# 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.

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**Abstract**

The European Renewable Energy Directive promotes the adoption of renewable self-consumption strategies for local production and shared consumption of energy. In this paper, the authors illustrate the plant named S.A.P.I.EN.T.E., an experimental facility designed to simulate Collective Self-consumption Groups (CSG) 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 (SC) and Self-Sufficiency (SS) that such a system architecture can achieve.

S.A.P.I.EN.T.E. installed at the ENEA Casaccia Research Center, is composed of four different sections: energy generation, energy storage, distribution system and energy utilities. A control system based on a programmable logic controller is used to manage energy flows and implement demand side management strategies.

We will show the plant structure, operating logics and control systems. We will demonstrate how the storage systems belonging to such a plant maximize self-consumption of locally produced energy through experimental test results.

We demonstrate effective resource management and control methods to enhance SC and SS in the context of CSG, adopting power to heat and load shifting strategies. We also show how converting electrical power into thermal power by means of a heat pump can enhance the energy coefficients, while also warrantying thermal comfort to the CSG users.

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

## 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 (JARSC). These initiatives promote local energy production and shared consumption as viable alternatives to traditional centralized energy systems. However, the transition 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 enhance the efficiency of REC and JARSC, maximizing self-consumption and self-sufficiency [1-8], demand side management strategies, such as load shifting driven by storage systems, are essential.

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.

Here, we show the plant structure, operating logics and control system capabilities. Through experimental tests results, we demonstrate how power-to-heat (PtH) control logic, applied on the heat pump, maximizes self-consumption of locally produced energy.

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

### 2.1. Description of the facility

The energy generation section is composed of a photovoltaic (PV) plant that 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 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.


**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 of 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 allows 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, Self-Sufficiency and Profit Indicator

In the context of CSG, 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.

Three main equations were considered. The first calculates self-consumption (SC), i.e. the energy generated by one's own renewable energy plant that is consumed on site. (Eq.1)

The second relates to self-sufficiency (SS), i.e. the share of the building's energy needs that is covered by the electricity generated by the photovoltaic plant (Eq.2)

Finally, a further profit indicator (PI) is considered, which evaluates the revenue from PtH logics compared to the baseline without control logics. (Eq. 3)

This coefficient can be defined through the following formula:

$$SC = \frac{Ep - Et}{Ep} \qquad \text{(eq. 1)}$$

Where:

Ep is the energy produced from renewable energy sources [kWh];

Et is the energy transferred to the national electricity grid [kWh];

A high SC 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:

$$SS = \frac{Ep - Et}{Ec} \qquad \text{(eq. 2)}$$

Where:

Ep and Et are defined above;

Ec is the total energy consumed [kWh];

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.

The last coefficient, the profit indicator, indicates how much of a benefit there is in applying Pth demand management logic compared to no demand management at all

$$PI = \frac{Rs - Rb}{|Rb|} \qquad \text{(eq. 3)}$$

With PI the profit indicator of the scenario considered compared to the baseline [%];

Rs is the economic cost/revenue balance of the Pth demand management scenario [€];

Rb is the economic cost/revenue balance of the baseline [€];

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 reduce greenhouse gas emissions and improve 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. Assumptions made and boundary conditions

A first set of tests was conducted under summer operating conditions, followed by a second set under winter conditions. The conditions under which these tests were carried out depended on several variables, such as:

- Common-area electricity consumption in the building, including lighting, elevator, and water booster systems (autoclave)
- Individual apartment energy consumption, with sensitive data gathered from the utility meters of four sample dwellings

Both types of consumption, common and individual, were based on a case study of a residential building located in Palermo, where energy use was monitored across both the summer and winter seasons. Another aspect considered was the thermal load, including both cooling and domestic hot water (DHW) demand in summer, and heating and DHW demand in winter. These load profiles were designed for a centralized generation system serving four apartments, with proportional distribution.

A further key dataset comprised the renewable energy generation curves, including:

- A photovoltaic (PV) production profile, obtained from real measurements taken from a PV system located at the ENEA Casaccia Research Center;
- Two simulated wind generation profiles: the first one used for winter tests, the second one, used for summer tests.

For the summer scenario, a hybrid generation system was considered, consisting of a 3 kW wind turbine and a 6 kW photovoltaic array. In the winter scenario, only a 9 kW wind turbine was considered for the wind power plant and the existing 11.6 kW plant at Casaccia for photovoltaics.

Using these input datasets, experimental tests were carried out with the aim of evaluating energy and economic performance indicators related to self-consumption within a group of energy users. Tests were conducted using the SAPIENTE experimental platform, starting from the objective of satisfying user comfort conditions. Load profiles for heating, cooling, and DHW were employed in conjunction with a centralized heat pump system to meet thermal demand.

Different testing scenarios were assessed based on the operation of energy generation sources. The baseline scenario involved no coordination between the heat pump operation and the renewable generation curve. Additional tests implemented power-to-heat strategies, with the heat pump operation scheduled to follow renewable generation patterns, including energy storage dynamics.

