The Role of Thermal Storage in Distributed Air-Conditioning Plants: Energy and Environmental Analysis

Piero Bevilacqua*, Stefania Perrella, Daniela Cirone, Roberto Bruno and Natale Arcuri

University of Calabria, 87036 Rende, Italy

Abstract: Energy efficiency is becoming a crucial target in the construction of a decarbonized society to guarantee sustainable development and tackle climate change issues. The building sector is one of the major players being responsible for a huge amount of primary energy, mostly related to heating and cooling services. Aside from intervening on the building envelope, intending to reduce energy demand, it is of fundamental importance to consider appropriate air-conditioning systems that can easily integrate renewable sources and rationalize energy use. Heat pumps are an appealing solution because of the renewable energy available in the external sources and because of the possibility to drive them with PV systems. Solar assisted heat pumps have therefore become a promising solution for energy efficiency in buildings, allowing lower primary energy demands and generating lower CO_2 emissions. The ulterior integration of thermal storage in the systems allows for a further improvement of energy efficiency. This paper investigates the achievable energy savings after interventions of energy efficiency on a building aggregate composed of four buildings. In particular, two different scenarios of improvement of the HVAC system substituting the existing plant with PV-assisted heat pumps are considered. The performances obtained with the use of single-heat pumps and a centralized one with thermal storage are investigated employing dynamic simulations conducted in the TRNSYS environment.

Key Words: TRNSYS simulation, Thermal storage, Centralized plant, Energy efficiency, CO_2 emissions reduction.

1. INTRODUCTION

The need to decarbonize the building sector, which is believed to account for about 40% of primary energy needs in Europe, is pushing toward ambitious targets of energy efficiency in buildings constructions and operation [1], [2]. On one hand, the developed awareness of the importance of the building envelope in providing repair from the outdoor severe climatic conditions has propelled the research and implementation of innovative active [3]–[10] and passive solutions [11]–[13]. Aside from the conspicuous use of thermal insulation, interesting solutions can be represented by the use of green roofs [14]–[26], solar walls [27]–[33], PCM incorporated in building elements [34]–[38]. Nevertheless, the HVAC plant plays an equally important role in determining energy performances. Recent advancements both in research and field applications are nowadays almost compelling the use of heat pumps as efficient, reliable, and clean generators for the annual air-conditioning of buildings [39]. Furthermore, combining solar source with heat pumps allows a double benefit: on the one hand, the use of solar energy is maximized, and on the other, the efficiency of the heat pump is increased, simultaneously optimizing and rationalizing the use of renewable sources [40]–[47].

Several authors have studied and analyzed both experimentally and analytically, the performance of helium-assisted heat pumps configured in direct series operation in relation to the type and characteristics of the components of the two subsets, cataloging their performance according to the offered service (domestic hot water, heating) and to the reference climate [48]–[51]. Similarly, other authors have investigated the performance of indirect systems [52]–[54], focusing on the effects and role of thermal storage on the performance of subsets [55]–[57]. Raghad S. Kamel *et al.* have provided a systematic review in which they first analyze and catalog the solar systems of the literature and then carry out a detailed bibliographic analysis of all the systems that integrate the use of the heat pump with solar collectors. The systems taken into consideration have been analyzed according to the type of heat pump used, the type of solar panel used, and the configuration adopted (in parallel, direct, and indirect series) [58]. Pinamonti *et al.* studied the integration of a water-water heat pump with a solar system equipped with a short-term and long-term storage tank through a dynamic simulation performed using TRNSYS. Long-term storage allowed to store the excess of solar energy collected by solar collectors in summer, and then use it to provide space heating during winter. This system allowed the solar fraction to increase by five percentage points [59]. Cagri Kutlu *et al.* analyzed the integration of an helio-assisted heat pump for the production of DHW with a

*Address correspondence to this author at the University of Calabria, 87036 Rende, Italy; Email: piero.bevilacqua@unical.it

thermal storage tank made with phase change material. The configuration has been studied by a transient model. The results showed that it is possible to obtain energy savings of about 12% [60].

The energy performances of a smart air-conditioning plant installed at the University of Calabria, made of a heat pump and a storage tank were investigated as an alternative electric storage system because the plant was assisted by a 4kWp PV generator [61]. In such a more complex HVAC plant design, the use of thermal storage is becoming an interesting technical solution as it is capable of providing several benefits [62]–[66]. The heat pump used with thermal energy storage is believed to shift their energy consumption, providing the opportunity to align to price signals to reduce consumer costs, especially in single-family houses belonging to an energy community. Power-to-heat technology such as heat pumps and thermal energy storage has been shown to both decarbonize heat and enable the cost-effective integration of more renewable electricity into the grid.

The impact of different heat storage sizes and heat pump powers on cost savings and shifting potential, when variable electricity prices based on the electricity market are applied, was analyzed in the Luxembourgish context [67]. The author aimed to demonstrate and emphasize the importance of the use of thermal storage, especially combined with renewable sources, to rationalize the use of energy for air-conditioning services of buildings. Recently, researchers are also focusing on developing accurate and reliable optimization algorithms to derive optimal operation schedules for heat pump-based grid-edge technology [68]. The impact of user demand patterns and load shifting scenarios on the volume of energy storage required for a heat-pump installation was analyzed in [69]. The authors used monitored data from several family homes to conduct simulations and found that the level of service for the householder is sensitive to the patterns of consumption, the thermal energy storage volume, and the electricity tariff.

A residential building in Stuttgart, equipped with a hybrid heat pump, a thermal energy storage unit, and a gas boiler as an integration system was investigated to determine the influence of electricity tariffs on the energy flexibility of the building and associated energy costs. The demand response programs led to higher utilization of thermal energy storage along with increased boiler consumption, by up to 17.1% and 12.1%, respectively, in case of maximum demand response intensity [70]. The capability of a cost-optimal control strategy to activate demand response actions in a building equipped with an air-source heat pump coupled with a water thermal storage system was assessed by comparing the results of a reference scenario with no demand response actions and several demand response scenarios [71]. The results illustrated the effectiveness of thermal energy storage for reducing the total system operational cost and its seasonal primary energy consumption, both with and without demand response actions.

This study presents the result of energy simulation performed on a real building aggregate made of four terraced houses in order to highlight the importance of the HCAV system in reaching goals of energy-saving and carbon emission reductions. The building aggregate is supposed to go through energy renovation actions, implemented only on the air-conditioning plant demonstrating the undoubted advantages of the use of heat pump and thermal storage and the importance of integration with renewable energy sources such as photovoltaic systems.

2.1. Case Study Building

The chosen case study is an existing building aggregate made of four terraced houses, being part of a bigger complex made of four rows of such constructions. It was chosen for the simulation since it represents a typical example of popular construction built between 1976 and 1980, that shows very poor energy performances, and very prone to be subject to energy renovation interventions. The two-story buildings have a gross surface of about 60 m^2 per floor and a floor height of 3 m as shown in Figure **1**.

Since the paper aims to investigate the interventions regarding the air-conditioning plant and the effect on the energy efficiency of the building, the envelope was modeled properly considering a thermal insulation layer to reach the minimum standard imposed by current Italian legislation. The main thermal properties of the layers composing the different building components are reported in Table **1** to Table **3**.

For the aim of the study, the building is supposedly located in Crotone (Italy) characterized by hot and dry summers, classified as subtype "Csa" (Mediterranean Climate) in the Köppen Climate Classification. Simulation was performed in TRNSYS 18 environment. For the aim of the study, each building was considered as a single thermal zone. DHW needs were not considered to focus only on the energy requirements for heating and cooling.

