers to sell the produced energy to the GSE, which, in turn, resells it. This financial mechanism is an alternative to the national electricity market, and the GSE pays the producers for each electrical kWh produced and fed into the grid [17]. Obviously, other forms of incentives related to the energy retrofitting of buildings are envisaged for private and public owners, such as the so-called Ecobonus, the thermal energy account, and the Energy Regeneration Programme of the Central Public Administration Building (PREPAC), but these mechanisms do not require that the equipment is supplied by renewable energy sources. Moreover, the support of financial subsidies to building decarbonization has also been widely recognized in emerging economies [12].

In 2020, renewables accounted for 20% of gross thermal consumption. Solid biomass (68%) and heat pumps (24%) accounted for most renewables in heating and cooling, while solar thermal covered only about 2%. Overall, renewable thermal energy is more commonly used in the northern and central regions of Italy than in the southern regions [11].

Nevertheless, solar technologies can be advantageous thanks to the availability of the resource and from an economic viewpoint [18,19], although it needs to be paired with a battery energy storage system (BES) due to its intermittent nature. As investigated in [19], if batteries are included, the most efficient configuration is a larger PV system

with the smallest possible battery due to the higher cost and shorter lifespan of the BES compared to PV systems. Also, the authors in [20] evaluated the techno-economic feasibility of the combination of PV + BES by considering different incentive schemes in a residential building and the conditions under which the BES is affordable. It is worth mentioning that thermal energy storage can also be used for optimizing an efficient building integrated PV/thermal plant by adopting a non-dominated genetic algorithm, as was carried out in [21], whose findings highlight the need for proper laws from governmental bodies to subsidize solar-powered plants.

The present study focused on the analysis of the energy–economic performance of a reference office building designed according to the near-ZEB level established by the Italian legislation. After ensuring the mandatory coverage percentage of the energy need by renewable sources, the area of the in situ PV system was varied to investigate the energy balance of the building and the economic profitability of the adopted solutions. The final aim of this work was to investigate how to surpass the nZEB level, managing firstly the net zero energy/zero emission (net ZEB) goals and secondly the positive energy building (PEB) by RES use goals. The EnergyPlus engine was used for the dynamic simulations in order to assess the building energy demand and the specific electricity production of each layout. The economic assessment was based on Authorities reports and regulations, taking into account the existing financial support mechanisms aimed at reducing GHG emissions in line with the objectives of the new EPBD.

## 2. Materials and Methods

### 2.1. Methodology

In a net ZEB, the renewable energy produced on-site must cover at least the total annual amount of the building energy need [22]. If the renewable energy production exceeds the energy consumption of the building, it is possible to reach the positive building objective. The feasibility of these goals must be evaluated both in terms of energy performance and economic aspects.

In this framework, the adopted methodology consisted of two main approaches. The first one involved the analysis of the energy performance, and the second one involved an economic evaluation. The applied method is depicted in the Figure 2.

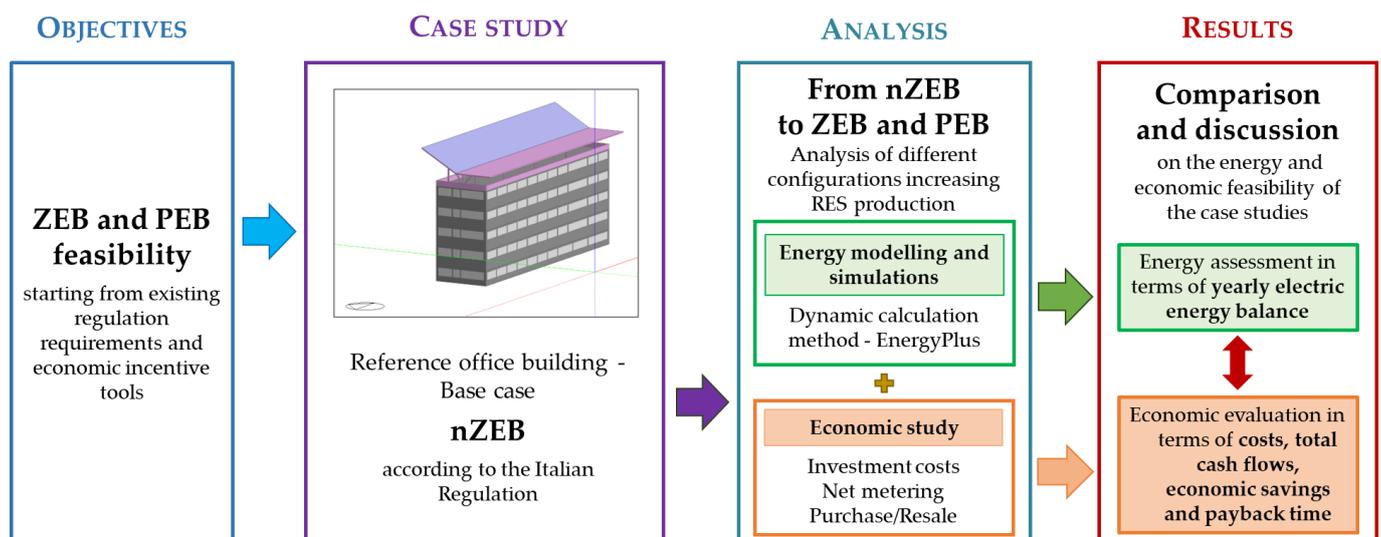


Figure 2. Methodology scheme.

The first step of this work was the definition of a new construction office building located in Rome, as described in detail in Section 2.2. Considered as the base case, it complies with the minimum energy requirements defined by Italian legislation [23] and it achieves the nZEB level. Once the reference building was defined, the analysis considered

additional configurations in which the coverage of the energy demand by using renewable energy production was improved by increasing the PV area. As aforementioned, the aim was to investigate different RES generation layouts and to verify whether they could achieve the net zero energy building (netZEB) or positive energy building (PEB) goals.

