# S.A.P.I.EN.T.E. Experimental Test Facility For Full-Scale Testing Of New Configurations Of Collective Thermal Electric Self-Consumption From Renewable Sources. First Experimental Test with Thermo-photovoltaic Collectors Plant

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### Abstract

The European Renewable Energy Directive (RED) promotes the adoption of Renewable Self-Consumption strategies for local production and shared consumption of energy. In this paper, the authors illustrate S.A.P.I.EN.T.E., an experimental facility consisting of several generation sections, energy storage and distribution systems designed to simulate energy communities and related experimental tests focused on maximizing self-consumption of locally produced renewable energy. We demonstrate, through experimental tests, the benefits in terms of energy self-consumption and self-sufficiency that such a system architecture can achieve. We show the results of the first experimental tests conducted on the Thermo-photovoltaic collectors **(**PVT) system installed in S.A.P.I.EN.T.E.

*Keywords:* *Self-consumption, Self-sufficiency, TPV, renewable energy*

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## 1. Introduction

In addressing the challenges posed by climate change and the energy crisis, the Renewable Energy Directive and its recent update (EU/2018/2001 - EU/2023/2413) encourage the proliferation of Renewable Energy Communities (REC) and Jointly Acting Renewable Self-Consumers. These initiatives promote local energy production and shared consumption as viable alternatives to traditional centralized energy systems. However, transitioning to these new system architectures introduces complexities, particularly regarding the stability and reliability of electrical grids due to the intermittent and uncertain output of renewable energy sources. Additionally, the growing and variable energy demand of consumers further compounds these challenges. To maximize the efficiency of REC, it is imperative to implement demand side management strategies, such as load shifting facilitated by storage systems, to prioritize self-consumption and self-sufficiency. [1-8]

We show the plant structure, operating logics and control systems. We demonstrate how the storage systems belonging to such a plant maximize self-consumption of locally produced energy through experimental test results. The plant named S.A.P.I.EN.T.E. (Sistema di Accumulo e Produzione Integrata di ENergia Termica ed Elettrica - integrated thermal and electrical energy storage and production plant), installed at the ENEA Casaccia Research Center, is an experimental facility composed of four different sections: energy generation, energy storage, distribution system and energy utilities. A control system based on a Programmable Logic Controller (PLC) is used to manage energy flows and implement demand side management strategies.

## 2. S.A.P.I.EN.T.E.

### 2.1. Description of the facility

The energy generation section is composed by a photovoltaic (PV) plant provides the plant with a peak power production of 11.6 kW. A thermo-photovoltaic collectors (PVT) plant consisting of 20 panels, each with a nominal thermal output of 770 W and a nominal electrical power of 320 W (for a total of 6.4 kWp), is also


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present. An air/water Heat Pump (HP) provides a maximum thermal power of 30.4 kW. A simplified schematic of the S.A.P.I.EN.T.E. system is shown, distinguishing the thermal section with dashed lines and the electrical section with continuous lines shown in Figure 1.

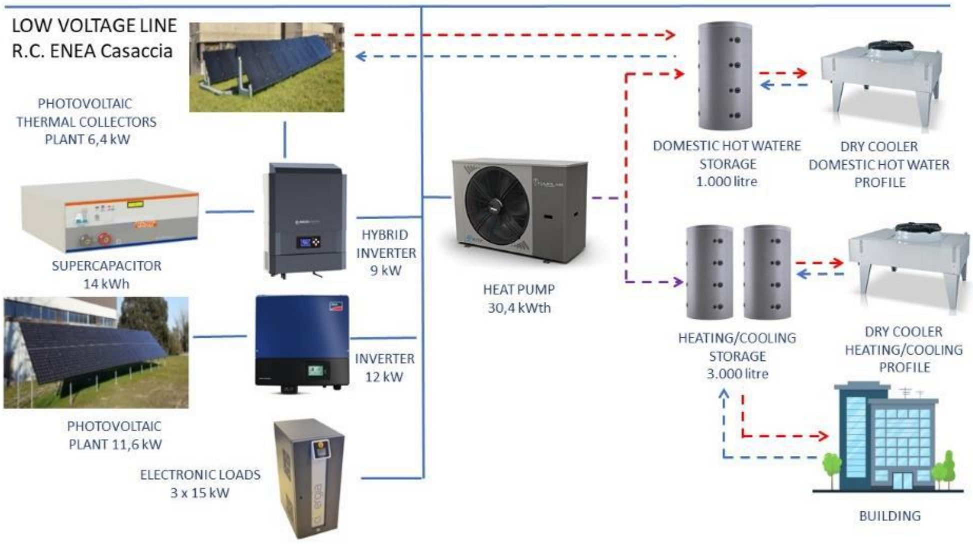


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**Figure 1: S.A.P.I.EN.T.E. system schematic. Continuous lines represent electrical connections, dashed lines thermal connections.**

The electrical section of the PVT powers a hybrid inverter, to which are connected 4 supercapacitors with a total capacity of 14 kWh, representing electrical storage section of S.A.P.I.EN.T.E. The thermal storage section consists of two thermal storage tanks for heating or cooling with a total capacity of 3.000 liters. Another 1.000 liters storage tank for domestic hot water (DHW) is present. The load section is composed by devices that can emulate thermal and electrical loads. Two 70 kW dry coolers are present, one connected to the heating and cooling tanks and the other to the DHW tank, that act as thermal load emulation section. The distribution system is equipped with solenoid valves, controlled by the PLC, which allow switching the load between the dry cooler, used for emulating the thermal load, and 9 fan-coils from 9 rooms in the nearby office building, acting as a real thermal load.