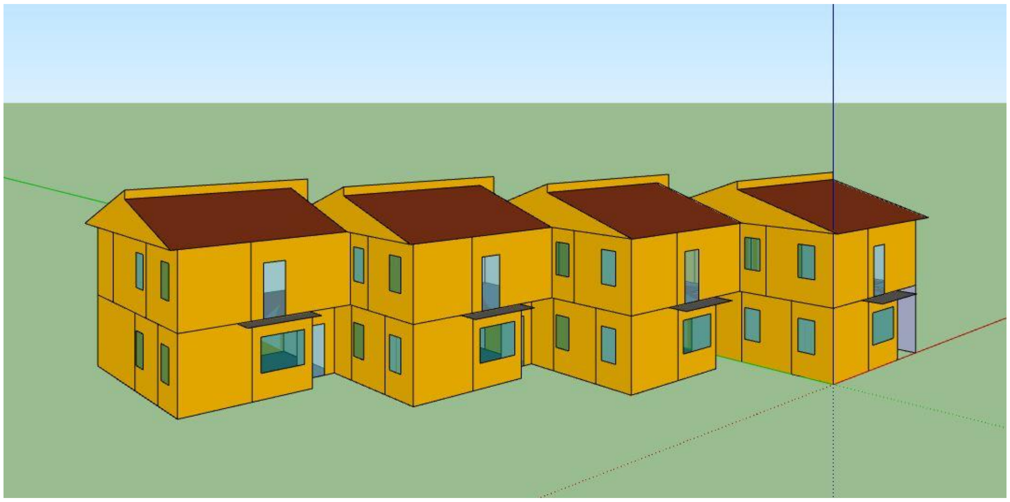

Figure 1: Geometrical model of the case study building.

Table 1: Thermal Properties of the External Wall Layers

Material	Thickness [cm]	Density [kg/m^3]	Specific Heat [J/kg K]	Thermal Conductivity [W/mK]
Plasterboard	2	1800	1000	0.9
Hollow bricks	8	1800	1000	0.4
Air gap	10	-	-	-
Hollow bricks	12	1800	1000	0.386
Plasterboard	2	1800	1000	0.9
Structural bonding	0.5	1400	1000	0.538
EPS Insulation	6	15	1260	0.031
Skim coat skim coat with reinforcement	2	1400	1000	0.538

Table 2: Thermal Properties of the External Roof Layers

Material	Thickness [cm]	Density [kg/m^3]	Specific Heat [J/kg K]	Thermal Conductivity [W/mK]
Plasterboard	2	1800	1000	0.9
Hollow bricks and concrete slab	24	1800	1860	0.858
Waterproofing	0.5	1200	920	0.169
EPS Insulation	8	15	1260	0.031
Air gap	3	-	-	-
Roofing tile	1.2	1800	840	0.825

Table 3: Thermal Properties of the Ground Floor Layers

Material	Thickness [cm]	Density [kg/m^3]	Specific Heat [J/kg K]	Thermal Conductivity [W/mK]
Tiles	1.2	400	1000	0.064
Lightened concrete slab	5	1400	1000	0.583
Waterproofing	0.5	1200	920	0.169
EPS Insulation	5	15	1260	0.03
Vapor barrier	0.3	500	1800	0.4
Reinforced concrete slab	10	1200	1000	0.333
Ground floor loose stone foundation	9.5	-	1000	-

Internal gains were defined according to the Italian national standard UNI 11300:1 [72] to differentiate them according to a schedule. Natural ventilation was assumed with a rate of 0.3 1/h as suggested by the same national standard.

Electrical load requirements for the building equipment' are set according to a weekly schedule defined on the basis of a statistical analysis of data from Italian national consumptions [73]. For two years for a sample of Italian families, the load curves were continuously acquired. In the same period, a set of information on the main electrical uses of the family was acquired every four months, in particular, the presence and type of the main household appliances, the energy class, the frequency, and the day/time of use. The results of the analysis are the four curves displayed in Figure **2** each defined for a single season. These loads were properly set in the TRNSYS environment.

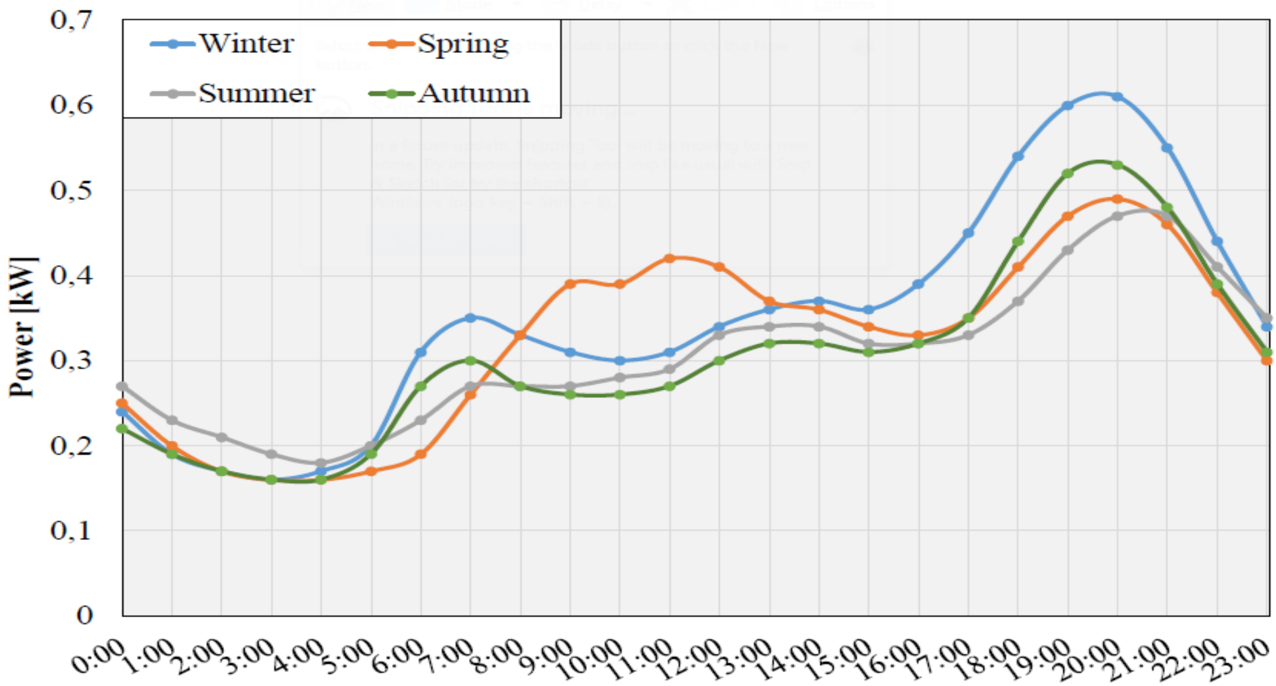

Figure 2: Electric load daily profiles of the building, differentiated for season.

2.2. Air-Conditioning Plant

2.2.1. Base Case Plant

The case base building, representing the most likely actual situation, is equipped with a traditional gas boiler supplied by natural gas with traditional radiators as emitters. The main parameters of the multi-stage boiler are reported in Table **4**. The heating setpoint temperature was assumed equal to 20 °C.

Table 4: Main Properties of the Gas Boiler

Boiler	
Fuel	Natural gas
Combustion efficiency	0.92
Boiler efficiency	0.89
Minimum Turn-Down Ratio	0.2
Rated power (kW)	4

Summer air-conditioning is assumed provided by single air-to-air heat pumps, as it is likely in the real case, with the following characteristics.

Table 5: Main Properties of the Heat Pump for Cooling Application

Heat Pump	
Type	Air-to-Air
Nominal Cooling Capacity	3.88 kW
Nominal EER	2.55
Airflow rate	185 l/s

2.2.2. Yearly Conditioning with Solar Heat Pumps

A first possible intervention for energy efficiency investigates the substitution of the gas boiler for heating and the air-to-air heat pump for cooling with a single air-to-water heat pump for each building for the yearly air-conditioning, replacing radiators with fan-coils as emission system.

Table 6: Main Properties of the Heat Pump for Yearly Air-Conditioning

Heat Pump	
Type	Air-to-Water
Nominal Cooling Capacity	3.88 kW
COP	2.55
EER	4.5
Airflow rate	185 l/s

As to improve the overall efficiency and the share from renewable sources, another intervention considers the installation of a 3 kW PV plant for each building. The photovoltaic poly-crystalline modules have a nominal power of 280 W with electric characteristics reported in Table **7**.