Similarly to the authors' previous works [24–26], all the cases were simulated with a dynamic calculation method using the EnergyPlus calculation engine [27], which is a widely used tool for energy performance assessment [28]. In fact, despite the fact that a wide range of computational tools are currently available to analyze and assess building energy demands [29], Energyplus has been widely adopted due to its leading role in dynamic energy simulations [28–30]. The dynamic calculation method enhances the accuracy of results by using hourly and sub-hourly climate data. The energy balance is calculated for each time step, aiming to consider heat transfer phenomena, taking into account the thermal capacity of the structures. Additionally, it is possible to estimate the energy loads and consumption, analyzing thermal and energy requirements tailored to user-specific profiles. Dynamic simulations provide a deeper understanding of the building's behavior, considering not only the temporal variability in properties but also multiple factors such as the characterization of the building envelope and system components, control, and operational profiles, as well as occupancy and usage patterns. These elements contribute to evaluate the building's energy performance in relation to indoor microclimatic conditions and external climatic influences [31].

The simulations covered the one-year reference period, based on a typical meteorological year in the city of Rome, in accordance with the current regulations [32].

As a result of the energy analysis, the annual electrical balance was conducted for each building configuration in terms of the following:

- Self-consumption,
- Battery load,
- Grid integration,
- Surplus of energy.

Subsequently, an economic assessment was carried out for the different configurations. The aim was to evaluate the economic impact of larger renewable energy production and to find out whether it is advantageous to increase the photovoltaic area (and therefore the demand coverage) or not. The investment cost due to the increase in RES use for each layout was quantified, and the economic saving was derived from the resulting energy saving.

To consider the surplus of energy produced by RES in the economic evaluation, two Italian financial schemes were applied for the evaluation: the "net metering scheme (Scambio sul posto)" [15] and the simplified "purchase/resale arrangement (Ritiro dedicato)" [17]. The first one is an incentive mechanism for producers of electricity from renewable sources, such as photovoltaics, that allows them to offset the electricity fed into the grid with the electricity drawn from the grid. This system is particularly advantageous for those who produce electricity intermittently, as in the case of solar plant systems, because it allows the electricity grid to be used as a sort of "virtual storage". In Italy, this mechanism is regulated by the Italian Regulatory Authority for Energy, Networks, and Environment (ARERA) and is managed by the Italian Energy Services Operator (GSE), which handles the incentives for renewable sources.

In summary, it works as follows: When the production plant system (e.g., PV) generates more electricity than the on-site demand, the excess energy is fed into the national electricity grid. On the contrary, when the electricity consumption exceeds the production of the plant, the necessary energy is drawn from the electricity grid. The user pays the bill periodically to the energy provider. At the end of the semester or the year, the GSE balances the energy fed into and drawn from the grid. If the energy fed into was larger than that drawn from the grid, the producer receives a financial contribution for the surplus energy. The net metering contribution ( $V_{net-met}$ ) is calculated as [33]:

$$V_{net-met} = \min [COE; VOE] + FRex \times El_{ex} \quad (1)$$

where:

- COE is the annual cost incurred for the purchase of electricity withdrawn, calculated as the product of the electricity withdrawn annually ( $El_w$ ) and the Italian National Single Price (NSP).
- VOE is the value in EUR of the electricity produced annually and fed into the grid ( $El_i$ ).
- FReX is the annual unit flat rate for net metering, expressed in cEUR/kWh.
- $El_{ex}$  is the electricity annually exchanged with the grid expressed in kWh. It is defined as the minimum between the  $El_w$  and the  $El_i$ .

For the assessment, the Italian NSP was assumed of 0.13 EUR/kWh, as defined in [34] for the year 2021. This reference year was selected as the most reliable of the last few years due to the stable energy price before the Ukrainian war.

The second financial scheme applied to the case study was the simplified “purchase/resale arrangement (Ritiro dedicato)” [17], which is related to small- and medium-sized electricity producers. The GSE purchases the electricity directly from the producers. Contracts can be stipulated by choosing between two tariffs: the hourly zonal market prices or the guaranteed minimum prices per MWh. If the market price exceeds the guaranteed minimum price, the producer receives an annual adjustment [35]. The aim is to support the diffusion of renewable energy production systems in Italy. In this study, the hourly zonal prices per MWh in 2021 were used to calculate the economic profitability of energy production by PV panels. The prices varied according to the Italian zone (Rome is in the south-central zone) and the hours of the day, as established by [35]. The prices changed monthly based on three time slots: F1 from 8:00 to 18:00 on working days; F2 from 7:00 to 8:00 and from 19:00 to 22:00 on working days, and from 7:00 to 22:00 on Saturdays; and F3 from 23:00 to 7:00 on working days and all day on Sundays and holidays (Table 1).

**Table 1.** Hourly zonal market prices by ARERA in EUR/MWh for 2021 [36].

Hourly Bands	Months											
	January	February	March	April	May	June	July	August	September	October	November	December
F1	68.84	59.29	59.74	68.44	70.41	88.7	109.03	117.21	162.41	226.21	251.35	293.72
F2	60.33	57.42	63.01	66.74	69.05	82.48	104.21	115.75	151.42	211.2	220.35	281.66
F3	51.25	39.95	53.09	55.09	57.6	73.58	89.91	99.21	137.61	183.12	194.35	242.02

Therefore, both mechanisms promote the production of energy from renewable sources by assigning it an economic value. This value aims to compensate for investment costs and to reduce energy bills for grid-supplied electricity.

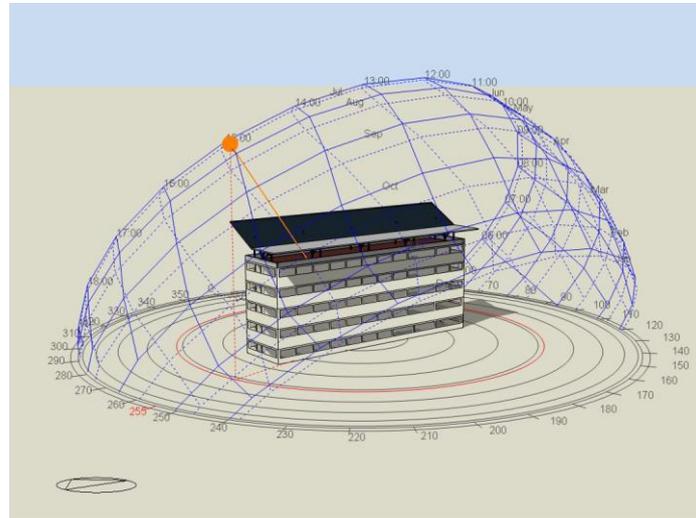
To complete the economic evaluation, the cost of grid integrations ( $C_{int}$ ) was calculated, resulting from the energy cost (as the sum of supply costs, general system charges, excise duties, and VAT, derived by [37]) multiplied for  $El_w$ . The total cash flow (Cf) was obtained as the difference between  $C_{int}$  and  $V_{net-met}$  or RID contribution and represents the annual expenditure incurred by the consumer/producer. Finally, the comparison between the PV investment costs ( $C_{inv}$ ) and the cash flows (Cf) was obtained for each configuration, and they were compared with the reference case, i.e., the 65% demand coverage from RES. Moreover, the simple payback time (SPB) was calculated.