The electrical load emulation section consists of three regenerative electronic loads (15 kVA each) capable of emulating electrical load profiles. If needed, these can be also used to emulate power generators.

## 2.2. Coefficient of Self-Consumption and Self-Sufficiency

In the context of REC, the coefficients of self-consumption (SC) and self-sufficiency (SS) are key indicators for assessing the efficiency and effectiveness of energy production and consumption within the community. The SC is expressed as a percentage and represents the fraction of energy produced from renewable sources that is used directly by the energy community, instead of being fed into the power grid, compared to the total energy generated from renewable sources.

This coefficient can be defined through the following formula:

$$SC = \frac{SCE}{TEP} \qquad \text{(eq. 1)}$$

Where:

- SCE = Self Consumed Energy is the energy produced and consumed directly within the community.

- TEP = Total Energy Produced is the total energy generated from renewable sources in the community.

A high self-consumption coefficient indicates that a large proportion of the energy produced is used directly within the community, reducing energy losses due to transmission and improving overall system efficiency.

The SS indicates the ability of the energy community to meet its energy needs through local renewable energy production, without having to depend on energy from the external power grid. It is expressed as a percentage and refers to the amount of self-consumed energy generated from renewable sources relative to the total energy consumed, including electricity taken from the grid.

This coefficient can be defined through the following formula:

$$SS = \frac{SCE}{TEC} \qquad \text{(eq. 2)}$$

Where:

- SCE = Self Consumed Energy is the energy produced and consumed directly within the community.

- TEC = Total Energy Consumed is the total energy used by the community, including energy taken from the grid.

A high coefficient of self-sufficiency shows that the community can meet a large part of its energy needs through local production, reducing dependence on the electricity grid and increasing energy resilience.

These coefficients are crucial for:

- Assessing the energy performance of renewable energy communities.
- Plan and optimize energy production and consumption.
- Promote sustainability and energy independence.
- Incentivize energy policies that encourage the use of renewable energy and the creation of energy communities.

Optimizing SC and SS brings to environmental, economic, and social benefits. It helps reducing greenhouse gas emissions and improving environmental sustainability, while also leading to economic savings for members of the energy community or collective self-consumption group. It improves the quality of life for participants through increased energy independence.

## 3. Control system and experimental strategies

### 3.1. PLC Management strategies

We implemented proportional-integral-derivative (PID) control to convert a portion of the electrical energy produced by the PV system to thermal energy. This consists of tracking the electrical energy produced by the photovoltaic system and using this exact amount to power the heat pump, therefore realizing a power-to-heat (P2H) strategy. The PID receives as inputs the power produced by the PV and the electrical power consumed by the HP and adjusts its output to minimize the difference between the inputs, controlling the speed of the HP compressor. By adopting this strategy, all the energy produced by the PV is used to power the HP, increasing the SC. In addition, our system shows the ability to meet thermal needs of the load, decreasing the need to draw electricity from the grid, therefore increasing the SS. PID regulation operates within a configurable range of HP operating temperatures, determined by low and high temperature setpoints that can be configured both for the thermal and DHW tanks. The electrical energy in excess is stored in the supercapacitors.

When the heat pump compressor starts operating, high peak power absorption can occur, which may exceed the instantaneous PV power production. The supercapacitors are used to instantly compensate for electrical power demand peaks. The load is managed through the PLC, which allows setting the thermal power profiles to be emulated with the dry cooler. The system parameters are monitored through a network of electrical and thermal sensors connected to the PLC.

Following these logics, the electrical power absorbed by the heat pump is limited by the signal generated by the PID to match power produced by the PV, so that the two profiles overlap. When the storage temperature reaches the high temperature setpoints, the control system deactivates PV tracking, turning off the heat pump. When the storage tank temperature falls below the low temperature setpoints, photovoltaic tracking is reactivated to feed the HP. The PID saturates the generated signal to its maximum value until the electrical power generated by the PV falls below the maximum power the heat pump can absorb, which is influenced by the coefficient of performance (COP) and the outdoor temperature.

In case wind power is used together with photovoltaic, the heat pump will go in tracking of the power produced by photovoltaic and wind power.

### 3.2. Experimental tests: boundary conditions

In this work, we conduced experimental tests focusing mainly in the summer season, producing and storing cold thermal energy and DHW. The load profile was designed proportionally to the electricity, central cooling, and DHW needs of an apartment building consisting of four units. This choice is mainly agreed upon as a function of the dimensions of the PV, storage tanks, and HP of S.A.P.I.EN.T.E.

The load profile of electrical energy, DHW and cooling load were kept constant throughout the experiment. This is to limit the number of variables and to be able to focus on the variation of SC and SS coefficients in relation to the diversification of renewable sources used such as PVT, PV and wind.

The figure 2 with the reference building cooling load and the reference DHW load is shown below. A higher peak is observed in the morning for both cooling and DHW load.