Table 7: Electrical Characteristics of PV Panels

Photovoltaic Panels	
Panel type	Poly-crystalline silicon
Area	1.627 m^2
Nominal Power	280 W
Voltage at max power	31 V
Current at max power	9.07 A
Short-circuit current	9.76 A
Open circuit voltage	38 V
Temperature coefficient of Isc	-0.31 %/°C
Temperature coefficient of Voc	0.05 %/°C
NOCT	45 °C

2.2.3. PV Assisted Heat Pump with Thermal Storage

In order to achieve a high level of efficiency and to highlight the importance of thermal storage, the air-conditioning plant of each building was replaced with a centralized air-to-water heat pump assisted by a photovoltaic plant supplying energy to inertial thermal storage. All the buildings are conditioned by fan-coils to be supplied by the centralized thermal storage volume. The main characteristics of the heat pump are reported in Table **8**.

Table 8: Main Characteristics of the Centralized Air-to-Water Heat Pump

Heat Pump		
Heat transfer fluid	Water	
Max supply temperature	60 °C	
Airflow rate	1500 l/s	
Heating	Nominal power	15.21 kW
	Power modulation range	7.1-15.9 kW
	Nominal COP	4.1
Cooling	Nominal power	15.69 kW
	Power modulation range	8.7-16.3 kW
	Nominal EER	4.9

This configuration still considers the presence of a PV plant that, instead of being dedicated to every single building, is supposed to form a unique electric generator at the service of the entire building aggregate in an optic of the energy community. The PV module characteristics are the same as those reported in Table **7**. Properties of the thermal storage are reported in Table **9**. The saturation temperatures set for the boiler are 45°C and 7°C for winter and summer, respectively, beyond which the eventual surplus is equally transferred to the grid.

Table 9: Characteristics of Heat Cylindrical Storage Tank

Storage Tank	
Heat transfer fluid	Water
Specific heat capacity	4.182 kJ/kg K
Fluid density	992 Kg/m^3
Thermal conductivity of the fluid	0.62 W/m K
Max storage temperature	99 °C
Tank volume	3 m^3
Tank height	1 m
Number of tank nodes	5
Top loss coefficient	0.923 W/m^2 K
Bottom loss coefficient	0.923 W/m^2 K
Edge loss coefficient	0.923 W/m^2 K

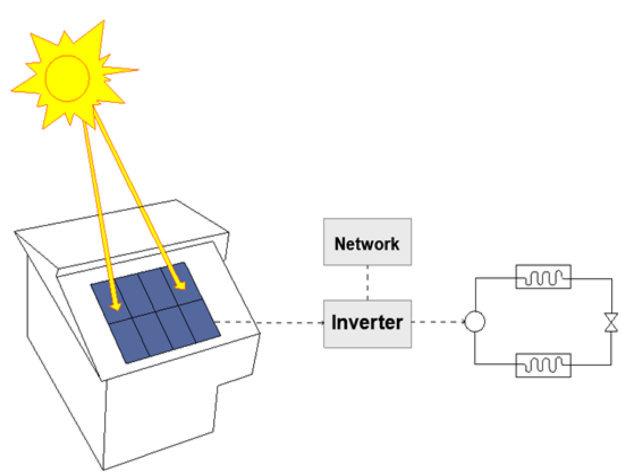

Figure 3: Schematization of the solar-assisted heat-pump configuration.

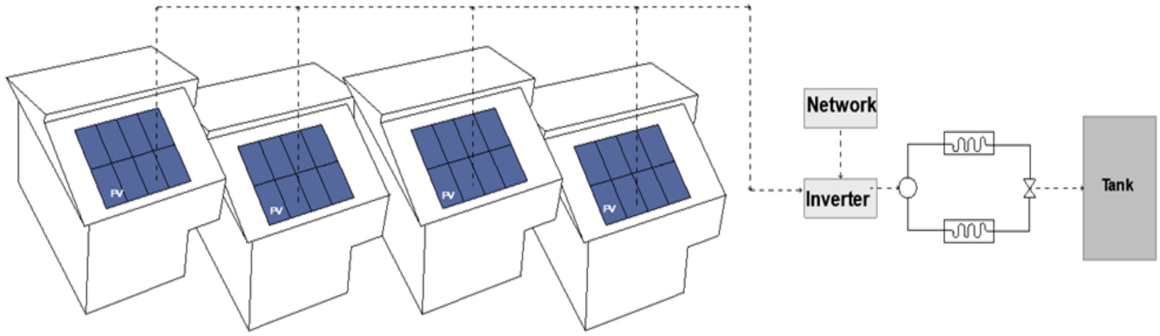

Figure 4: Schematization of a centralized solar assisted heat pump with thermal storage.

In order to maximize and rationalize the use of the solar source, considering that in the optic of energy community the space available for the installation of a PV plant is not solely confined to the buildings roof area, in the case of the centralized system two sizes of PV peak power were considered (12 kW and 16 kW) at a parity of storage tank volume, supposed to be available for the whole aggregate without defining separate plants for each building.

For all the considered plant solutions, the CO_2 emission to the atmosphere has been evaluated considering an emission factor of 0.427 kg CO_2 per kWh of energy produced considering the average thermoelectric production on the Italian territory [74]. The emission factor of natural gas was set as 2,75 kg of CO_2 per kg of burnt natural gas [75].

A final economic analysis is conducted to assess the monetary advantage of the use of the proposed interventions. For such evaluation the following parameters are supposed:

- Cost of electricity from the grid: 0.3 €/kWh
- Revenue from electricity supplied to the grid: 0.09 €/kWh
- Cost of natural gas: 1 €/Stm^3

3. RESULTS AND DISCUSSION

3.1. Base case scenario

Figure **5** displays the monthly heating and cooling energy needs of the base case scenario for the four buildings belonging to the aggregate. As it can be appreciated, due to the similar geometric configuration, both heating and cooling need are quite similar for the four buildings, with the two external (B1 and B4) and the two internal (B2 and B3) buildings showing in pair almost equal consumptions.

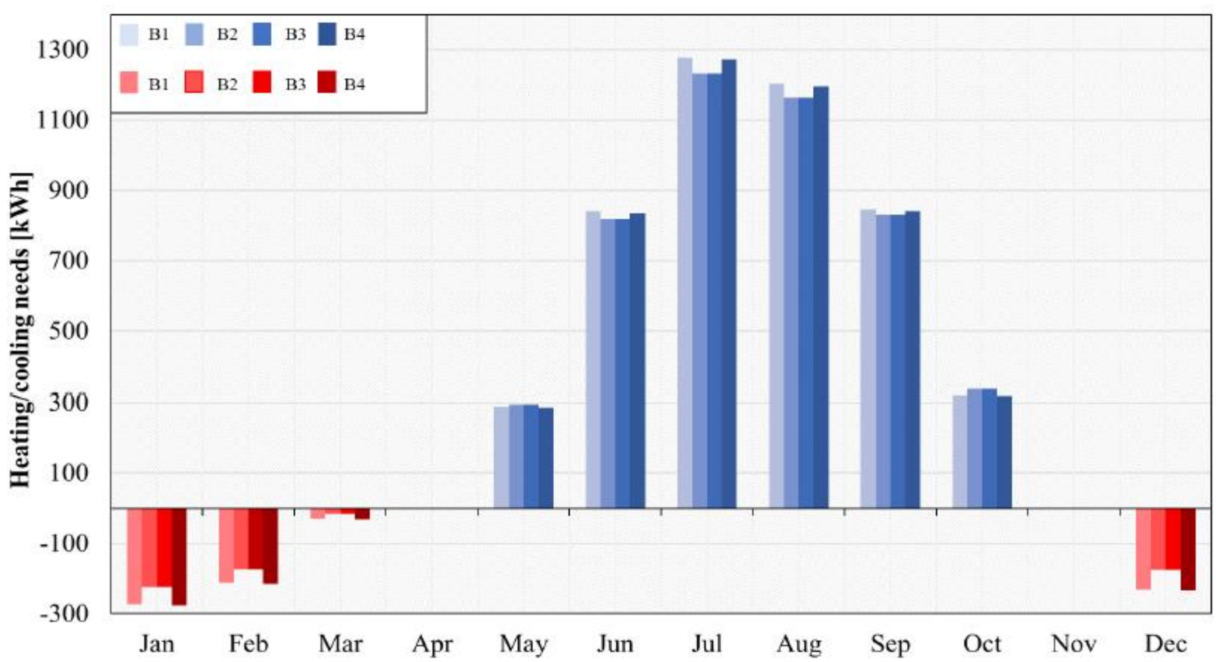

Figure 5: Monthly heating and cooling needs of the four buildings for the base case scenario.