The final step was the comparison between the energy and economic results across the different configurations and the applied financial tools.

## 2.2. The Reference Office Building (Base Case)

The case study (Figure 3) was derived from previous research [24] as a representative Italian office building type located in Rome (Italian climate zone D). In fact, the Italian non-residential building stock comprises approximately 10 million building units, of which nearly 680,500 are office spaces [24]. Offices are becoming one of the most concerning building types due to their increasing energy consumption trends. The architectural

design, geometry, building envelope components, and mechanical systems used in the case study were based on the most common features of office buildings in Italy, as identified by [38,39]. These studies indicate that the predominant structures are made of concrete with externally insulated walls, while air-to-water heat pumps are among the most common air-conditioning systems.



**Figure 3.** Three-dimensional building model of the case study.

Considering this context, the case study was modeled to reflect the typical characteristics of newly constructed office buildings in Italy, aiming to represent a broad range of modern office structures. Moreover, Rome was selected as the study's location, as it is one of the largest cities in Italy, characterized by extensive built-up areas, ongoing urban expansion, and high population density. The analyzed case study, as described subsequently, serves as a starting point for evaluating the feasibility of achieving net zero energy building (Net ZEB) and positive energy building (PEB) targets. It also provides a foundation for generalizing the methodology to the Italian office building stock in alignment with the EU's decarbonization goals and transition to ZEB.

The office building includes offices, open areas and meeting rooms across the five floors of the building, with a net area of 481 m<sup>2</sup> per level.

The façades feature a streamlined design with continuous “ribbon” windows, and the building is oriented so that its longer sides face north and south. The building is characterized by a high-performance building envelope. The thermo-physical parameters and thermal transmittance of the building envelope components were set in accordance with the minimum energy requirements established by Italian legislation [23], ensuring compliance with the transmittance thresholds for external walls (brick masonry with rock wool external insulation), intermediate floor ceilings (traditional insulated brick–cement ceilings + floating floor hosting electrical and water systems), and the roof (flat brick–concrete insulated slab). Double-glazed windows with argon in the cavity and an aluminum frame are provided, with dynamic integrated shading systems tailored to local solar radiation levels to maximize shading as a passive cooling strategy.

The adopted thermal and mechanical systems (DHW and HVAC), as well as lighting and transports systems, are fully electric and contribute to both good energy performance and the achievement of the nZEB level for the reference base case. Heating and cooling are provided by Variable Refrigerant Flow (VRF) systems (one outdoor unit and five indoor units, one per floor), while DHW is supplied by a heat pump. It is possible to find all the building characteristics in detail in reference [24], and they are summarized in Table 2.

**Table 2.** Main characteristics of the building envelope and mechanical system for the reference office building in Rome.

Building Envelope	U-Values [W/m <sup>2</sup> K]
Brick walls (0.07 m rock wool ext. insulation)	0.28
Ground floor with 0.08 m EPS insulation	0.27
Flat roof with 0.06 m EPS insulation	0.25
Double-glazed windows	1.20
Mechanical Systems	Rated Power [kW]/Efficiency (COP or EER) [-]
VRF (heating)	23.74/4.73
VRF (cooling)	21.10/4.83
Heat pump (DHW)	1.9/3.4

As the renewable energy production system, photovoltaic (PV) panels are incorporated into the building design. The photovoltaic panels are installed on the roof, exploiting the presence of a wide canopy that gives the possibility to extend the available area of the installation. Each PV panel has 415 W rated power and 21.3% efficiency. In the reference base case, they are installed in an area of 183 m<sup>2</sup>, with a rated power of 40 kW. In such a way, the renewable energy production reaches 65% of the coverage of the building's energy demand. This value was chosen to ensure the mandatory minimum coverage from renewable energy production required by Italian legislation [13,14], which sets the strictest threshold for public buildings. The PV field is coupled with a storage system able to supply up to 44 kWh, with a round-trip efficiency of 96%. Finally, a 95% efficiency inverter delivers the electricity to the building and/or the electric grid.

### 3. Results

The methodology described in Section 2 was applied to the office building adopted as a case study to determine the annual energy demand.

Starting from the reference office building, where the building envelope, HVAC systems, and occupancy are fixed, the PV area was varied in order to achieve three different levels of energy demand satisfaction through renewable energy production. As mentioned, the base case with a 183 m<sup>2</sup> PV field on the roof ensures 65% of the annual electricity demand, including heating, cooling, lighting, transport, and mechanical ventilation. In addition, two further configurations were studied. The first one achieves full coverage by RES (100%) to meet the goal of net zero energy. In this case, the PV field is 281 m<sup>2</sup> and has a rated power of 60 kW, and the electrical energy production equals the integration from the grid. The second additional configuration uses a larger PV area of 362 m<sup>2</sup> with a rated power of 77 kW to exceed 100% coverage by RES and to investigate the performance of a so-called "positive energy building" (PEB). The three photovoltaic layouts are listed in Table 3.

**Table 3.** Rated power, percentage coverage, and energy target achieved for the three PV layouts considered.

		183 m <sup>2</sup>	281 m <sup>2</sup>	362 m <sup>2</sup>
Rated power	[kW]	40	60	77
Energy demand coverage	[%]	65	100	129
Target achieved		nZEB	ZEB	PEB

The energy generated by the three layouts is depicted in the bar chart in Figure 4, showing the self-consumed energy in blue, the electricity from storage in grey, the integration from the grid in red, and the surplus dispatched to the grid in green. Concerning self-consumption and the battery, it can be noted that the benefit of PV surface increase is significant going from 183 to 281 m<sup>2</sup> where the two percentage contributions increased from 42.5 and 6.7 to 55.3 (+30.1%) and 10 (+49.3%), respectively; the percentage growth from 281 to 362 m<sup>2</sup> was limited to 11.8% for self-consumption (55.3 to 61.8) and 5% for the battery (10 to 10.5). The same trend was achieved but with higher values for the reduction in the electricity integrated from the grid, which ranged from 50.8 to 34.7 (−31.7%) to 27.6 (−20.5%).

