E3S Web of Conferences **710**, 06004 (2026) https://doi.org/10.1051/e3sconf/202671006004
54th AiCARR International Congress

Use of photovoltaic/thermal systems, heat pumps and electrical and thermal storage for the energy self-sufficiency of residential buildings

Antonio Gagliano[1], *Giuseppe M.* Tina[1], and *Stefano* Aneli[1*]

[1]Department of Electrical, Electronic and Computer Engineering, University of Catania, Italy

Abstract. Promoting complete decarbonization by relying on renewable sources for energy supply is a key strategy in the building sector. However, the intermittency, non-programmability, and spatial-temporal mismatch characteristics of renewable energy pose challenges to their compatibility with the electricity grid due to the mismatch between energy production and demand. This study compares the performance of generation systems consisting of a heat pump, a photovoltaic or photo-voltaic/thermal system, and electrical and/or thermal storage. In these systems, the charging and discharging phases of the storage systems are managed based on energy production and demand, with the goal of maximizing energy self-sufficiency while limiting exchanges with the grid. Using a reference building located in Sicily (Catania), the annual performance of the different system configurations was simulated using TRNSYS software. The system comprising a photovoltaic system and thermal and electrical storage increases self-consumption from 34.1% to 71.2% and self-sufficiency from 27.9% to 59.9%, compared to systems without storage systems. The system with a photovoltaic/thermal system and dual storage achieves 96.2% self-consumption and 86.9% self-sufficiency. This latter configuration al-lows for the goal of a nearly energy self-sufficient building

Key words: Self-consumption, renewable energy, electrical and thermal storage, zero-energy buildings, system configurations.

1 Introduction

The continuous increase in global average temperatures is causing the intensification of heat waves, degrading the quality of air, land and water availability [1]. The years 2023-25 were the three warmest years on record, with 2024 setting a record where the global average temperature was more than 1.5°C above the pre-industrial average [2] and a further in-crease of 1.5°C is projected by 2050 [3]. One of the main causes of global warming is greenhouse gas emissions, over 36% of which are attributable to the building sector. Of these, approximately 80% comes from thermal needs: heating, cooling, and domestic hot water

* Corresponding author: stefano.aneli@unict.it

production [4]. With this in mind, the European Union has outlined several strategies to promote the transition to a climate-neutral energy system by 2050, aiming for an 80% reduction in annual greenhouse gas emissions compared to current levels. These strategies are primarily based on increasing the use of renewable sources and reducing final energy consumption [5].

Currently, more than two-thirds of the heating needs of buildings are met by combustion systems that could be replaced by heat pumps (HPs), which would reduce CO2 emissions by more than 70% compared to the most efficient condensing gas boilers [6]. The combination of heat pump systems with photovoltaic panels allows the exploit of clean, self-produced electricity, and the reduce of energy needs, managing to reduce costs by 50% and CO2 emissions by up to 73% com-pared to a conventional system [7].

Technological challenges in developing solar heat pump systems are the intermittent nature of renewable energy resources and the time lag that occurs be-tween energy availability and building energy demand [8], which creates the need for energy storage technologies to achieve optimal operation of these systems.

Many studies have investigated heat pump systems powered by PV systems and equipped with energy storage technologies, to increase the self-consumption of solar energy [9, 10]. The combination of heat pumps and thermal storage (TS) has been discussed in the review presented in [11], where analyzing 59 publications, an average performance in-crease of 27% was observed, compared to the system without storage. Research by [12] highlighted that thermal energy storage, which can be classified as a power-to-heat solution, has led to greater profitability than the increase in electric vehicles (EVs) in terms of grid operation. Making the adoption of TS for heat pumps even more cost-effective is the possibility of taking advantage of differentiated electricity tariffs, as well as providing ancillary services to the grid [13].

A further improvement in the performance of solar-powered heat pumps can come from the adoption of hybrid photovoltaic/thermal (PV/T) solar systems, capable of simultaneously producing electrical and thermal energy with higher efficiencies than conventional solar systems [14]. The combination of PV/T systems with heat pumps, known as PV/T-HP, provides better performance than heat pumps powered by solar thermal collectors (ST-HP) [15], although the heat recovered from PV/T systems is slightly lower than that obtained from solar thermal panels, the simultaneous production of electricity allows a significant reduction in the energy requirement for the heat pump [16, 17], obtaining an increase in the COP between 4.55 and 13.25% compared to that of the HP-ST [18]. With the aim of increasing the exploitation of self-produced energy in buildings equipped with solar systems and the simultaneous reduction of the use of the electricity grid, often overloaded by consumption peaks or injection peaks from photovoltaic systems, this study analyses the effectiveness of the use of thermal (TS) and electrical (ES) storage systems in residential buildings equipped with solar systems for on-site energy production and electric heat pump systems to meet the building's thermal needs.

The analyses were conducted through hourly dynamic simulations over the entire calendar year, developing a model in the TRNSYS environment [19] that includes the building, the plant systems, and the users' usage profiles. Particular attention is paid to evaluating the performance of the building-plant system as a whole, with a specific focus on indicators such as self-consumption, energy self-sufficiency, and the limitation of grid exploitation.