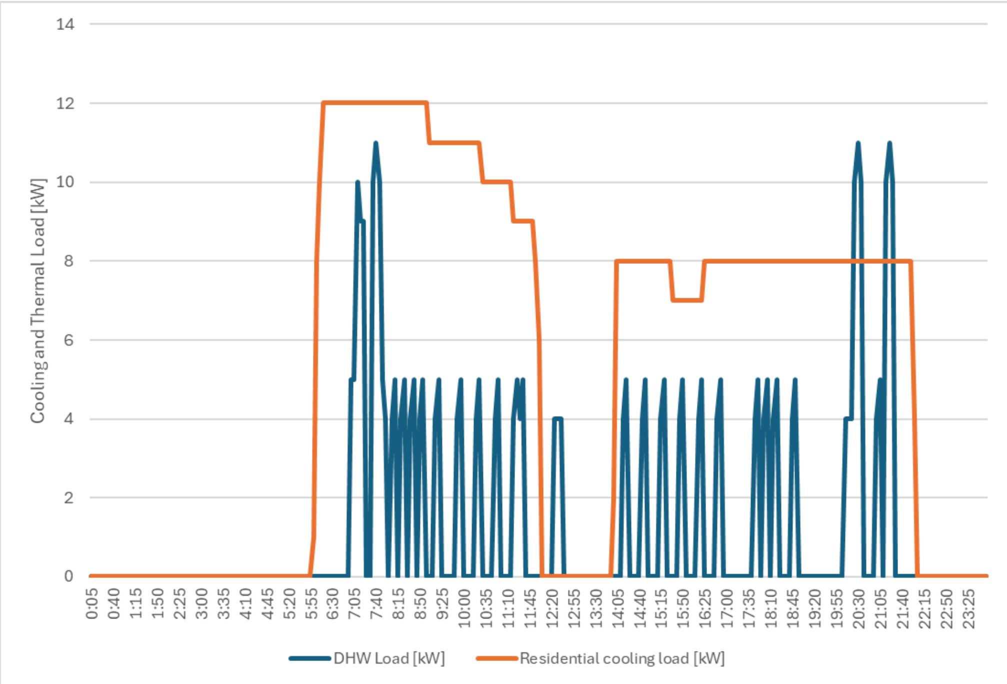


**Figure 2 DHW and residential cooling load**

Two loads are considered, the first domestic hot water and the second for cooling the building. The loads are taken constant to reduce the number of variables and emphasize the aspects of self-consumption and self-sufficiency. We considered standard DHW and cooling load profiles, not investigating the exact typology, but focusing on the plant behavior. We focused on the weekly load trends and leave the weekend analysis for further discussion

Regarding generation from renewable sources, a characteristic day of a summer month was chosen to be replicated in the experiments. Analyses were made on the contribution of PVT in meeting the DHW load. Finally, analyses were made substituting PV generation with PVT and wind-power generation. The peak power of the PV and wind system remained the same as that of the PV system alone. Through a Montecarlo method [9], we generated the electrical load profile of the building, shown in figure 3 together with the PV generation profile.

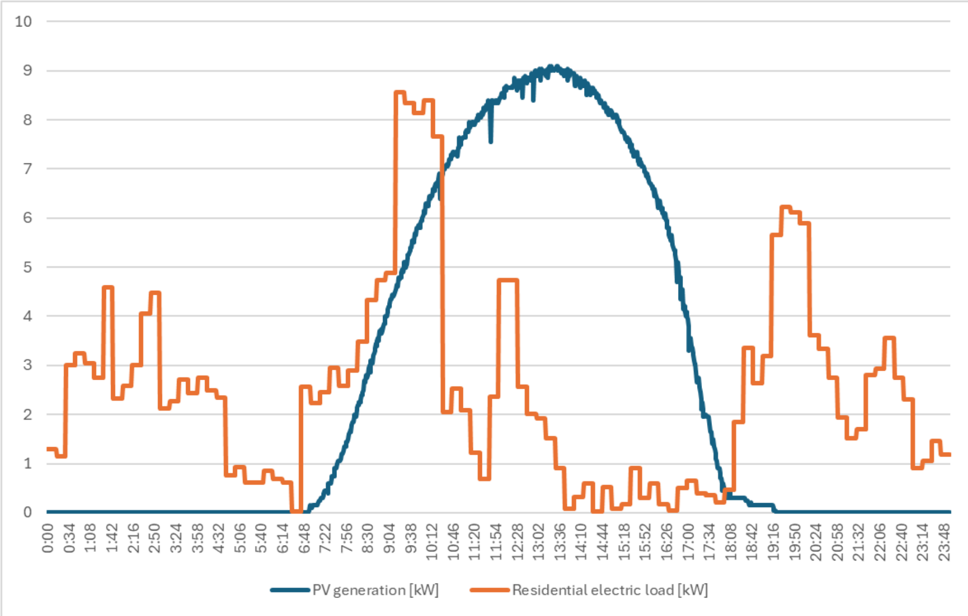


**Figure 3 Residential electrical load and summer photovoltaic generation curve**

The benefits of the supercapacitor storage system were analyzed in previous publications related to the S.A.P.I.EN.T.E. system [10], supercapacitors are a viable and effective alternative to lithium-ion batteries in the context of REC, since these can be very useful for handling peak loads that exceed the PV generation curve. In fact, the application of these devices resulted in a 10 % increase in SC compared to the case where they were not used.

A scenario with produced wind energy is also considered. This scenario is developed from wind detection data that occurred in the research center and simulated in the software, virtually. Thus, the wind generation is simulated and not real but follows a pattern consistent with the climatic conditions at the location where the S.A.P.I.EN.T.E. system is installed.