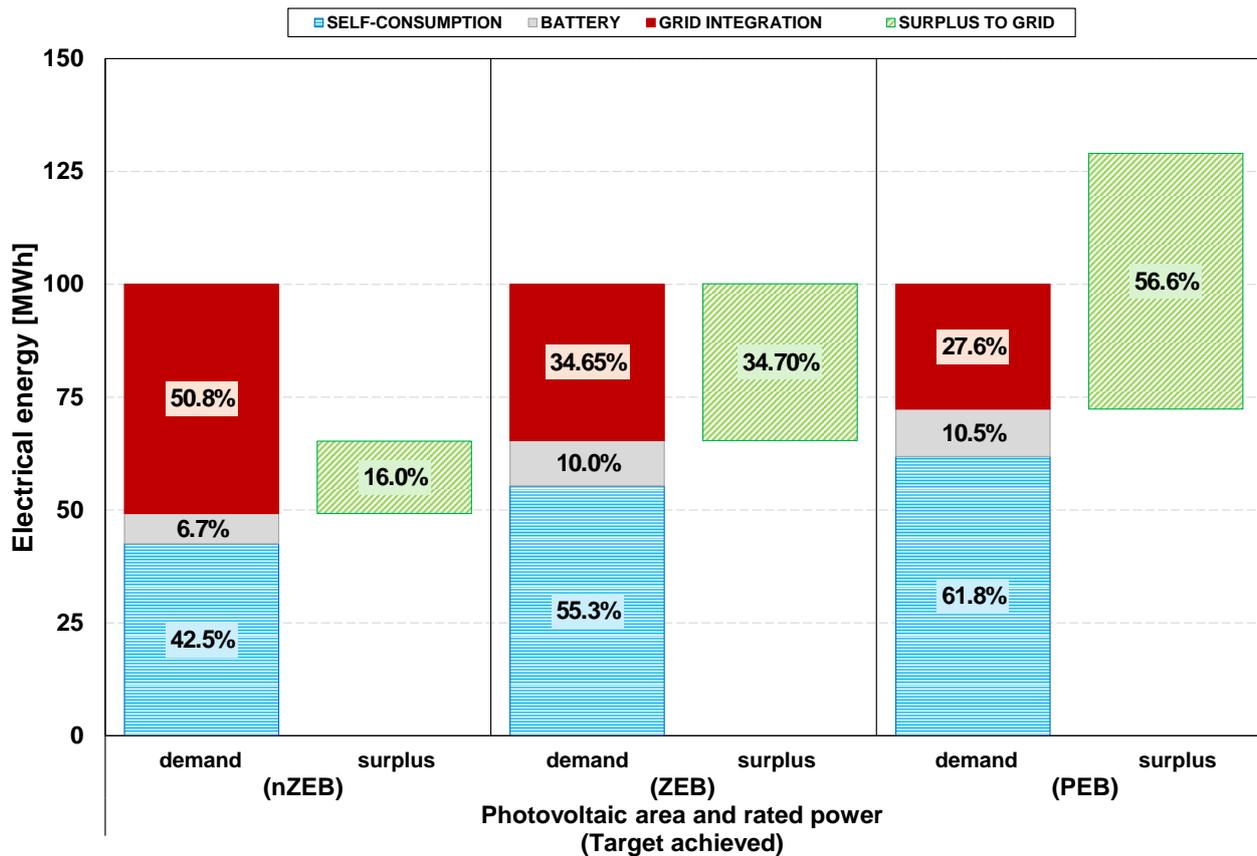


Figure 4. Electrical energy balance for the three generation layouts.

Focusing on the comparison between the energy integrated from grid and surplus generation, the primary energy, net of distribution, and transmission losses, was taken into account. Based on the equivalent electrical efficiency of Italian power plants, set as 0.504 in 2022 by the Italian government agency ISPRA [40], Figure 5 shows the primary energy balance for the three layouts: for each case, there are two bars, where the red one indicates the required primary energy related to the electricity integration from the grid, and the green-hatched one represents the primary energy that is not used by national thermoelectric plants thanks to the surplus generated by the PV field. It should be noted that the primary energy was calculated by dividing the electrical energy used for the integration and the surplus, shown in Figure 4, by the equivalent electrical efficiency of Italian power plants. The chart in Figure 5 clearly indicates the benefit of surplus production for the national grid: the nZEB case still needs 101 MWh of primary energy to fulfil the electricity demand from the grid, but the surplus of 16 MWh of electrical energy fed into the grid involves a potential primary energy saving equal to 32 MWh per year; thus, the actual primary energy demand for the 183 m<sup>2</sup> PV field is 69 MWh, i.e., 101 MWh minus 32 MWh. Concerning the ZEB case, it can be seen that the primary energy demand for the integration equals the primary energy avoided due to the surplus; finally, in the PEB layout, there is a 55 MWh primary energy need and there is a 112 MWh primary energy avoidance, meaning that there is still 57 MWh primary energy consumption avoided from grid, which corresponds to almost 29 MWh of electrical energy to be used by other consumers somewhere else in the national grid.