2 Methodology, Modeling and case study

This chapter describes in detail the different system configurations investigated, the main indicators used to evaluate and compare the performances, as well as describing in detail the mathematical model used for the calculation and the case study.

2.1 Investigated system configurations

Initially, the performance of the conventional configuration (BASIC) is deter-mined, where the building is simply equipped with a PV system and a HP system. In this configuration, the heating and cooling needs are met by a radiant system powered by an electric air-to-water HP, while the domestic hot water (DHW) needs are met by a HP water heater (HPWH). The electricity required to operate the HPs, along with that required for the building's other electrical devices (lighting and various appliances), will use, if available, the energy produced by the photovoltaic system. The analyses consider the system to be connected to the grid; therefore, if there is a deficit in PV energy production compared to the building's electricity needs, electricity is drawn from the grid; conversely, all unused surplus is fed into the grid.
Subsequently, the effects of using thermal and/or electrical storage are evaluated by adding them to the conventional system (BISTORAGE). Initially, the effects of one storage system at a time (electrical or thermal) are observed through para-metric analyses conducted as the storage capacity varies. The effect on performance is then evaluated by combining both storage systems. It should be kept in mind, however, that the two storage systems allow for the storage of two different forms of energy (thermal and electrical), so specifically developed logics are analysed to maximize the overall performance of the entire system.
Finally, the PV system is replaced by a photovoltaic/thermal solar system (PV/T) capable of simultaneously producing thermal and electrical energy (BIS-TORAGE-PV/T), so as to directly store the thermal energy produced by the solar system in the TS without the need to generate heat via the heat pump, especially during the mid-seasons.
Figure 1 shows the system layouts of the three solutions studied.
To compare the effects of thermal and electric storage, the capacity of both storages must be defined using the same energy scale. Therefore, the volume of the thermal storage tank will be converted into equivalent electrical capacity, calculated as the electrical consumption of a HP to supply the same amount of energy stored in the TS. This is calculated by dividing the maximum thermal capacity of the tank by the nominal COP of the HP:

$$C_{el} = \rho \cdot V \cdot c_S \cdot (T_{MAX} - T_{SET}) / COP \quad (1)$$

Where ρ indicates the density of the fluid (in this study water), V the volume of the storage tank, c_S the specific heat of the fluid, T_{MAX} the maximum temperature that can be reached by the HP (55°C), T_{SET} the temperature of use for heating (35°C).

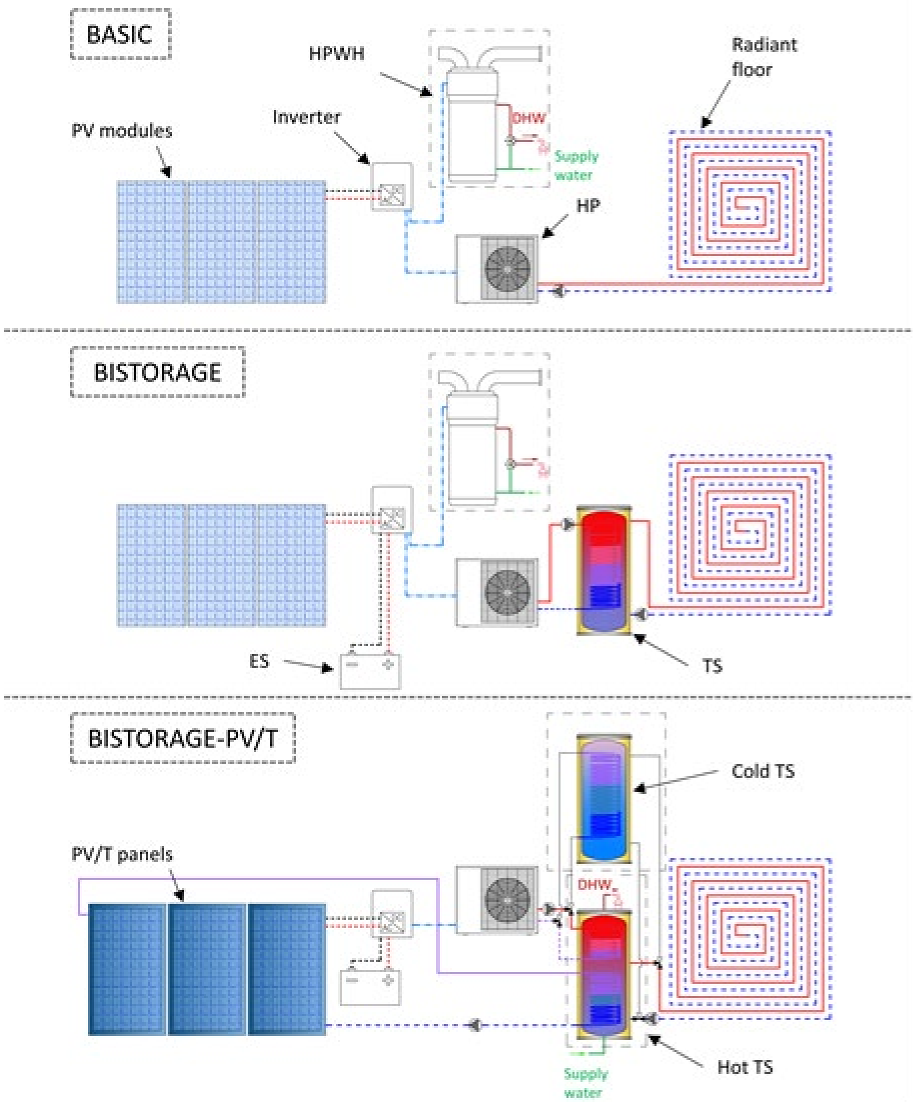

Fig. 1. Investigated plant solutions

2.2 Key metrics for evaluating performance

Characterizing the effectiveness of the above-mentioned energy systems must take into account not only their mere efficiency, but also other significant factors, which have been assessed through a series of performance indicators introduced below.