It is also possible to appreciate how for the considered Mediterranean climate, and for building with an adequate level of thermal insulation of the envelope, the cooling requirements are conspicuously superior to the heating ones. The maximum energy required for the heating season is 756.9 kWh (B4) whereas for the summer season is 4776.8 kWh (B1).

Considering the presence of the traditional boiler and the air-to-air heat pump, Figure **6** (left) shows the natural gas consumption to satisfy the winter energy demand and the associated CO_2 emissions into the atmosphere, and Figure **4** (right) shows the electric energy for the heat pump summer operations, alongside the associated kilograms of CO_2 emissions. Naturally, these results reflect the trend already observed in Figure **3**, where the natural gas consumption is almost equal, in pairs, for the four buildings, with a maximum of 48.63 kg (B1) found in January with a corresponding mass of 133.74 kg of emitted carbon dioxide. As regards the electricity absorption from the electrical grid for the heat pump operation, from Figure **6** (right), we can see how in July and August the request is high and similar, with a maximum of 952.2 kWh and a correspondent CO_2 emission of 406.4 kg.

Finally, the monthly total electrical consumption is shown in Figure **7**, which is the sum of the electric load for house equipment and the request of electricity for the operation of the heat pump. Clearly, in the winter months, the values reported refer exclusively to the households since the heating service is provided by a boiler.

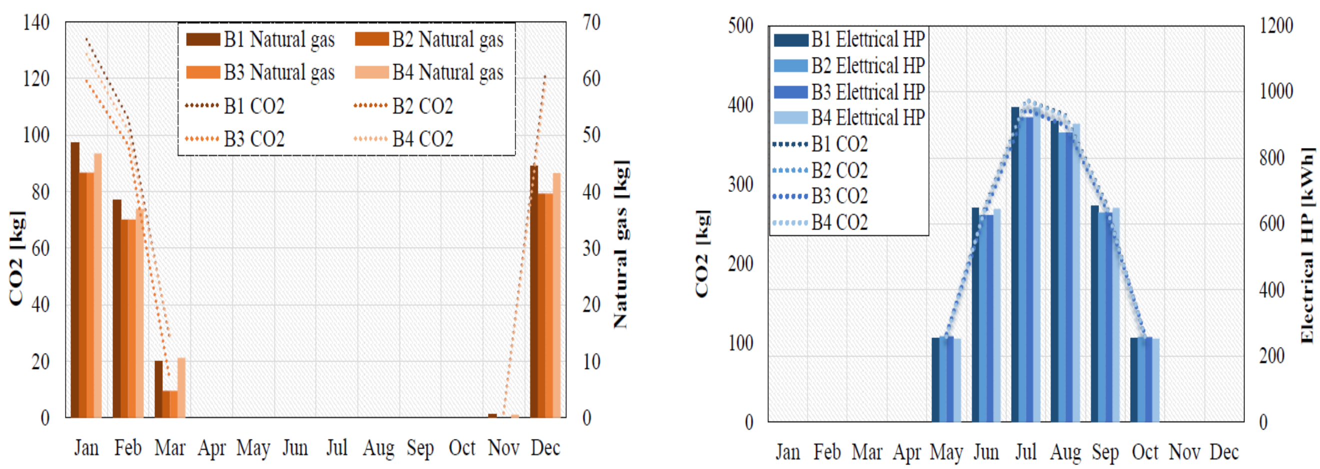

Figure 6: Natural gas consumption and CO_2 emissions for the heating service (left) and electrical energy consumption and CO_2 emissions for the cooling service (right) of the base case scenario.

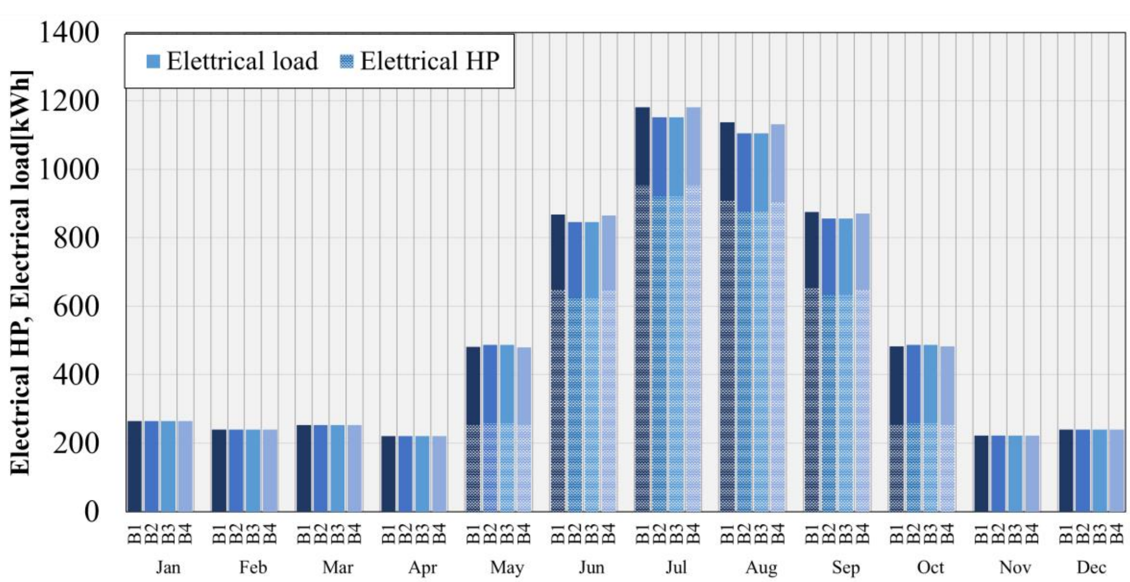

Figure 7: Total electric energy consumption for the four analysed buildings in the base case scenario.

Finally, Table **10** summarizes the main results obtained for the entire building aggregate.

Table 10: Summary of the Energy and CO_2 Results for the Base Case

	B1-B4
Heating [kWh]	2683.3
Cooling [kWh]	18878.4
CO_2 [kg]	12 400
Electrical HP [kWh]	14479.3
Electrical tot [kWh]	25666.5

3.2. Use of Single Solar Assisted Heat Pumps

The first intervention supposes the replacement of the natural gas boiler and of the air-to-air HP in each building with an air-to-water HP that supplies the necessary thermal energy for both heating and cooling. Furthermore, for each house, a 3 kW peak PV plant was considered. Such a solution represents a conspicuous step toward a high-efficient and eco-friendly solution for the air-conditioning of dwellings, since the heat pump can provide heating and cooling load through the use of clean energy, and the use of electricity produced by the PV allows to increase the share of self-consumed renewable energy. The PV plant is of the grid-connected type and therefore exchanges energy with the national electric grid.

Figure **8** shows for each building the electrical consumptions of the heat pump to satisfy the heating and cooling services. The greatest heating demand of 289 kWh is found for B1 house in January where the greatest cooling demand of 871 kWh in July is also found due to a major surface exposed to solar radiation. Globally, the whole aggregate building requires a demand of 2573.8 kWh for heating and of 13017.4 kWh for cooling.