Wind generation is introduced to see how self-consumption and self-sufficiency coefficients can be affected by diversified generation.

Between the case in which the wind curve is predicted and the case in which the wind profile is not predicted, the installed capacity of renewables is considered constant, and thus PV has a trend with installed capacity of exactly half, as it is replaced by the installed capacity from wind.

Finally, everything was systematized and summarized through tables.

## 4. Experimental

In the first experimental session we focused on the contributions of the PVT system to DHW. Finally, we highlighted the overall test results in the wind plus PV mode.

### 4.1. PVT in DHW

Four days of energy production were compared, in which PVT thermally powered the DHW storage. No thermal load was applied. In the first case, we operated the PVT circulator without any special external condition; in the second case, the storage was kept at a temperature of 30 °C to maximize the thermal performance. On the next two days, the PVT was kept off and we analyzed how the water circulation would affect the efficiency of the PV section of PVT.

Below is the summary table of the tests carried out showing the type of operation considered, in our case the type of operation is for domestic hot water production, the thermal and electrical source refers to the same PVT system. In cases A and B the thermal source is used, turning on the circulator, in case C and D on the other hand it is kept off with the idea of raising the temperature on the panels and see how this aspect can affect the electrical efficiency.

In this section we focus on the electrical efficiency of PVT and look at how, in this system, the electrical production performance can be affected by the conditions in which the PVT thermal collectors are set to work.

**Table 1 Schematic summary of the tests performed on the PVT**

| Case | A | B | C | D |
|---|---|---|---|---|
| Type of operation | DHW | DHW | DHW | |
| DHW Thermal Source | PVT | PVT | OFF | |
| Electric Source | PVT | PVT | PVT | |
| Storage System | DHW Storage | DHW Storage | DHW Storage | |
| Thermal profile | None | Storage temperature at 30 °C | None | |

The first two cases (A) and (B) showed the potential of the PVT system and how its contribution to the heat generation in DHW is maximized when the DHW load is continuously operating. It can contribute to important savings in the industrial and commercial sectors where heat absorption is continuous and programmable.

From the following figure 4 one can see the thermal efficiencies in the cases where the circulator is kept on. Case B, the one with the storage tank kept at the constant temperature of 30 °C has the best thermal efficiency and for the longest time.

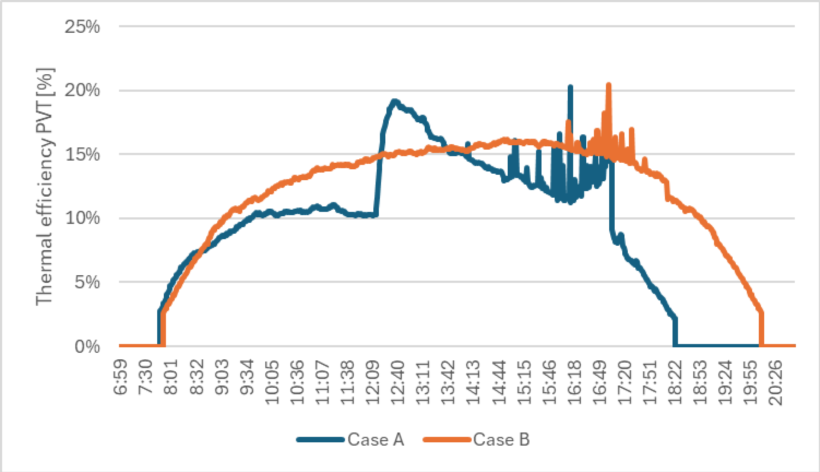


**Figure 4 PVT thermal efficiency case A and B as represented in the table**

From the latest tests, represented by figure 5, it is shown that the electrical output during the day is not affected by temperature if the temperature remains within ten degrees, rappesented by figure 6.