All indicators were calculated in a post-processing phase using the results obtained from the TRNSYS simulations.

A key parameter, very common in the presence of plants for the production of renewable energy sources, is the demand coverage factor (f_{DEMAND}) defined by the ratio between the energy produced by the solar system (E_{PROD}) and the total load of the building (E_{DEMAND}).

$$f_{DEMAND} = 100 \cdot E_{PROD} / E_{DEMAND} \quad [\%] \qquad (2)$$

However, the demand coverage factor does not differentiate the energy produced and self-consumed (E_{SC}) from that fed into the grid ($E_{EXPORTED}$) or withdrawn from the grid ($E_{DELIVERY}$), therefore other indicators have been defined which allow the self-consumption capacity of the different configurations studied to be identified.
A first parameter is the rate of self-consumed energy (f_{SC}), which indicates how much of the energy produced is self-consumed.:

$$f_{SC} = 100 \cdot E_{SC} / E_{PROD} \quad [\%] \tag{3}$$

Values of f_{SC} close to 100% indicate that almost all of the energy produced is self-consumed, but do not provide information on the share of energy eventually drawn from the grid. Alternatively, the self-sufficiency factor (f_{SS}) indicates the percentage of self-consumed energy compared to the total load of the building.

$$f_{SS} = 100 \cdot E_{SS} / E_{DEMAND} \quad [\%] \tag{4}$$

Values close to 100% of this parameter indicate that almost all of the energy requirement is covered by energy produced on site and, even more importantly, directly self-consumed, without injections or withdrawals from the grid.
Finally, another important indicator is the grid usage coefficient (C_{USAGE}), which indicates the ratio of the building's energy flow to the grid in the presence of solar systems ($E_{EXPORTED}$ + $E_{DELIVERY}$) compared to what would be achieved in the absence of systems and that is equal to the total electricity consumption of the building without solar systems.

$$C_{USAGE} = (E_{EXPORTED} + E_{DELIVERY}) / E_{DEMAND\ (no\ FV)} \quad [\%] \tag{5}$$

This parameter plays a crucial role, because sometimes in buildings equipped with sources for the production of electricity, if not self-consumed, all the energy fed into the grid can disturb the balance of the electricity grid, with the risk of mal-functions and even blackouts.

2.3 Digital Model

The performances of the investigated building-plant systems were assessed using numerical simulations conducted with TRNSYS 17.2 software in dynamic mode, utilizing a time step of 15 minutes. Figure 2 illustrates the digital model of the “BIS-TRORAGE-PV/T” configuration. This generation system comprises panels (type 560), piping, a pump (type 3), and a controller (type 2). The electrical components include an inverter (type 48) and a battery (type 47).

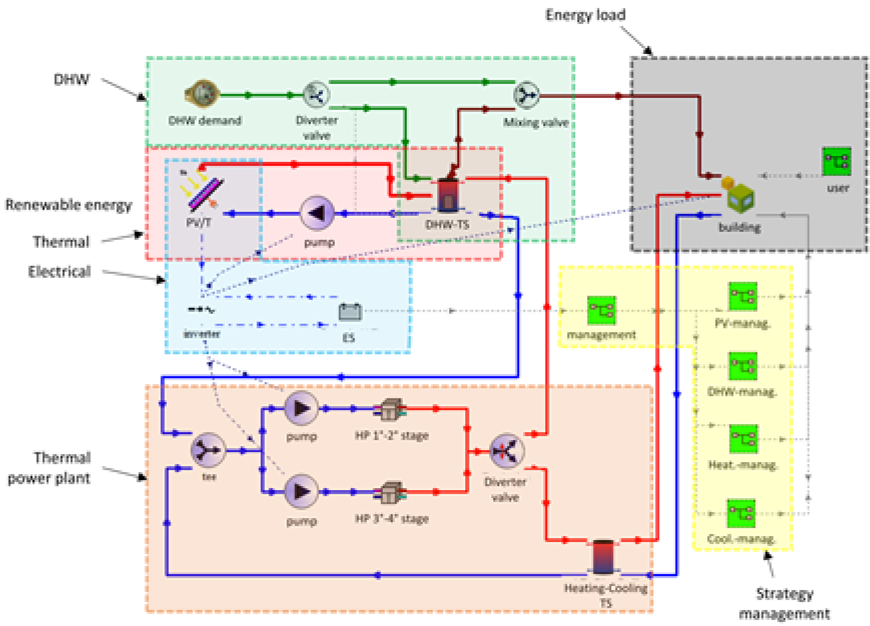

Fig. 2. TRNSYS digital model: BISTORAGE-PV/T configuration

Thermal energy production for heating and cooling is managed by heat pumps, which are simulated by linking two double-stage type 1221 units to create a four-stage system. The distribution system includes circulation pumps, tees, diverters, and a TS tank (type 534). The $TS_{heat\text{-}cool}$ is present in all configurations, and in the configuration without TS it has a volume of only 50 litres, acting as an inertial tank for the HP.
In this setup, the TS is equipped with two heat exchangers: one for the solar circuit and another for potential integration with the HP. In alternative configurations, the tank connects to a HPWH.
The system is managed by controllers that analyse the building's energy requirements, climate conditions, and renewable energy production. They determine the operating procedures for managing the generated energy, including the charging and discharging of the two storage systems, as well as any interactions with the grid.