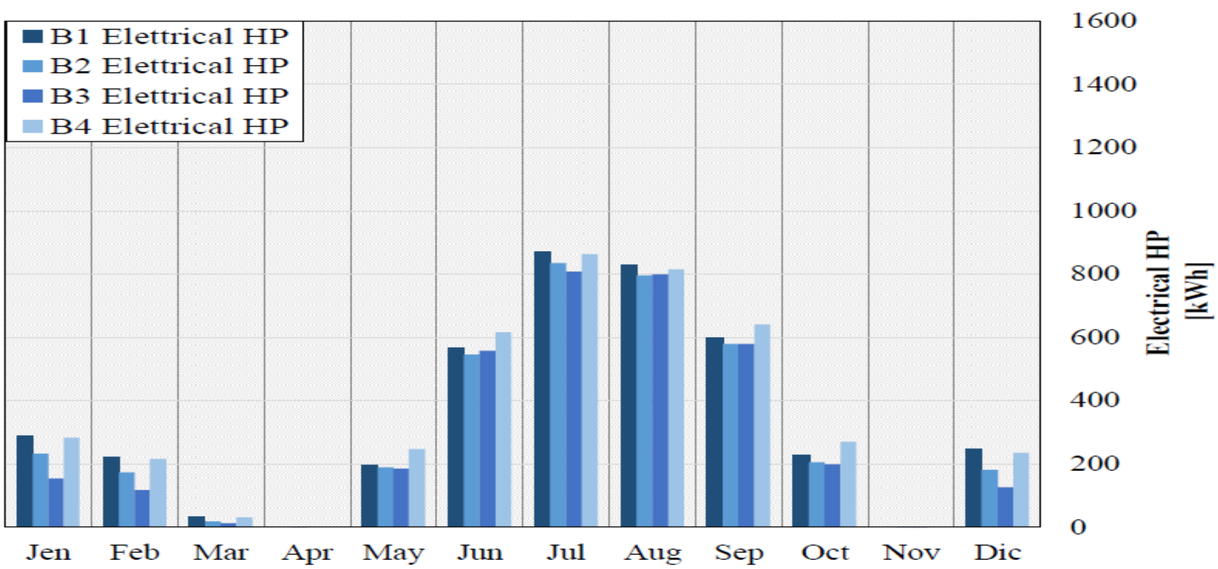

Figure 8: Electrical consumption for the heating service and cooling service for the single solar assisted heat pumps.

Table 11: Electrical Consumption for the Heating Service and Cooling Service Single Solar Assisted Heat Pumps

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
B1	289	223	34	0	195	568	871	827	600	228	2	248
B2	232	173	18	0	189	546	835	796	579	205	0	180
B3	154	116	13	0	185	558	808	799	579	198	0	125
B4	283	216	31	0	246	616	863	815	641	269	2	235
B1+B4	**958**	**728**	**95**	**0**	**816**	**2287**	**3377**	**3237**	**2399**	**901**	**2**	**790**

All values are in unit kWh

When domestic users' electric loads are added to the heat pump electric requirements, the total electric energy is reported in Figure **9**. It can be seen how in intermediate seasons, such as April and November, the required electric energy is solely attributed to the domestic loads. The annual sum for the whole aggregate gives 7454 kWh for heating and 18444 kWh for cooling.

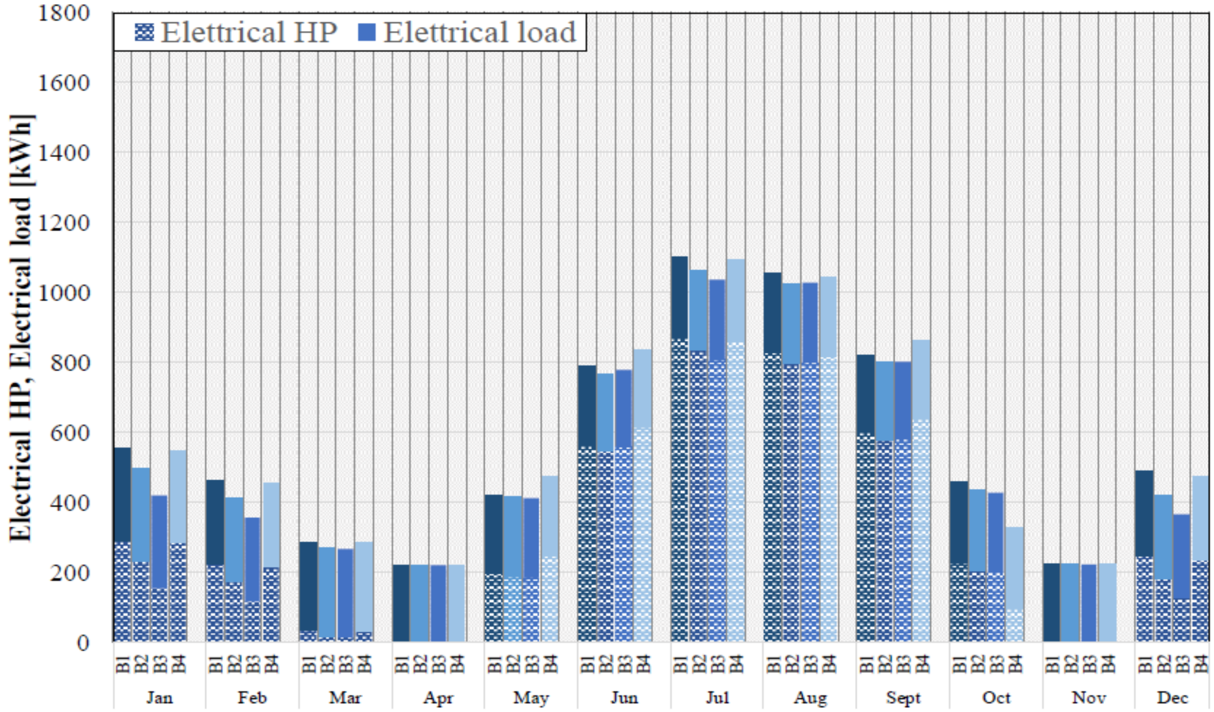

Figure 9: Total electric energy consumption for the four analyzed buildings for the single solar assisted heat pumps.

Considering the presence of the PV plant, thanks to the hourly simulation results, it is possible to account in detail for the electric energy produced by the plant and directly self-consumed by the users. Results of such computations are reported, in monthly summary, in Figure **10**, along with the CO_2 emissions. The CO_2 emissions are computed considering only the share of electric energy requested from the heat pump and for the domestic loads withdrawn by the electric grid. The total amount of carbon dioxide produced for the four buildings accounts for 11434.2 kg.