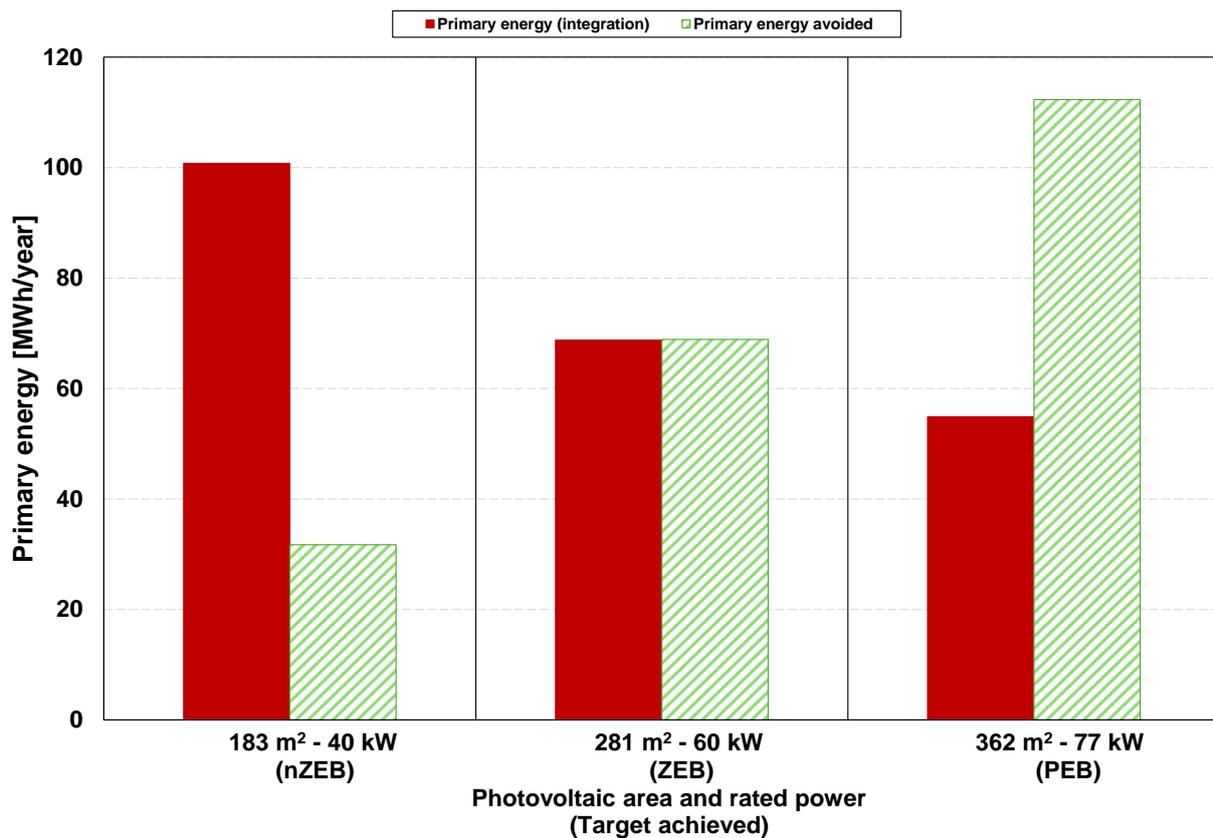


Figure 5. Primary energy comparison between integration from and surplus to the grid.

In addition to the energy analysis, the investment costs related to the three PV fields were investigated. The 183 m<sup>2</sup> area serves as the baseline for the investment, as it represents the minimum energy coverage required for new buildings [13,14]; hence, the additional costs for the 281 m<sup>2</sup> and 362 m<sup>2</sup> cases were evaluated and are shown in Figure 6 with gray vertical bars. Moreover, on the same chart, the actual operating costs are shown for the no-subsidy (black line with circles), SSP (blue line with squares), and RID (green line with triangles) cases. Such operating costs take into account the expenditure for the electricity integrated from the grid minus the earnings from the net metering or purchase/resale, if any. The economic analysis is detailed in Table 4 for the three cases. According to the regulations in force, the baseline investment is mandatory for the nearly ZEB level; therefore, for the ZEB and PEB cases, only the additional investment was considered. It can be noted that for the 362 m<sup>2</sup> (PEB layout) case, the further expense is almost double the 281 m<sup>2</sup> (ZEB layout) case. For the baseline case, the SSP and RID mechanisms allow for annual savings of 31% (EUR 2800) and 18% (EUR 1675) in terms of operating costs, respectively. In the ZEB case, the net metering incentive is notably profitable, reducing operating costs by 94%, compared to the 60% saving achieved with the RID mechanism. Conversely, the major economic benefit for the PEB case is related to the purchase/resale scheme, which generates a positive income over the year, while the advantage of SSP is limited to a 95% saving of the operating costs. Hence, increasing the photovoltaic field beyond the minimum area required by law represents a significant financial effort, resulting in a simple payback period (SPB) of 13.3 years for the ZEB layout (281 m<sup>2</sup>) and 17.2 years for the PEB layout (362 m<sup>2</sup>). However, the financial mechanisms investigated in this study can significantly decrease the payback time to 6.5 for the ZEB case and 8.2 years for the PEB case.