2.4 System management

The system is designed to maximize self-consumption while minimizing energy exchanges with the grid. This is achieved by optimizing the use of thermal or electrical storage (TS or ES) or by employing their combined use (TS+ES).
In a basic configuration without storage, energy demand can be fully or partially met by solar production (self-consumption), with any production surpluses or deficits compensated for by the electricity grid.
In a system configuration equipped with only an Electric Storage (ES), any surplus PV generation is managed by storing the excess energy in the storage system. This allows the stored energy to be utilised at different times. However, this setup may result in the ES capacity being oversized unnecessarily.

In contrast, a system configuration that employs only a Thermal Storage (TS) can generate thermal energy through a HP. When there is an overproduction of electrical energy, this surplus can be redirected to the HP, allowing it to provide heating or cooling as needed, even when there isn't an immediate thermal load. It's important to note that the energy storage capacity of the TS is limited by the condensation and evaporation temperatures of the HP during the respective heating and cooling periods.
In a system configuration that incorporates both electrical and thermal storage, surplus energy generated by the solar system can be used to charge the thermal tank by activating the HP, allowing thermal energy to be stored in the TS. Therefore, it is crucial to establish management strategies that optimize the capabilities of both storage systems, thereby increasing the self-consumption rate and enhancing the degree of self-sufficiency.
Two strategies are envisaged: the first (storage-strategy) consists of storing thermal energy based on the battery state of charge (SoC), while the second (power-strategy) is based on instantaneous electrical power produced by the PV or PV/T system. "Storage-strategy" involves the gradual switching on of the HP, precisely at 25% of the HP power (1st stage) if the SoC is higher than 40%, 50% of HP power (2nd stage) if the SoC exceeds 50%, and so on up to the maximum HP power if the SoC exceeds 70%. "Power-strategy" involves switching on the HP when the PV-generated electricity exceeds the electricity required, without evaluating the SoC of the ES. The HP is started when the electricity produced by solar plant is greater than the instantaneous electrical load, plus the power required to start the HP. The greater the excess power available, the greater the power available for the HP, provided that a positive electrical energy balance is ensured.

2.5 Case study

The analyses were conducted using a single-family building as a reference, based on climate data from the city of Catania, which has 833 heating degree days and an annual horizontal solar radiation of 1,632 kWh/m².
The building design, defined in IEA Task 44 [20], consists of two floors above ground, each with a net floor area of 70 m². The roof is double-pitched: one side facing south with a surface area of 28.40 m² and a slope of 45°, and the other side facing north with a surface area of 58.80 m² and a slope of 30°.
The ratio of heat-dissipating surface area (S) to heated/cooled volume (V) is 0.59. The walls facing north and south have a gross surface area of 83.80 m², with window areas accounting for approximately 3.6% for the north exposure and 14.3% for the south exposure. The walls facing east and west have a gross surface area of 54.30 m², with window openings comprising 7.6% of the surface area.
The focus of this study is on buildings with strong energy performance, which includes systems for renewable energy production and HP systems. Consequently, the thermal characteristics of the building envelope components are assumed to have good thermal insulation, with a thermal transmittance of 0.286 W/(m²K) for walls, 0.197 W/m²K for roofs, and 1.50 W/m²K for windows.
Artificial lighting is activated when horizontal solar radiation falls below 100 W/m². The energy consumption for lighting is set at 2.5 W/m² of floor area. Additionally, internal heat gains are estimated at 75.0 W of sensible heat and 55.0 W of latent heat per person. According to the Italian standard UNITS11300-2, the consumption of DHW is established at 186 litres per day, following a standard daily profile (EN 15316:2007). The daily electricity requirement is based on common household appliances and lighting, as referenced in [21].
The heating and cooling system includes an electric air-to-water HP with a maximum thermal output of 9.5 kW. The emission system is based on a radiant floor system. The sizing of the HP was determined according to the building's maximum heating needs during winter and

summer. Its performance is based on a commercial model with a heating coefficient of performance (COPH) of 4.59 at an ambient temperature of 7°C and a flow temperature of 30/35°C. Additionally, it has a cooling coefficient of performance (COPC) of 3.79 at an ambient temperature of 35°C and a flow temperature of 23/18°C.
The solar energy plant is installed on a south-facing slope and can be either a PV plant with a peak power output of 4.80 kW or a PV/T plant with a peak power output of 4.75 kW, depending on the evaluated scenario. The PV plant consists of sixteen monocrystalline (c-Si) modules, each with an efficiency of 18.4%, a temperature coefficient of 0.40%, and a power output of 300 W under standard test conditions (STC). In contrast, the PV/T plant is made up of 19 unglazed and uninsulated WISC panels, which have an electrical efficiency of 15.4%, a temperature coefficient of 0.44%, and a peak power output of 250 W. The optical efficiency of these panels is 55.0%, and the heat loss coefficient is 15.76 W/(m²K).
The energy model for the PV/T collectors has been previously validated by [22] using experimental data gathered from a PV/T pilot plant installed at the University of Catania [23].