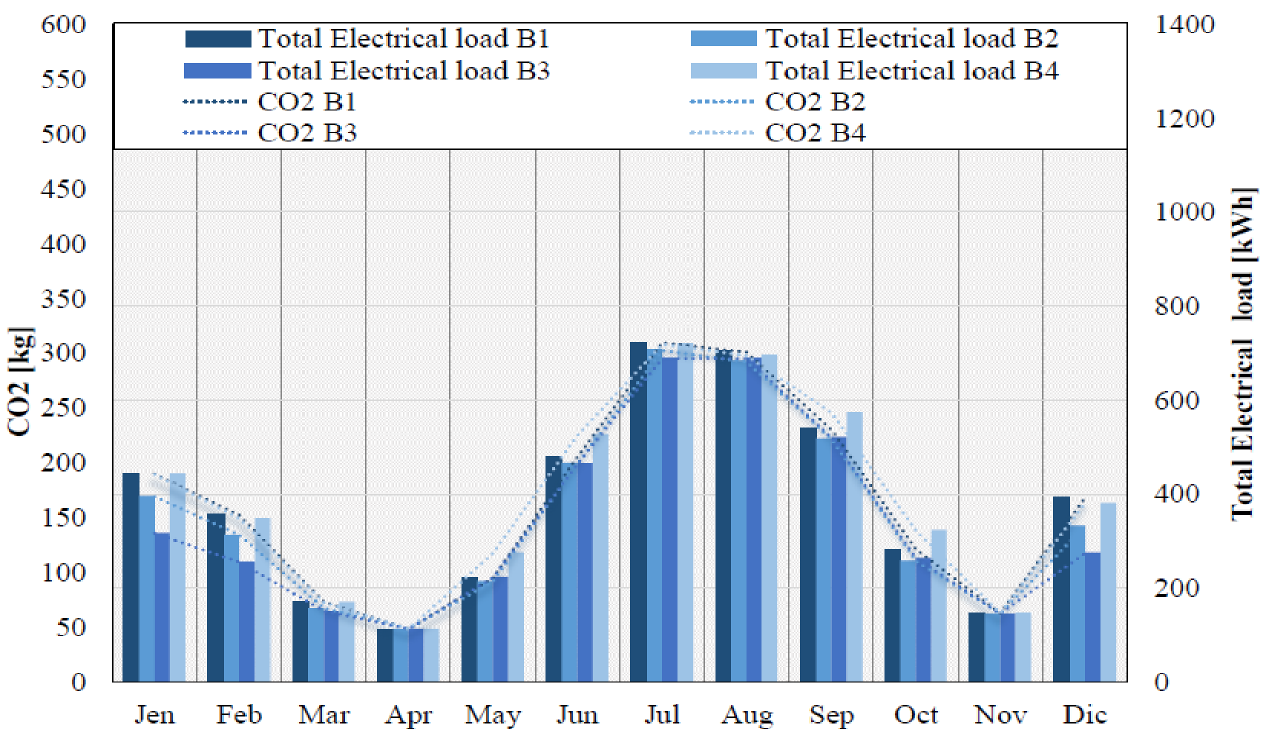

Figure 10: Net monthly total electric consumption, considering the PV self-consumed energy.

Figure **11** shows, for each house, the amount of electricity produced and directly consumed, the amount produced but not consumed instantly and therefore supplied to the national grid, and finally the amount withdrawn from the grid. This last case occurs when the total electric load is greater than the photovoltaic production and/or when a lack of synchronism between demand and production occurs at certain times of the day. For the B1 building, we can see how the amount of 356 kWh of energy is produced and directly consumed in July against the production of 583 kWh. In winter months, on the other hand, proportionally to the production, the self-consumed quota also decreases being of the order of about 100 kWh for all the houses, with a maximum value of 110 kWh self-consumed energy in March against the 155kWh fed into the grid.

Finally, the monthly percentage of self-consumed energy, compared to the total PV production of all houses, is reported in Figure **12**. The highest percentages of self-consumption are achieved in July and August (62 and 61% respectively) while the lower is found in April and November (23% and 27%, respectively) because of the absence of air-conditioning demand. In the coldest winter months of December and January, however, the total self-consumed energy reached an appreciable threshold of 36% and 39%, respectively.

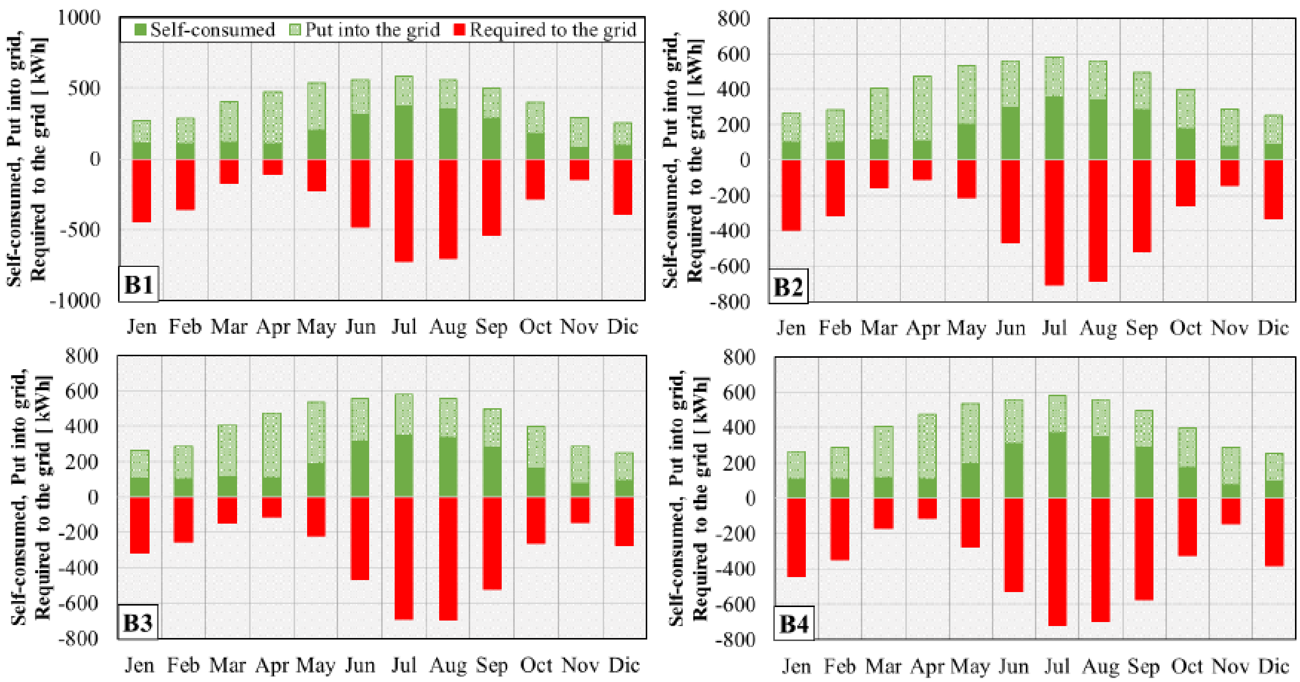

Figure 11: Monthly electric energy self-consumed, supplied, and withdrawn from the national grid for the four different houses.

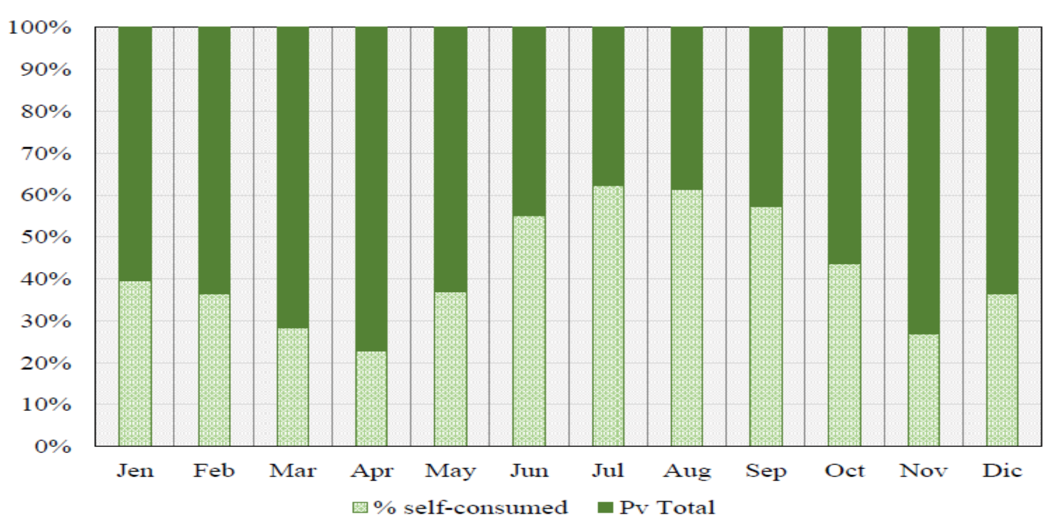

Figure 12: Monthly percentages of total self-consumed and produced electric energy for the whole building aggregate

The summary of the findings for the single PV assisted heat pumps scenario is reported in Table **12**.