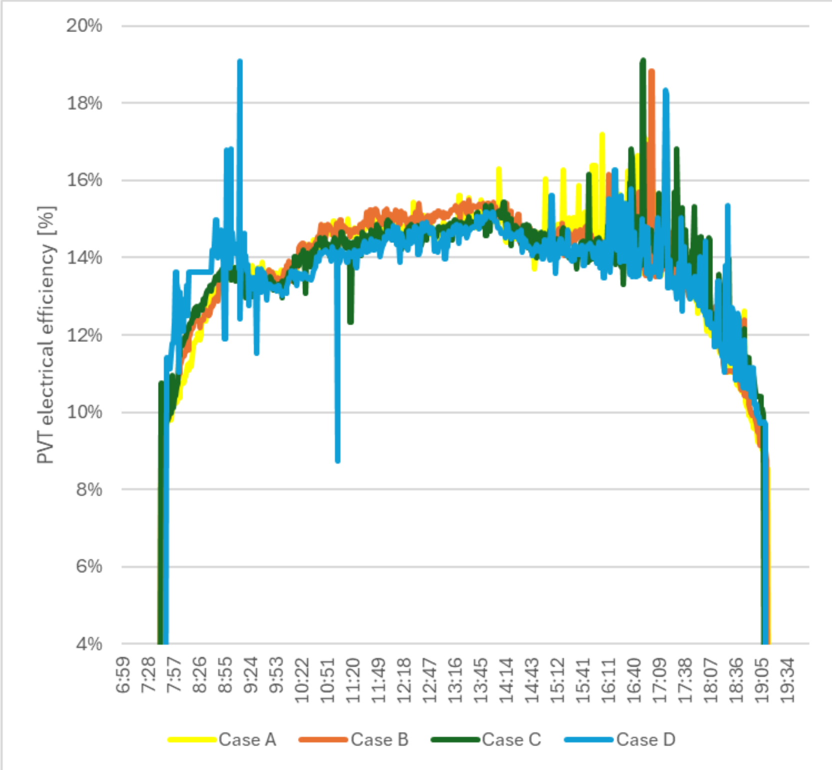


**Figure 5 Electrical efficiency in the four cases described in the table**

Below in the figure 6, note the trend of reference water temperatures inside the PVT panels in the four different cases. The first two with circulator on and the last two with circulator off.

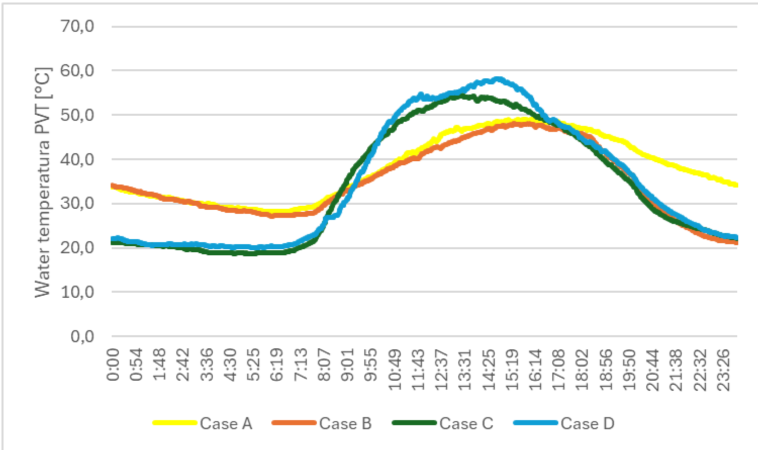


**Figure 6 Water temperature of PVT in the four cases described in the table**

If we zoom in, we can see that the hydraulic circuits at lower temperature have a higher electrical efficiency of PVT during peak hours. This interesting behavior will be investigated with further experiments, to evaluate how lower input temperatures can affect the electrical efficiency of our PVT, while producing heat for the DHW storage.

## 4.2. Production of cold thermal energy

In experiments conducted producing cold thermal power, two typical days were compared, maintaining the same residential cooling load. In the first case, the HP worked by providing comfort according to its own logic. In the second case, the HP was employed in the P2H strategy. This logic is realized to maximize SC, being able to have a few degrees of adjustment depending on the storage temperature. Below we summarize the boundary conditions in Table 2 in which the two tests were done, which differ only regarding the HP control strategy.

**Table 2 Summary data of experiments for summer cooling case E to F**

| Case | E | F |
|---|---|---|
| Type of operation | Cooling | Cooling |
| Thermal Source | HP | HP |
| Electric Source | Grid and PV summer profile | Grid and PV summer profile |
| Thermal profile | Residential cooling load | Residential cooling load |
| Electrical profile | Residential electric load | Residential electric load |
| HP control strategy | No | PV profile tracking |

In the first case (E), the HP followed its internal logics while providing thermal comfort following the thermal load demand, independently from the PV curve. In the second case (F), we applied the P2H strategy to control the HP. It can be seen from Figure 7 how the HP operates independently of the photovoltaic bell.

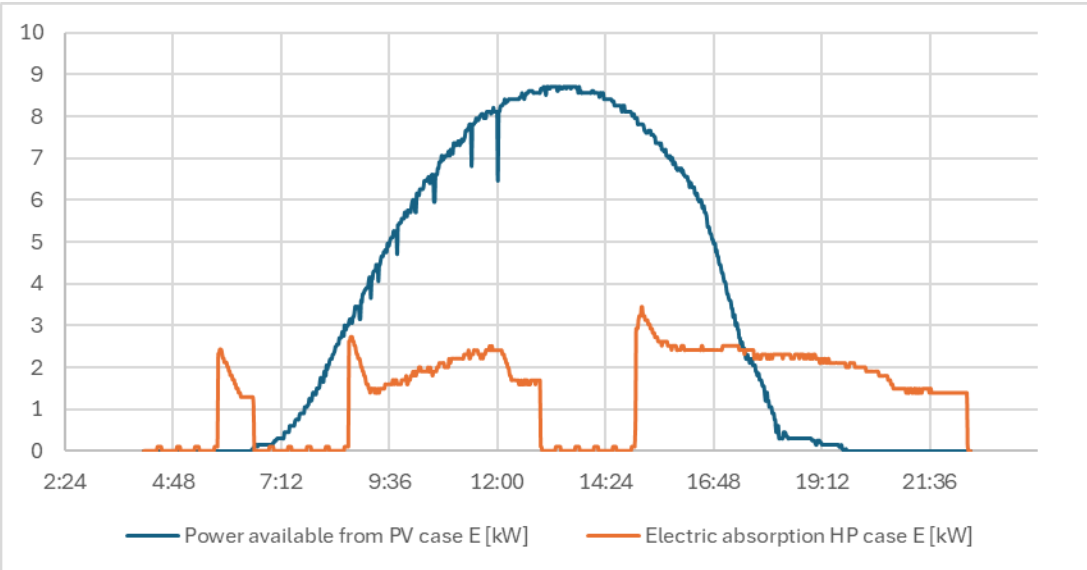


**Figure 7 Power available from PV and Electrical Absorption of HP (case E)**

From Figure 8 below, it is clear how the heat pump strategy goes in tracking of the PV bell by limiting the maximum absorption to renewable production.