3 Results

This section presents the results of dynamic simulations conducted using the TRNSYS software for various proposed configurations. Specifically, section 4.1 details the results of the basic configuration, which consists of a PV solar system without any energy storage. Section 4.2 explores the impact of incorporating thermal and electrical storage on the overall system performance. Finally, section 4.3 presents the results obtained by substituting the PV solar system with a PV/T system.

3.1 BASIC Configuration

The analyses were conducted using a single-family building as a reference, based on climate data from the city of Catania, which has 833 heating degree.
The basic configuration of the building includes HP systems and a 4.8 kW PV system, but it does not have energy storage.
To analyse the energy dynamics, we calculated the energy needs, energy pro-duction, and the amount of energy self-consumed, drawn from the grid, or fed back into the grid for two typical days: one in winter (on the left) and one in summer (on the right), as shown in Figure 3.
The electrical power outputs are categorized as follows: heating (red dotted line), cooling (blue dotted line), DHW (green dotted line), consumption of electrical devices (yellow dotted line), total consumption (solid black line), and electricity produced by the solar plant (solid blue line). Additionally, the area under the curves has been shaded to distinguish between the following: energy drawn from the grid (black area), energy fed into the grid (blue area), and energy self-consumed (red area).

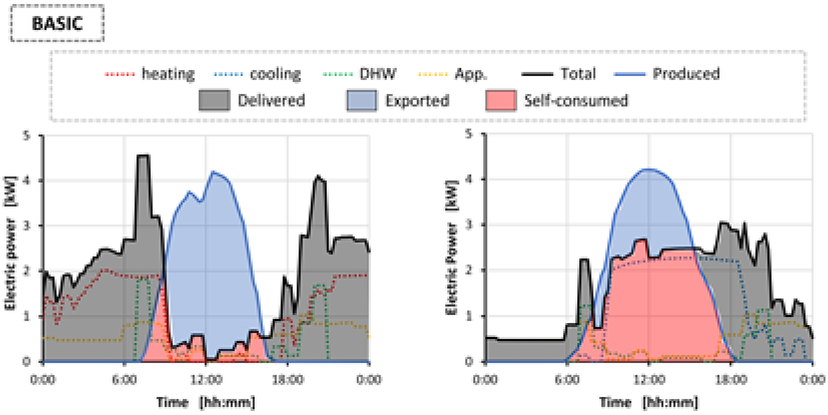

Fig. 3. Daily energy requirement and electricity production for the BASIC configuration

In the BASIC configuration during winter days, there is a significant mismatch between energy demand and the power produced by the photovoltaic system. Energy demand is typically low during the day, when self-consumption can be maximised, while it peaks at other times due to the need for heating and electrical devices, primarily for lighting. Energy demand is very low during the day when self-consumption could be maximized, while it peaks during other hours due to the need for heating and electrical devices, primarily for lighting. As a result, self-consumption remains very low, leading to an imbalance in electricity exchange with the grid, both in terms of energy injected and withdrawn. In contrast, during summer days, self-consumption increases because most of the electricity demand is related to cooling. However, the absence of energy storage solutions leads to considerable overproduction of electricity during the day, while there is still a need to draw electricity from the grid during the evening hours.

Regarding annual results, this configuration has a total electricity requirement of 10,830 kWh/year, or 77.3 kWh/m² (square meter of floor space), while electricity generation from PV is 8,855 kWh/year, with a demand coverage factor (f_{DEMAND}) of 81.8%. Therefore, the building's net energy requirement decreases from 77.3 to 55.8 kWh/m² thanks to PV generation, but the self-consumed energy rate (f_{SC}) is only 34.1%, while the self-sufficiency factor (f_{SS}) is 27.9%. Finally, it's important to note that the grid utilization ratio (C_{USAGE}) is 126%, meaning that the presence of a PV system, while reducing the electricity drawn from the grid, results in an overall in-crease in global energy exchanged with the grid due to the enormous amount of electricity exported resulting from the significant mismatch between energy production and demand. Indeed, in the absence of a PV system, C_{USAGE} is 100%, as all electricity is imported from the grid.

3.2 BISTORAGE Configuration

This section presents the results of a system equipped with two types of energy storage: thermal and electrical. Figure 4 illustrates the results of a parametric analysis, which examines how energy storage capacities affect system performance. The effects of the storage systems are evaluated both individually-using only electrical storage (ES, represented by the green line) and only thermal storage (TS, rep-resented by the blue line) as well as in combination for the two strategies discussed earlier: “storage-strategy” (shown by the black line) and “power-strategy” (indicated by the red line).