Table 12: Summary of the Results for the Single Solar Assisted Heat Pumps Scenario

	B1-B4
Electrical tot [kWh]	17700
CO_2 [kg]	7559
PV production [kWh]	20404
PV consumption [kWh]	9

3.3. Use of a Centralized Solar Assisted Heat Pump with Thermal Storage

The second intervention supposes the replacement of the single heat pumps for each building, with a centralized heat pump combined with a thermal storage tank to supply the whole aggregate system. This solution allows to convert electricity into thermal energy using the heat pump and to use it in deferred mode.

Figure **13** shows the total electric consumptions for the building aggregate heating and cooling, including the users' load and without considering the PV production. Again, for the heating period, the consumption is maximum in January where it assumes the value of 1960.7 kWh, while, in the cooling period, the highest consumption occurs in July where it assumes the value of 4073.6 kWh.

The consumption related to the sole operation of the heat pump was compared with the case of single heat pumps for each building in Table **13** to highlight the advantage of using a centralized heat pump that supplies thermal storage. In almost the totality of the months (except for March), a reduction can be appreciated, being the highest, in absolute value, in July where the use of such a system allowed to save 215 kWh.

The monthly net total electric energy consumption for the two cases is reported in Figure **14**, along with the associated CO_2 emissions. In both cases, the monthly trend is fairly similar, but greater reductions are naturally appreciated when a 16 kW PV plant is installed. Globally for the latter, the annual energy consumption amounted to 15 489 kWh against the 16 023.5 kWh for the 12 kW case. In terms of CO_2, the adoption of a greater PV size led to emissions of 6613.8 kg, 305 kg less than the smaller PV case.

Figure **15** reports the share of monthly PV electric energy self-consumed, supplied to the national grid, and withdrawn from it to satisfy the total electric requirements.

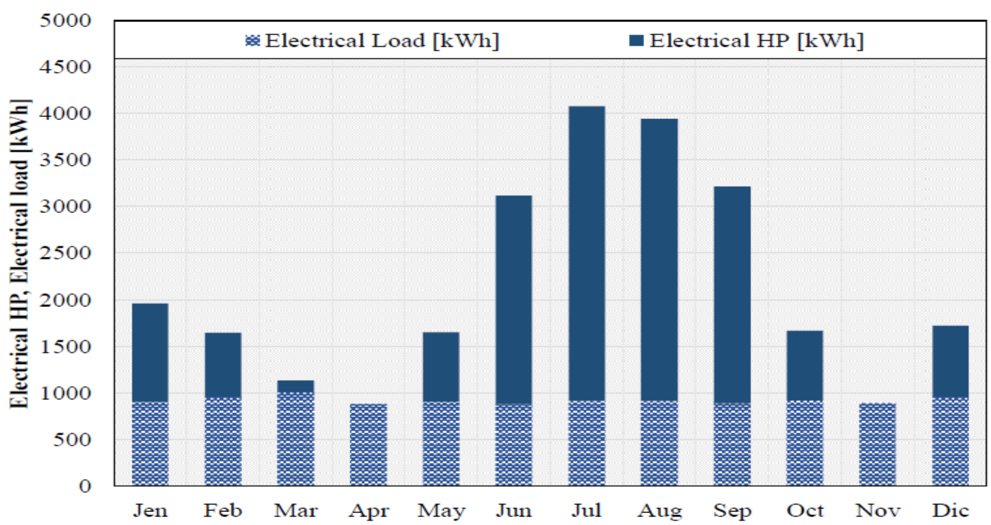

Figure 13: Total electric energy consumption for centralized solar assisted heat pump.

Table 13: Comparison of the Electric Consumption of the Heat Pump

	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
B1-B4 (Single)	958	728	95	0	816	2287	3377	3237	2399	901	2	790
B1-B4 (Centralized)	900	688	118	0	743	2236	3158	3022	2325	750	0	761
Reduction (kWh)	-58	-40	+23	0	-73	-51	-219	-215	-74	-151	-2	-29
Percentage reduction	-6%	-5%	+24%	0%	-9%	-2%	-6%	-7%	-3%	-15%	-100%	-3%

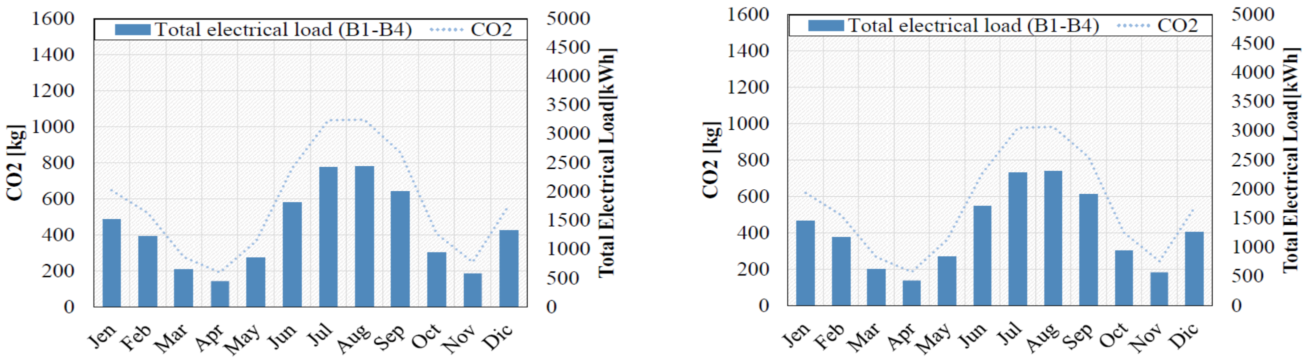

Figure 14: Net monthly total electric consumption and CO_2 emissions, considering the PV self-consumed energy with a 12 kW plant (left) and 16 kW plant (right).

Figure 15: Monthly electric energy self-consumed, supplied, and withdrawn from the national grid for the whole aggregate with a 12 kW plant (left) and 16 kW plant (right).

For the 12 kW case, the self-consumed energy ranged from the minimum of 307 kW in November, to the maximum of 1648 kWh in July. The share withdrawn from the grid reached the highest value in August (2432 kWh) whereas the lowest value was found in April (447 kWh). Annually, the PV plant produced 20416 kWh. If a PV plant of 16 kW is considered, the yearly production rises to 28568 kWh and the share of self-consumed energy reaches a maximum of 1788 kWh again in July. The share withdrawn from the grid was reduced to 2299 kWh for the most requiring month of August and to 431 kWh in April.

In Figure **16**, the monthly percentages of self-consumed and produced electric energy are reported. In both cases, the lowest self-consumption is found in April and November where there is a very low demand for air-conditioning, and the PV plant supplies exclusively the users' electric loads. When the PV plant is increased from 12 kW to 16 kW, the self-consumption raises to 71% in July, falling to 59 % in June, while in the coldest winter months the percentage is about 40%.

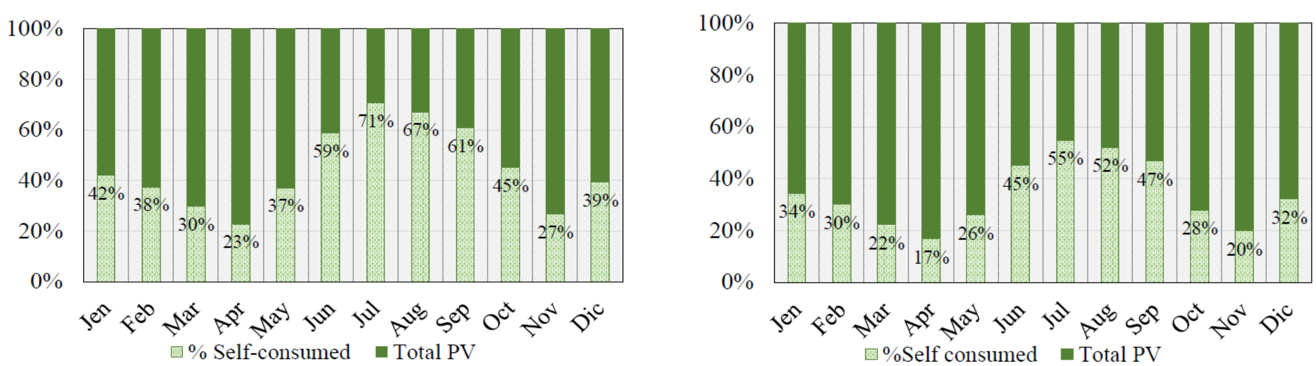

Figure 16: Monthly percentages of total self-consumed and produced electric energy for the whole building aggregate with a 12 kW plant (left) and 16 kW plant (right).