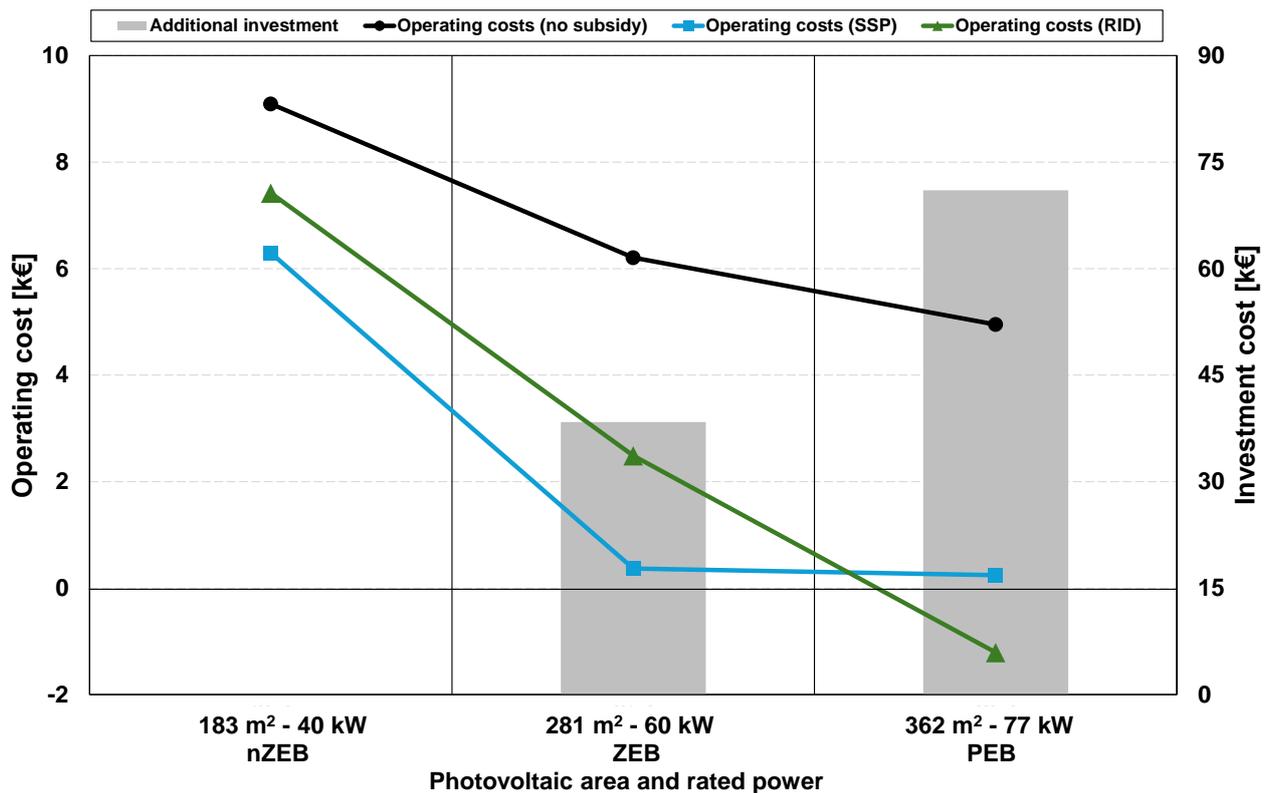


Figure 6. Economic analysis, including investment, cash flow, and SPB.

Table 4. Economic analysis details.

		183 m <sup>2</sup> (Baseline nZEB)	281 m <sup>2</sup> (ZEB)	362 m <sup>2</sup> (PEB)
PV investment cost	[EUR]	144,081	182,481	215,121
Additional investment	[EUR]	-	+38,400	+71,040
<b>NO SUBSIDY</b>				
Operating costs	[EUR]	9092	6205	4950
Simple payback	[yr]	-	13.3	17.2
<b>NET METERING (SSP)</b>				
Operating costs	[EUR]	6292	368	244
Simple payback	[yr]	-	6.5	11.7
<b>PURCHASE/RESALE (RID)</b>				
Operating costs	[EUR]	7417	2485	-1209
Simple payback	[yr]	-	7.8	8.2

#### 4. Discussion

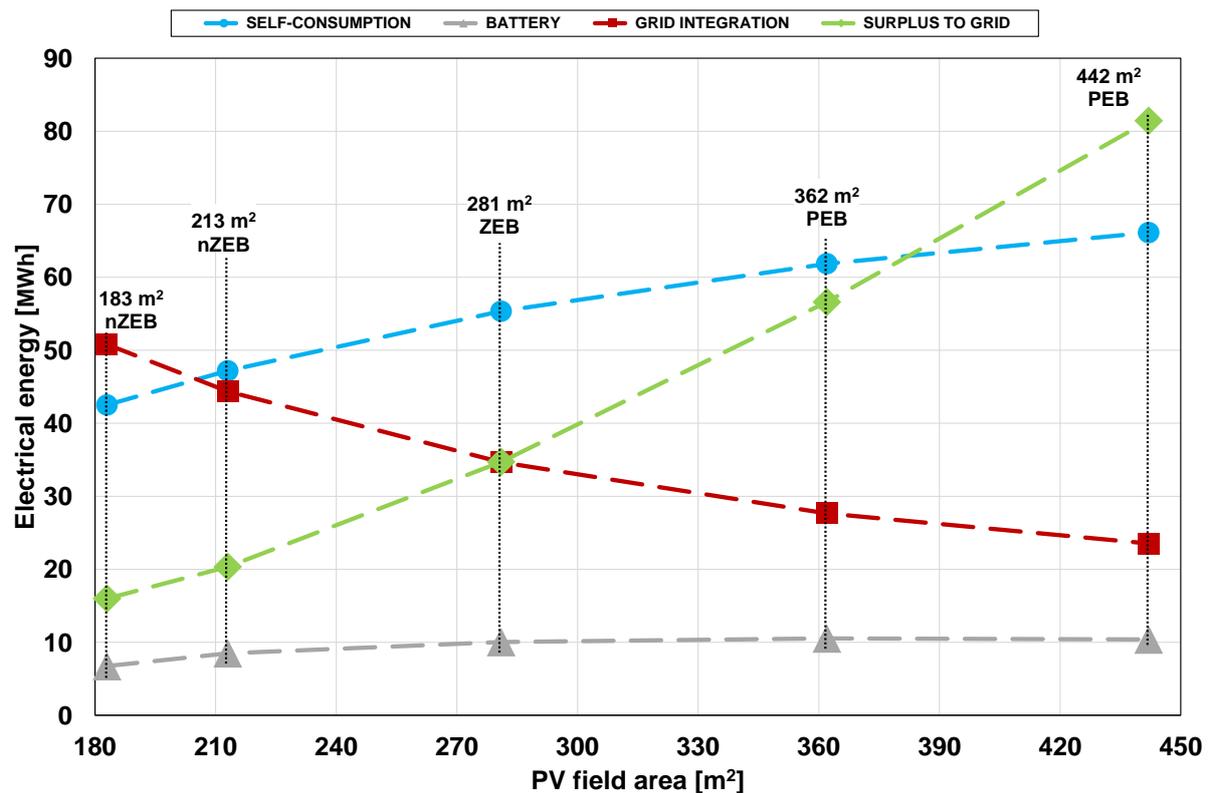
The Results Section highlighted an acceptable simple payback time (SPB) for the ZEB scheme and a larger SPB for the PEB scheme. To establish a more reliable trend, two additional layouts were included in the analysis: a PV field of 213 m<sup>2</sup>, which can ensure an intermediate value between 65 and 100% of the energy demand coverage by RES, and another case of 442 m<sup>2</sup>, i.e., the maximum area of the PV field on the building canopy. Therefore, five layouts were considered for evaluating the energy–economic trends, and the results are listed in Table 5.