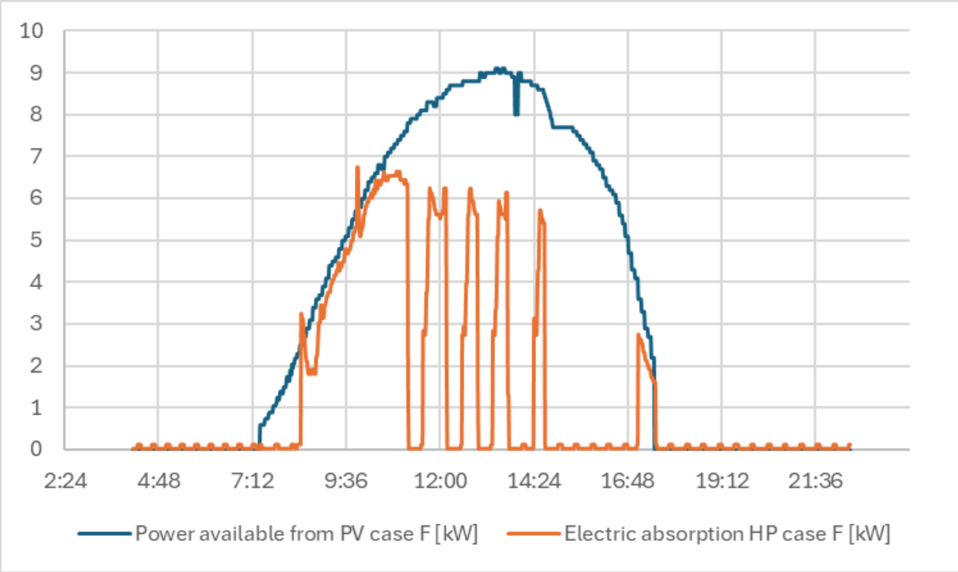


**Figure 8 Power available from PV and Electrical Absorption of HP (case F)**

Then, we report the results summarized in Table 3 emphasizing the different energies that are considered for the calculation of the coefficients. In (F) case, the performance indices reach very high values. We calculated the energy coefficients from the experimental results shown above.

***Table 3 Summary parameters of experimental tests E and F***

| Case | E | F | |
|---|---|---|---|
| Electricity produced by PV | 64 | 64 | kWh |
| Electrical energy absorbed by the HP in total | 26 | 23 | kWh |
| Electrical energy absorbed by the HP in self-consumption | 15 | 22 | kWh |
| Thermal energy produced by the HP | 121 | 107 | kWh |
| Electricity self-consumed utilities | 3 | 5 | kWh |
| Electricity taken from the utility grid | 56 | 54 | kWh |
| Electricity fed into the grid | 47 | 37 | kWh |
| Calculation Energy Coefficients | | | |
| SC | 0,27 | 0,42 | - |
| SS | 0,21 | 0,32 | - |
| Daily COP | 4,7 | 4,6 | - |

The table shows that in the second case SC and SS are increased mainly because the energy absorbed by the HP is used during the PV generation hours, therefore minimizing the energy absorptions outside from the PV production curve.

## 4.3. Wind and PV Energy

In this case, a scenario of cooling and DHW in a residential setting were compared. The sources were PV and wind power. The electrical load is considered. The only difference between the two systems is the use in the second case of the PVT, so the heat load related to DHW consumption has an advantage in that it is no longer met by the HP alone but by the HP plus the PVT. Below is Table 4 summarizing the boundary conditions of the last two tests, which differ only from the use of PVTs as the thermal source in the (AB) case.

**Table 4 Summary parameters of experimental tests with photovoltaic and wind generation**

| Case | AA | AB |
|---|---|---|
| Type of operation | DHW + Cooling | DHW + Cooling |
| DHW Thermal Source | HP | PVT + HP |
| Electric Source | PV + Wind | PV + Wind |
| Thermal profile | Residential cooling and DHW heat load | Residential cooling and DHW heat load |
| Electrical profile | Residential electrical load | Residential electrical load |

In Figure 9 the generation curve (PV + wind) and the residential electrical load are shown, during the daylight hours, when the PV production is available. The four curves shown are related to the electrical load of the building and the wind and photovoltaic renewable sources, and finally, the fourth curve is the sum of the individual contributions of wind and photovoltaics.