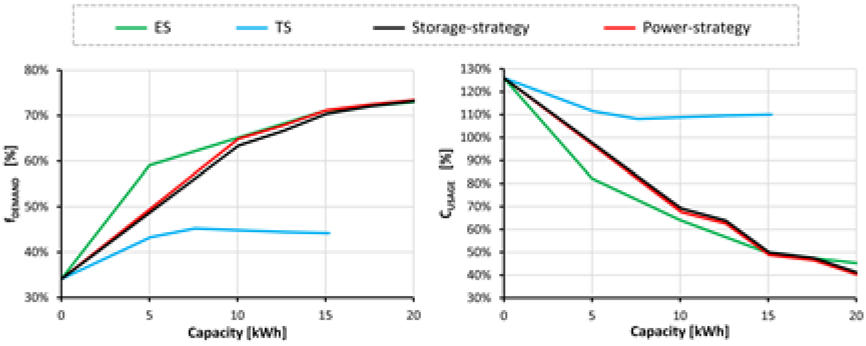

Fig. 4. Effect of storage capacity on self-consumption rate (left) and grid usage (right)

In this study, the storage capacity is related to electrical capacity. In the case of the TS, the equivalent electrical capacity is calculated using Equation 1. For the dual storage system, the capacity is the sum of both the battery and thermal capacities.

While the demand coverage factor remains constant, since the PV production and the building's energy needs do not change (except for negligible storage losses), the primary impact of having storage is on the amount of energy that is self-consumed and the interactions with the grid.

Generally, as the ES capacity increases, the proportion of self-consumed energy (as shown in Figure 4, left) rises significantly up to a capacity of 15 kWh. It in-creases from approximately 34% without storage to over 71%. Beyond this point, the rate of increase continues, but it does so at a much slower pace.

Conversely, using only TS allows for a significant improvement in performance up to approximately 7.5 kWh of capacity (1500 litres of volume), where it reaches 45%, but then fails to further increase the self-consumption rate due to the heat losses.

With dual storage, very similar results are achieved between the two strategies, given the same equivalent electrical capacity, compared to the ES-only scenario. However, it should be noted that, for example, the dual storage with a capacity of 15 kWh is the result of combining a 10 kWh ES and 1000 litres of TS. This is a very important result that, for the same performance, allows for a reduction in ES capacities, which have a significant impact from both an environmental and economic perspective.

The application of due management logic yields similar results, demonstrating a 1% advantage for the approach that manages the power generated by the PV.

Additionally, regarding the grid utilization coefficient, when storage capacity is increased, the grid utilization decreases from 126% in the base configuration to approximately 50% with an equivalent capacity of 15 kWh. Moreover, the TS-only configuration does not contribute to a reduction in the energy flows with the grid.

Figure 5 shows the heat flows for a winter and a summer day, for the 15 kWh storage configuration (10 kWh of ES capacity and 5 kWh of TS capacity). The change in the SoC of the ES refers to the right axis (green line).

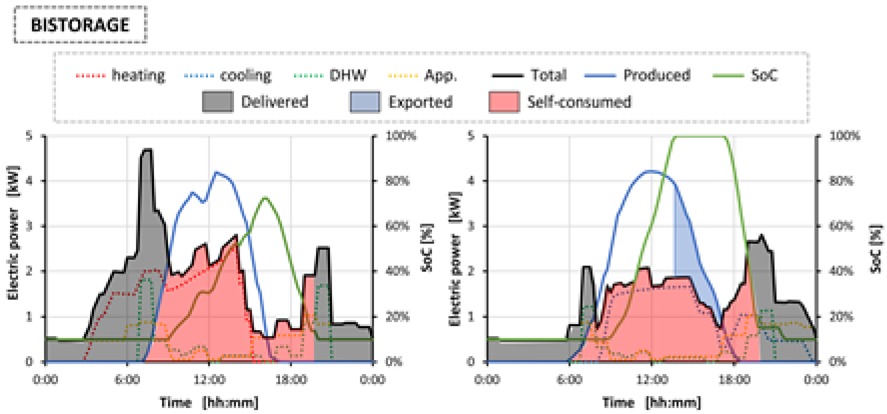

Fig. 5. Daily energy requirement and electricity production for the BISTORAGE configuration

Compared to the BASIC configuration, during winter days, the energy produced by the PV is fully utilized.

Thermal energy demand is roughly in phase with PV production, and excess generation is stored in the ES, which would otherwise be fed into the grid. Even in the summer season, a very high level of self-consumption occurs; however, around 3:00 PM, the ES is fully charged, resulting in the export electricity into the grid, albeit limited.

In terms of annual results, incorporating storage greatly decreases the building's net energy requirement. Specifically, it reduces the energy requirement from 55.8 kWh/m² in the BASIC configuration to 28.6 kWh/m². The f_{SC} improves to 71.2%, compared to just 34.1% without storage. Additionally, the f_{SS} increases from 27.9% to 59.9%. As a result, the CUSAGE is significantly lowered to 48.8%, compared to 126% for the BASIC configuration.

3.3 BISTORAGE-PV/T Configuration

Figure 6 presents the results of simulating the use of hybrid PV/T panels in place of conventional PV. This simulation maintains a dual storage system with a total capacity of 15 kWh, consisting of 10 kWh of ES capacity and 5 kWh of TS capacity.