Based on the electrical energy balance depicted in Figure 4, the single components of the five layouts are shown in Figure 7, where the trend of each component can be seen. Following the increase in the PV area, from the first admissible nZEB layout (183 m<sup>2</sup>) to the

full-canopy field (442 m<sup>2</sup>), both the self-consumption (blue line) and the grid surplus (green line) results increased but with different ratios. The grid integration (red line) decreased with the increase in the PV area, becoming already lower than the self-consumption amount at 213 m<sup>2</sup> and slightly lower than the surplus for the ZEB case; this condition is the same as that shown in Figure 4, where the values of the grid integration and surplus were 34.67 and 34.72 MWh, respectively. From the first (362 m<sup>2</sup>) to the second studied PEB case (442 m<sup>2</sup>), the last curve crossing occurred when the grid surplus became greater than the self-consumption amount. Finally, the battery trend deserves a separate analysis: between 183 and 213 m<sup>2</sup>, it increased from 6.7 to 8.5 MWh (almost 26%), and from the 213 m<sup>2</sup> case to the ZEB case, it still increased to 10 MWh (+18%). From the ZEB case to smaller-area PEB case (362 m<sup>2</sup>), there was still an increase in the battery use, even if only slightly (+5%), while going from 362 m<sup>2</sup> to the full-canopy layout, it modestly decreased from 10.5 to 10.4 MWh. To explain this trend change, it should be considered that all the studied cases had the same energy demand; thus, an increase in the photovoltaic area does not ensure an actual increase in the exploited produced electricity due to specific temporal demands.

**Table 5.** Rated power, percentage coverage, and energy target achieved for the five PV layouts considered.

		183 m <sup>2</sup>	213 m <sup>2</sup>	281 m <sup>2</sup>	362 m <sup>2</sup>	442 m <sup>2</sup>
Rated power	[kW]	40	45	60	77	94
Energy demand coverage	[%]	65	76	100	129	158
Target achieved		nZEB	nZEB	ZEB	PEB	PEB



**Figure 7.** Electrical energy components for the five studied cases.

Furthermore, the percentage differences in the primary energy and cash flow were calculated with reference to the baseline for each case and are depicted in Figure 8. The results are shown for both support mechanisms, and despite the amount of primary energy avoided being the same for a given PV area, the differences in the operating costs between the SSP and RID cases are meaningful. Although the avoided operating costs due to

the application of RID increased linearly (blue squares), the economic benefits caused by the SSP mechanisms did not (orange circles); the net metering scheme encourages the appropriate design of the renewable energy field whilst avoiding oversizing for economic profitability. This rationale can be appreciated by considering the orange line shown in Figure 8, as it demonstrates a strong increase up to the ZEB layout (281 m<sup>2</sup>), after which the avoided operating costs remain constant. As clearly shown in Figure 8, the two additional layouts of the photovoltaic field (213 and 442 m<sup>2</sup>) were relevant to confirm the trend of profitability arising from the three initial layouts (183, 281, and 362 m<sup>2</sup>) for both the financial mechanisms. Moreover, the different profitability values shown by the two schemes can be explained based on their formulations: the revenue gained from the net metering is strictly related to the minimum between the electricity purchased and the electricity resold (Equation (1)), while the revenue gained from the RID scheme is only a function of the surplus electricity multiplied by the hourly zonal price. Therefore, a large amount of electricity exceeding the building demand only involves an economic benefit for the RID scheme, while it is not considered in the SSP scheme since the surplus becomes higher than the amount of purchased energy; on the other hand, to maximize the profitability of the SSP scheme, the PV field should be designed with the aim of equalizing the two energy components, i.e., the energy purchased and sold.

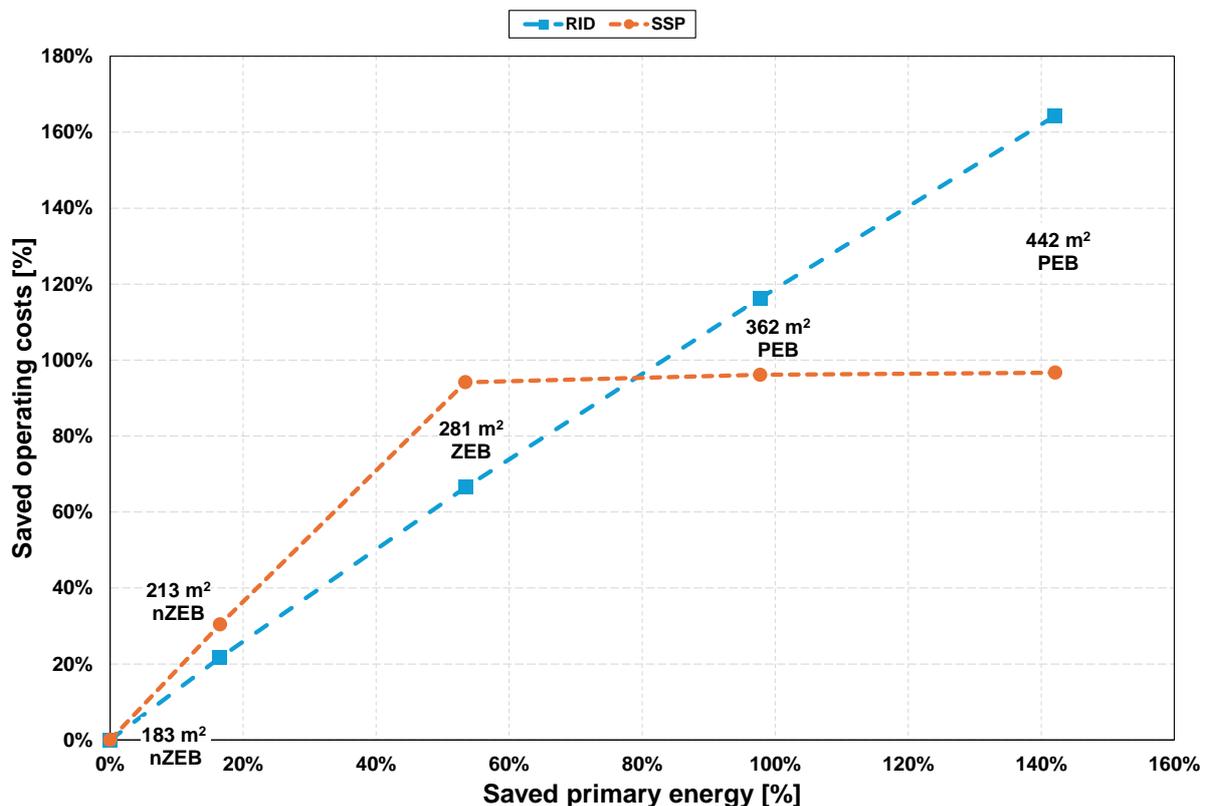


Figure 8. Energy and economic comparison against 65% RES case.