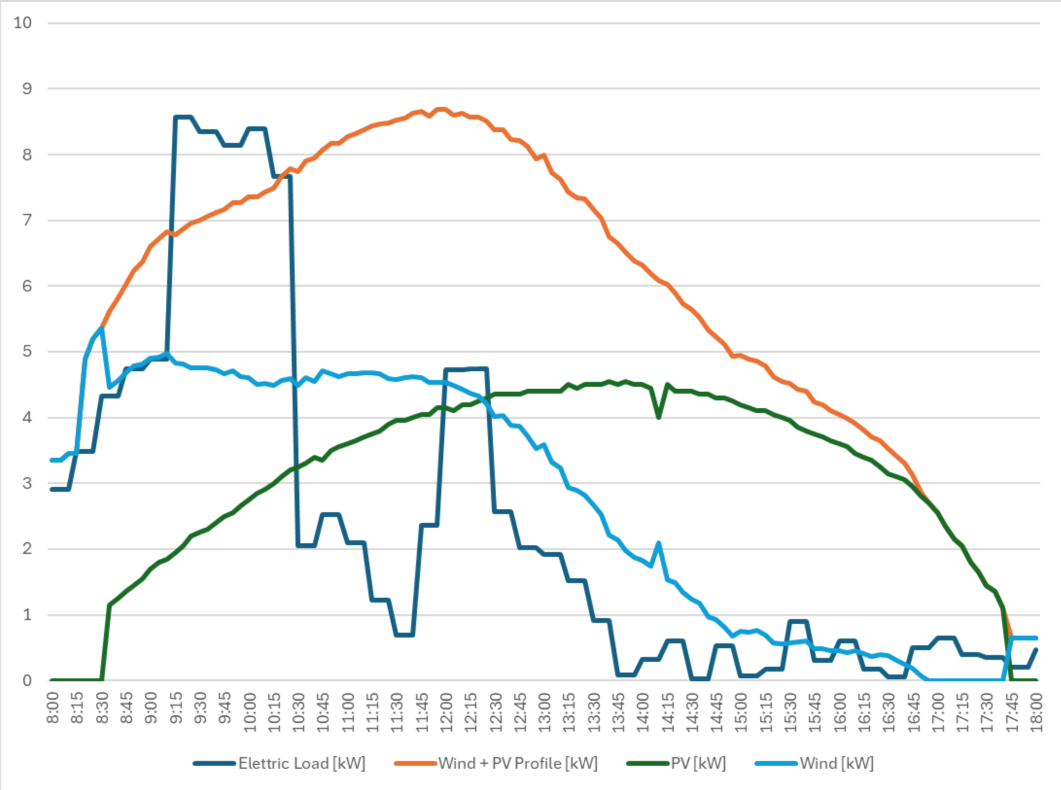


**Figure 9 PV and wind power generation profile together with residential electrical profile.**

The peak power of the PV and wind power system is the same as in previous cases where only PV was evaluated

In Figure 10 below, note how the HP followed the PV and wind generation curve until the evening when to meet the thermal load of cooling and DHW it left the tracking logic and entered a comfort logic. We show the graph obtained while the HP was used in P2H strategy, following the wind + PV curve to ensure the maximum possible absorption during generation hours, therefore maximizing SC.

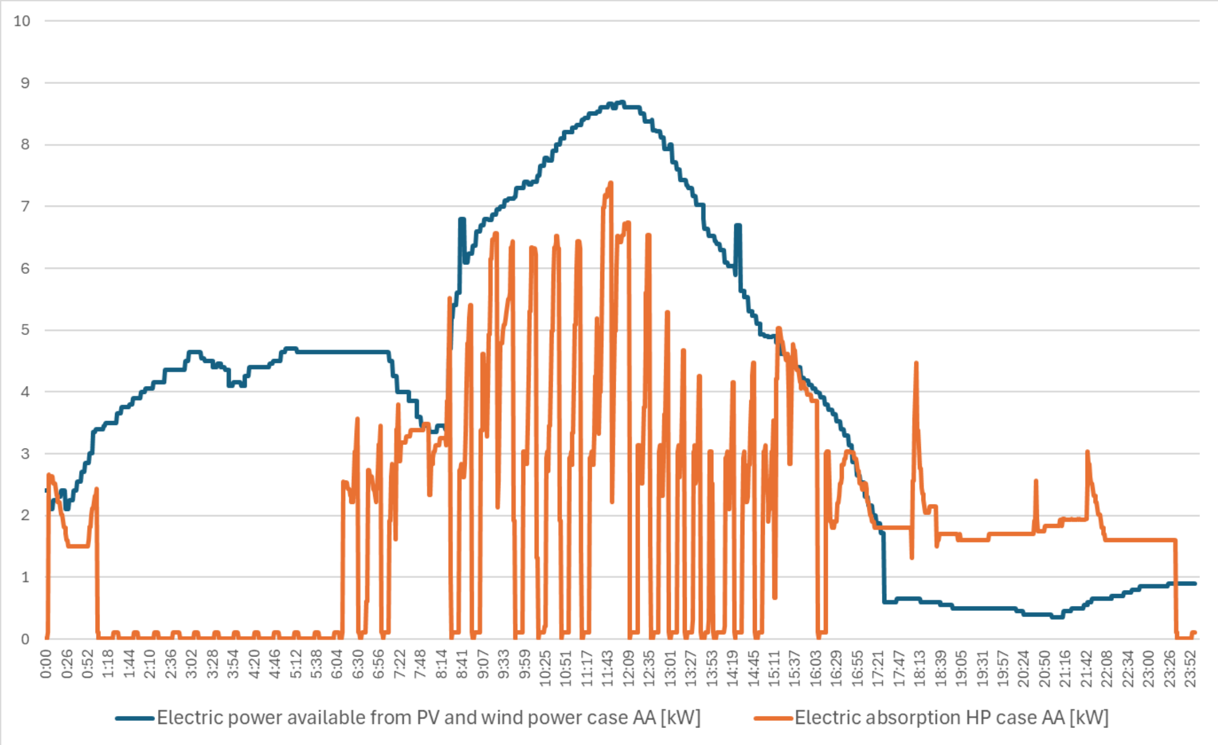


**Figure 10 Electric power available from PV and wind power and power absorbed by HP (case AA)**

Figure 11 below shows the performance of the heat pump in the case where, in addition to having PV and wind as electrical sources, there is also PVT as thermal contribution. The heat pump followed the PV and wind generation profile until the evening when the pdc exited the tracking logic and entered the comfort logic to ensure the comfort of the users.