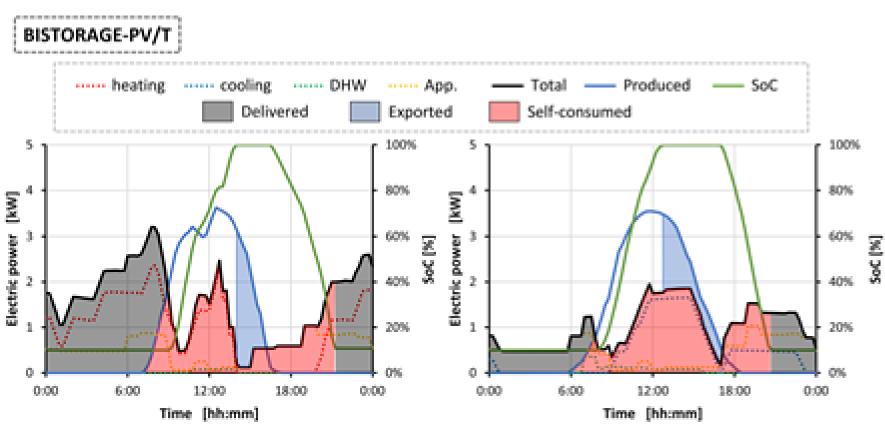

Fig. 6. Daily energy requirement and electricity production for the BISTORAGE-PV/T configuration

The use of hybrid panels significantly reduces peak electricity demand. For instance, during the winter season, the morning peak drops from nearly 5.0 kW with other configurations to approximately 3.0 kW. Additionally, the evening peak, which typically occurs after 11:00 PM, is also shifted, helping to maintain grid stability during one of the most critical periods around sunset. In the summer season, electricity peaks are virtually eliminated, with maximum withdrawals reaching only 1.5 kW. Any limited overproduction of electricity can be more effectively managed by converting it into thermal energy using the HP. Moreover, this configuration offers the potential to provide ancillary or demand response services.
The annual results, obtained by simulating the BISTORAGE-PV/T configuration, are characterised by a significant reduction in the total electrical load to ap-proximately 7,920 kWh/year, that is 56.6 kWh/m^2 (a reduction of approximately 25% compared to the other configurations), thanks to the thermal energy directly supplied by the panels. Even more so, considering the high share of self-consumed energy, the building's net energy requirement drops to only 7.4 kWh/m^2 compared to 28.6 kWh/m^2 for the similar configuration with conventional PV, allowing for 96.2% self-consumption. Similarly, the f_{SS} improve from 27.9% without storage, to 59.9% with conventional PV and double storage, and to 86.9% for the BISTORAGE-PV/T configuration. Finally, CUSAGE stands at around 45%.

4 CONCLUSIONS

This study evaluated the performance of systems that include photovoltaic (PV) systems, photovoltaic/thermal (PV/T) systems, electric heat pumps (HP), and both electrical (ES) and thermal (TS) energy storage systems. Three specific configurations were analysed: the first configuration featured a PV system paired with a HP without any storage (BASIC); the second configuration included both thermal and electrical storage (BISTORAGE); and the third configuration utilized a PV/T instead of a PV system (BISTORAGE-PV-T).
These systems were modelled using the TRNSYS environment, where management strategies were defined to optimize self-consumption and electricity ex-changes with the grid. BASIC configuration, while achieving a demand coverage factor of 81.8%, shows a significant mismatch between demand and energy production, resulting in a self-consumption rate of 34.1%. However, the inclusion of energy storage increases self-consumption to 71.2%. Moreover, replacing conventional PV modules with PV/T panels can elevate self-consumption levels to 96.2%.
Another key benefit of the proposed system is its ability to reduce peak withdrawals from the grid, which can negatively impact the stability of the national electricity grid. This configuration can lower peak demand by nearly 2.0 kW. Addition-ally, it significantly decreases reliance on the electricity grid, reducing reliance from 126% without storage to 45% with storage. This reduction in grid interaction is vital for the energy transition, as it lessens the need for grid modernization and as-sociated investments.
The findings of this study emphasize that achieving decarbonized, net-zero-emission buildings goes beyond merely installing renewable energy systems. To fully meet energy requirements through self-production and self-consumption, it is essential to integrate electrical and thermal storage systems.

References

1. G. Konapala, A.K. Mishra, Y. Wada, M.E. Mann, Climate Change Will Affect Global Water Availability through Compounding Changes in Seasonal Precipitation and Evaporation. Nat. Commun. **11**, 3044 (2020).
2. https://climate.copernicus.eu/copernicus-2025-was-third-hottest-year-record