The results clearly highlight that financial mechanisms play a crucial role in the energy transition toward zero-emission buildings, as acknowledged in the EPBD revision, which aims to facilitate more targeted financing tools for the building sector. Without incentives, the high initial investment costs result in longer payback periods, making such projects less appealing to investors. Moreover, with the aim of facilitating the diffusion of RES plants, financial subsidies that consider externalities (e.g., avoided costs of carbon emissions, reduced air pollution) and multiple benefits (e.g., improved indoor thermal comfort, health and well-being, and indoor air and environmental quality) [41] should be considered, decoupling the energy transition from the fluctuation in national energy prices.

## 5. Conclusions

In this work, the energy and economic benefit of some PV layouts supplying an office building were investigated; the studied photovoltaic layouts covered an amount of the building energy demand that ranged from 65% to 158%. The numerical model of the building and its renewable energy plant were simulated with an EnergyPlus-based software package, while the economic assessment considered two fiscal mechanisms supported by the Italian Government. The assumptions of this study were based on the application of the mandatory minimum energy requirements for new constructions in Italy, which also establish the minimum values of transmittance (for building envelope components) and energy efficiency (for HVAC and DHW systems) to ensure compliance with Italian nZEB standards.

The design of the photovoltaic field area should take into account both regulations and energy–economic criteria. In accordance with the Italian law, there is a minimum threshold of the energy demand that must be covered by renewable sources equal to 65% for public buildings. With regard to the energy–economic criteria, the following well-known trade-off should be considered: while increasing the photovoltaic area leads to greater electrical energy production, it also results in higher investment costs. However, the operating costs decrease due to the reduced amount of energy that needs to be integrated.

As expected, the energy benefits rise with the increase in the photovoltaic area: self-consumption and surplus energy fed into the grid both grow, along with the utilization of the battery. However, the latter remains consistently around 10% of the annual electricity demand of the ZEB, even at the maximum PV area. Concerning the integration from the national grid, the amount of energy required diminishes as the photovoltaic area increases. In fact, the integration from the grid represents the largest component of the energy balance in the first case (nZEB) but drops to the third-largest component for the full-canopy PV setup, being surpassed by self-consumption and grid surplus. The present study also showed significant potential in terms of primary energy savings once the annual zero energy building target has been achieved. Indeed, for cases with a PV field area greater than that of the ZEB case, there is additional electricity generation that is not needed by the building, whose demand is already satisfied. Hence, this surplus of electrical energy is dispatched into the grid and contributes to a potential primary energy saving on a national level.

Furthermore, to perform a comprehensive assessment of the running costs, economic subsidies must be taken into account. The two subsidies currently in force in Italy, net metering (“Scambio Sul Posto”, SSP) and purchase/resale (“Ritiro Dedicato”, RID), proved to be advantageous in different situations: for an energy production from RES of up to 100% of the building’s demand, the net metering mechanism provided a larger earning than the RID scheme; with an energy production from RES exceeding 100% of the building’s demand, the purchase/resale scheme was able to decrease the expense for energy requirements, even achieving a positive balance for larger areas of the photovoltaic field. However, both the subsidies analyzed in this work have some aspects worth being considered. From an economic point of view, they reduce energy bills as the energy drawn from the grid can be offset by the energy fed into the grid; focusing on the objective of building stock decarbonization, such financial mechanisms represent supporting tools to promote the use of renewable energy, helping to reduce GHG emissions.

This study also highlighted the importance of financial support mechanisms for promoting energy efficiency measures in building renovations, which might not be economically sustainable otherwise. Additionally, the Energy Performance of Buildings Directive (EPBD) encourages Member States to effectively develop and utilize funding and financial tools that facilitate investment mobilization. In this context, leveraging these instruments is essential to accelerating the decarbonization of the building stock, as mandated by the EPBD. These measures contribute to improving energy performance standards for non-residential buildings and new constructions. Moreover, they support and promote the integration of solar technologies in all new buildings, ensuring they are “solar-ready”, while advancing the phasing-out of fossil fuels in alignment with the EPBD’s objectives. However, because this work focused on an Italian office building, it should be noted that the financial mechanisms applied are

established by the current Italian legislation, and their applicability is thus limited to the studied case. Future in-depth research could expand the analysis to include various building types, such as residential, commercial, and other buildings, to assess the long-term impacts of renewable energy strategies from both energy and economic perspectives. This approach would also enable a deeper understanding of the implications of diverse usage profiles based on building functions and the applicability of incentive schemes under varying conditions. As a result, more specific policy recommendations could be formulated to refine these schemes and increase their effectiveness and relevance in policy contexts.

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## Nomenclature

Cf	Cash flow	[EUR]
C <sub>int</sub>	Cost of energy grid integration	[EUR]
C <sub>inv</sub>	Investment cost	[EUR]
COE	Annual cost of the electricity withdrawn	[EUR]
COP	Coefficient of performance	[-]
EER	Energy efficiency ratio	[-]
El <sub>ex</sub>	Electricity annually exchanged with the grid	[kWh]
El <sub>i</sub>	Electricity fed into the grid	[kWh]
El <sub>w</sub>	Electricity withdrawn from the grid	[kWh]
FR <sub>ex</sub>	Annual flat rate for net metering	[cEUR/kWh]
NSP	National single price	[EUR/kWh]
PE	Primary energy	[kWh]
PB	Simple payback time	years
U	Thermal transmittance	[W/m <sup>2</sup> K]
V <sub>net-met</sub>	Net metering value	[EUR]
VOE	Economic value of the electricity produced annually	[EUR]

## Acronyms and Abbreviations

BEMS	Building Energy Performance Simulation
BES	Battery energy storage systems
DHW	Domestic Hot Water
EPS	Expanded Polystyrene Insulation
HP	Heat Pump
HVAC	Heating, Ventilation and Air Conditioning
nZEB	Nearly Zero Energy Building
Net ZEB	Net Zero Energy Building
PEB	Positive Energy Building
PV	Photovoltaic
RES	Renewable Energy Sources
TES	Total Energy Supply
TFC	Total Final Consumption
VAT	Value Added Tax
VRF	Variable Refrigerant Flow
ZEB	Zero Energy Building

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