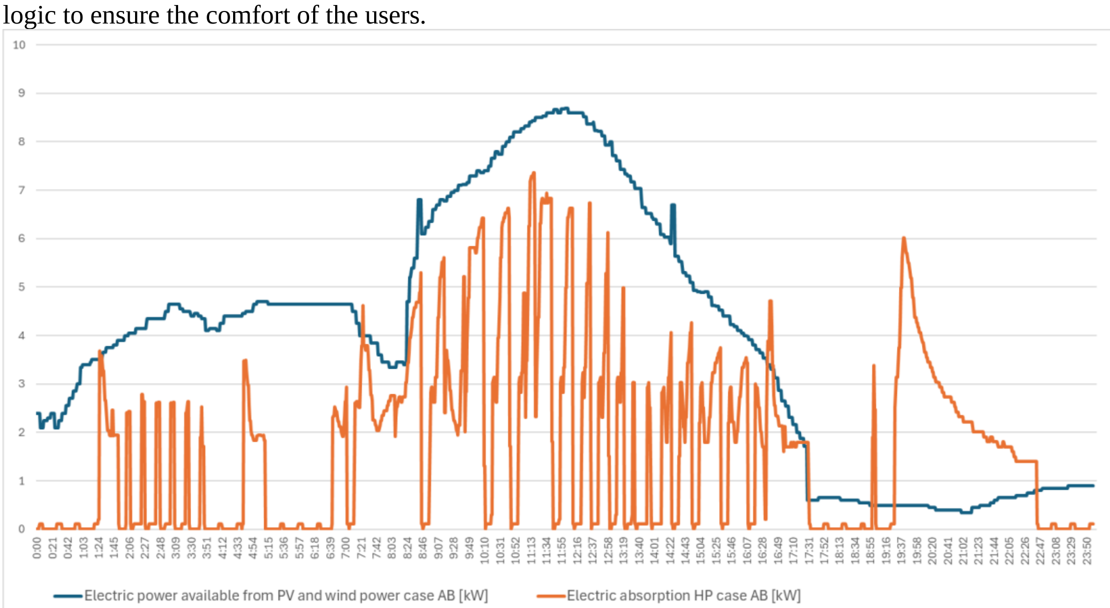


**Figure 11 Electric power available from PV and wind power and power absorbed by HP (case AB)**

No strong evidence is remarked upon from these graphs, in fact even the results summarized in the table 5 below underscore these aspects, the only factor that emerges is a slight increase in the SS factor. Further testing will be needed to obtain clearer data. Table 5 shows the energies considered in the calculation of the coefficients and the calculation of the SC and SS coefficients. In the (AB) case where PVT are used as thermal sources, there is a SS three percentage points higher than in the (AA) case.

| Case | AA | AB | |
|---|---|---|---|
| Electricity produced by PV plus Wind | 94,9 | 94,9 | kWh |
| Electrical energy absorbed by the HP in total | 43,7 | 40,1 | kWh |
| Electrical energy absorbed by the HP in self-consumption | 29,4 | 30,5 | kWh |
| Thermal energy produced by the HP | 194,0 | 170,9 | kWh |
| Electricity self-consumed utilities | 9,3 | 8,6 | kWh |
| Electricity taken from the utility grid | 25,6 | 26,2 | kWh |
| Electricity fed into the grid | 56,2 | 55,8 | kWh |
| Calculation Energy Coefficients | | | |
| SC | 0,41 | 0,41 | - |
| SS | 0,49 | 0,52 | - |
| Daily COP | 4,4 | 4,3 | - |

**Table 5 Summary parameters of experimental tests AA and AB**

Note how SC remains constant between the two cases while SC has a slight increase in the second case. This data is not very significant; the contribution of PVT is sensitive and difficult to quantify. Having a PV + wind generation curve results in a higher SS than the case of using only PV.

Comparing these two trials where wind power is used versus the previous two cases (E) and (F) where only PV is used, it can be seen that diversifying renewable sources can increase benefits compared to SS because it allows you to meet consumption for more time during the day but the SC remains constant because the difficulty of using all the energy that is produced remains almost constant.

## 5. Conclusion

Realizing RECs that show high self-consumption and self-sufficiency rates by sharing the energy locally produced from renewable sources not only follows the recent EC directives, but also have a direct impact on the global environment. In this work, we demonstrated effective resource management and control methods to enhance SC and SS in the context of RECs, adopting P2H and load shifting strategies. Moreover, we demonstrated how diversifying generation capabilities, making the power production available throughout the whole day can have a beneficial impact. We also shown how converting electrical power into thermal power by means of a HP can enhance the energy coefficients, while also warrantying thermal comfort to the RECs users. Finally, we demonstrated that the thermal section of a PVT plant, if used in the right context, can improve system performance.

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