Data in Table **13** shows the percentage increase of electric energy self-consumption compared to the previous case of single heat pumps without thermal storage. Even at a parity of PV peak power (12 kW), the centralized system with thermal storage can rationalize the energy use, providing a percentage increase of up to 14%. If the PV peak power is augmented to 16 kW, the self-consumption share increases by 22% and 24% in January and December, respectively, and by 23% in July.

The summary of the findings for the centralized solar-assisted heat pumps scenario is reported in Table **15**.

Table 15: Summary of the Results for the Centralized Solar Assisted Heat Pumps Scenario

	PV 12 kW	PV 16 kW
Electrical tot [kWh]	16 203.5	15 489.1
CO_2 [kg]	6 918.9	6 613.8
PV production [kWh]	20 416.0	28 568.4
PV consumption [kWh]	9 686.9	10 401.4

Table 14: Percentage Increase of Electric Self-Consumption Compared to the Single Heat Pump Use

Percentage Increase of Single HP	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
12 kW	7%	3%	5%	0%	1%	7%	14%	9%	6%	4%	0%	8%
16 kW	22%	16%	11%	4%	2%	15%	23%	19%	15%	5%	4%	24%

Finally, to evaluate the economic advantages of the proposed centralized system, a revenue estimation is carried out considering the operational cost associated with the natural gas for the base case scenario, the cost of electricity withdrawn from the grid, as well as the economic revenue from selling the surplus PV energy to the grid. Figure **17** shows the monthly total cost for the heating and cooling services and users' electric loads. The base case scenario offers the highest cost in each month since it relies on a traditional boiler for heating and there is not any renewable source. Moving to the case of the use of single heat pumps for air-conditioning with separate PV plants, a decrement of monthly cost can be observed, which becomes drastic in summer months. In the coldest month of January, the total expense dropped from 563.35 € of the base case to 422.26 € for single heat pumps, to 347.71 € for the centralized plant with 16 kW of PV power. In the hottest month of July, the expenses for the same cases were: 2014.36 €, 773.50 €, and 552.95 € respectively.

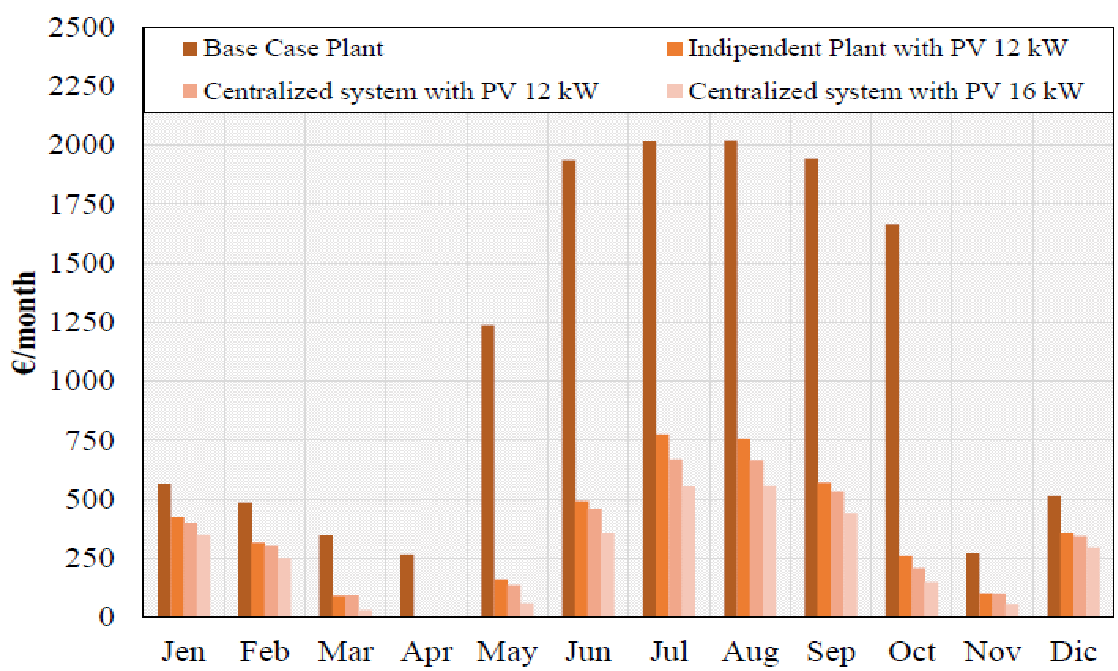

Figure 17: Monthly total cost for the heating and cooling services and electric loads demand.

The economic advantage was found to be more evident for the centralized heat pump with the highest PV peak power, where the economic savings were higher than 38% in winter months, and higher than 73% in summer months. On an annual level, the heating, cooling, and electric loads energy consumptions reduced from 13 246.70 € of the base case scenario to 3 081.15 € for the centralized HP with 16 kW PV plant. Results confirmed the indisputable supremacy of heat pumps as generators, especially when coupled with a renewable energy source.

CONCLUSIONS

Solar-assisted heat pumps have become a promising technology to improve energy efficiency in buildings, allowing lower primary energy demands and CO_2 emissions. This paper investigated the energy, economic and environmental advantages of the use of PV-assisted heat pumps for building air-conditioners. With reference to a building aggregate composed of four houses, an intervention of energy efficiency was supposed, by replacing the traditional generators with PV-assisted heat pumps. Furthermore, to highlight the benefits of the use of thermal storage, in an optic of energy community, the single heat pumps were supposed to be replaced by a centralized one that works on thermal storage, which, in turn, supplies the whole building aggregate. The same storage was further considered as a sui-generis system where electricity surplus is transformed into thermal energy, more easily to employ in differed manner.

Hourly dynamic simulations in the TRNSYS environment showed that when the traditional generators are replaced with single heat pumps, thanks to the share of renewable energy provided by the aerothermal source combined with the electricity production from the PV plant, a high level of energy efficiency can be achieved with a percentage of self-consumed energy from PV, on an annual level of 44% and with a conspicuous reduction of CO_2 emissions that dropped to 7 559 kg compared to the 12 400 kg of the case base scenario.

The use of a centralized heat pump combined with thermal storage to supply the four buildings was more appealing, which further allowed to reduce the net total electric consumption from 17 700 kWh of the previous case to 16 203.5 kWh with the same PV plant size (12 kW) and to 15 489.1 kWh when a PV plant of 16 kW is used. A higher level of energy efficiency was also detected with a monthly self-consumption percentage that reached 71% in July for the 16 kW PV. From an economic point of view, the total expenses for heating, cooling, and electric loads amounted to 13 246.70 € for the base case scenario and fell to 3 081.15 for the centralized HP with a yearly economic reduction of 76.7%.

Conclusions are obtained for a Mediterranean climate that is characterized by a conspicuous amount of solar radiation. If the same procedure is applied to colder and more continental climates, results may be different and, in particular, a reduction of the economic and environmental advantage produced by the PV plant is to be expected.

The study allows us to conclude that the use of a centralized heat pump with a thermal storage system, in an optic of energy community, can be advantageous for different reasons, which include providing relevant energy and economic savings and allowing to design of a generator with a lower power when compared to the use of single heat pumps for each building.

ACKNOWLEDGMENT

This work was partially supported by the Italian Ministry of University and Research through the project comes to funded by the National Operative Program "Research and Innovation " 2014-2020 (PON "R&I" 2014-2020).

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Received on 22-10-2020 Accepted on 18-12-2020 Published on 30-12-2020

DOI: https://doi.org/10.15377/2409-9821.2020.07.7