3. V. Masson-Delmotte, P. Zhai, H.O. Pörtner, et. al.; Summary for Policymakers. In Global Warming of 1.5°C; An IPCC Special Report on Impacts of Global Warming of 1.5°C above Pre-industrial Levels in Context of Strengthening Response to Climate Change, Sustainable Development, and Efforts to Eradicate Poverty; Cambridge University Press: Cambridge, UK, 3-24 (2024).
4. European Commission—Department. Energy. In Focus: Energy Efficiency in Buildings; European Commission: Brussels, Belgium, 2020. Available online: https://commission.europa.eu/news/focus-energy-efficiency-buildings-2020-02-17_en
5. IEA, Are renewable heating options cost-competitive with fossil fuels in the residential sector?, IEA, Paris https://www.iea.org/articles/are-renewable-heating-options-cost-competitive-with-fossil-fuels-in-the-residential-sector, (2021).
6. IEA, Clean Energy Market Monitor: Heat Pumps; IEA Publications: Paris, France, 2024. Available online: https://www.iea.org/reports/clean-energy-market-monitor-march-2024.
7. M.A. Nazari, J. Rungamornrat, L. Prokop, V. Blazek, S. Misak, M. Al-Bahrani, M.H. Ahmadi, An Updated Review on Integration of Solar Photovoltaic Modules and Heat Pumps towards Decarbonization of Buildings. Energy Sustain. Dev. **72**, 230–242 (2023). DOI:10.1016/j.esd.2022.12.018
8. M. Haller, E. Bertram, R. Dott, T. Afjei, F. Ochs, C. Sunliang, K. Siren, and J.C. Hadorn, Models of Sub-Components and Validation for the IEA SHC Task 44 / HPP Annex 38 Part A: Summary, (2013).
9. M. Battaglia, R. Haberl, E. Bamberger, and M. Haller, Increased Self-Consumption and Grid Flexibility of PV and Heat Pump Systems with Thermal and Electrical Storage, Energy Procedia, **135**, 358–66 (2017). DOI:10.1016/j.egypro.2017.09.527
10. M. Pinamonti1 and P. Baggio, Thermal and Electric Storage Optimization for Solar-Assisted Heat Pump Systems in Residential Buildings, Proceedings of the 16th IBPSA Conference Rome, Italy, (2019)
11. C. Ermel, M.V.A. Bianchi, A.P. Cardoso, P.S. Schneider, Thermal Storage Integrated into Air-Source Heat Pumps to Leverage Building Electrification: A Systematic Literature Review. Appl. Therm. Eng. **215**, 118975 (2022). https://doi.org/10.1016/j.applthermaleng.2022.118975
12. G. Oluleye, J. Allison, G. Hawker, N. Kelly, A.D. Hawkes, A Two-Step Optimization Model for Quantifying the Flexibility Potential of Power-to-Heat Systems in Dwellings. Appl. Energy **228**, 215–228 (2018). https://doi.org/10.1016/j.apenergy.2018.06.072
13. G.M. Tina, S. Aneli, A. Gagliano, Technical and Economic Analysis of the Provision of Ancillary Services through the Flexibility of HVAC System in Shopping Centers. Energy **258**, 124860 (2022). https://doi.org/10.1016/j.energy.2022.124860
14. A. Gagliano, G.M. Tina, S. Aneli, S. Nižetić, Comparative Assessments of the Performances of PV/T and Conventional Solar Plants. J. Clean. Prod. **219**, 304–315 (2019). https://doi.org/10.1016/j.jclepro.2019.02.038
15. J. Yao, H. Xu, Y. Dai, M. Huang, Performance Analysis of Solar Assisted Heat Pump Coupled with Build-in PCM Heat Storage Based on PV/T Panel. Sol. Energy **197**, 279–291 (2020). DOI:10.1016/j.solener.2020.01.002
16. K. Sezen, A. Gungor, Comparison of Solar Assisted Heat Pump Systems for Heating Residences: A Review. Sol. Energy **249**, 424–445 (2023). https://doi.org/10.1016/j.solener.2022.11.051

17. B. Chhugani, P. Pärisch, S. Helmling, F. Giovannetti, Comparison of PVT—Heat Pump Systems with Reference Systems for the Energy Supply of a Single-Family House. Sol. Energy Adv. **3**, 100031 (2023). https://doi.org/10.1016/j.seja.2022.100031
18. H.U. Choi, K.H. Choi, Numerical Study on the Performance of a Solar-Assisted Heat Pump Coupled with a Photovoltaic-Thermal Air Heater. Energy **285**, 129480 (2023). DOI:10.1016/j.energy.2023.129480
19. S.A. Klein, W.A. Beckman, et al., TRNSYS - A Transient Simulation Program. ASHRAE 82, 1976.
20. R. Dott, M.Y. Haller, J. Ruschenburg, F. Ochs, J. Bony, The Reference Framework for System Simulations of the IEA SHC Task 44/HPP Annex 38 Part B: Buildings and Space Heat Load; International Energy Agency: Paris, France, 2013.
21. A. Gagliano, F. Nocera, G.M. Tina, Performances and Economic Analysis of Small Photovoltaic Electricity Energy Storage System for Residential Applications. Energy Environ. **31**, 155–175 (2020).
22. A. Gagliano, G.M. Tina, S. Aneli, D. Chemisana, Analysis of the Performances of a Building-Integrated PV/Thermal System. J. Clean. Prod. **320**, 128876 (2021). https://doi.org/10.1016/j.jclepro.2021.128876
23. A. Gagliano, G.M Tina, F. Nocera, A.D. Grasso, S. Aneli, Description and Performance Analysis of a Flexible Photovoltaic/Thermal (PV/T) Solar System. Renew. Energy **137**, 144-156 (2019). https://doi.org/10.1016/j.renene.2018.04.057