Key performance indicators such as SC and SS were calculated to estimate both the utilization of locally produced renewable energy and the extent to which user demands were covered. Economic indicators were also considered, including physically self-consumed energy, energy purchased from the grid, energy exported to the grid, virtually self-consumed and real self-consumed energy. Each of these flows was assigned a specific cost/incentive coefficient, based on applicable Italian laws and regulatory frameworks. The time resolution used for energy flow analysis was hourly.

Environmental indicators were also evaluated, including primary energy savings (expressed in TOE, Tons of Oil Equivalent), and avoided $CO_2$ emissions due to renewable energy generation, this last value was taken from ISPRA tables of 2022 for the Italian thermoelectric production and equivalent to 0,431 kg$CO_2$/kWh.

Additional performance metrics included: Coefficient of Performance (COP) of the heat pump; distribution efficiency, defined as the ratio between the heat delivered through two dry-coolers, one for DHW and one for space heating/cooling and the total heat produced by the heat pump. Finally, two further coefficients were introduced to quantify the deviation between the actual thermal load delivered via the dry-coolers and the ideal thermal load required.

# 4. Control system and experimental strategies

## 4.1 PLC Management strategies

We implemented proportional-integral-derivative (PID) control to convert to thermal energy a portion of the electrical energy produced by the PV system. 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 Pth 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.

When the heat pump compressor starts operating, high peak power absorption can occur, which may exceed the instantaneous PV power production. 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 and the same in the case of considering only the wind power plant.

## 4.2. Boundary conditions for the experimental tests

The characteristic curves referring to the month of July, for the summer tests, and to the month of November, for the winter tests, have been considered. The characteristic curves are the photovoltaic and wind power generation curves, the building's electrical consumption and the electrical consumption of the users in the building. The heat demands curves for domestic hot water, heating and cooling.

The characteristic curves of the building's electricity demand and the users in the building are shown below

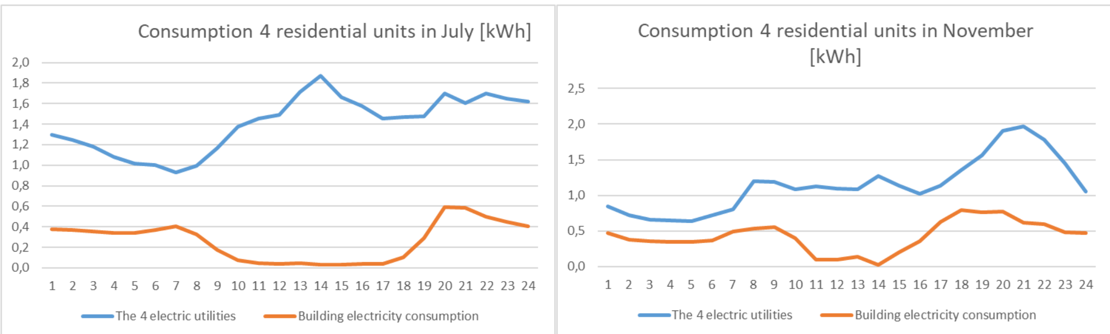



**Figure 2 Characteristic curves of the electricity demand of the building and the users in the building for summer and winter.**

The load profile was designed to be proportional to the electricity, central cooling and domestic hot water needs of an apartment block consisting of four units. This choice was agreed upon mainly according to the size of the photovoltaic, storage tanks and heat pump of S.A.P.I.EN.T.E.

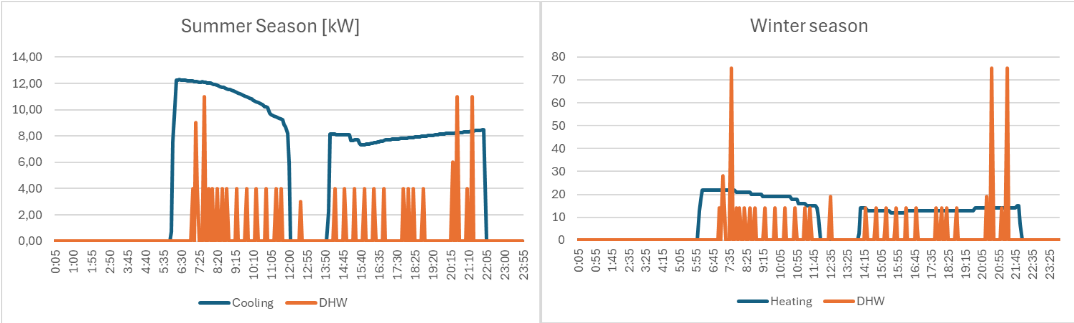


**Figure 3 Characteristic curve for domestic hot water, heating and cooling demand divided according to seasonality.**

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 PV and wind or using Pth logics.

Regarding generation from renewable sources, a characteristic day of July was chosen to be replicated in the summer experiments, and the same was done with November for the winter tests.

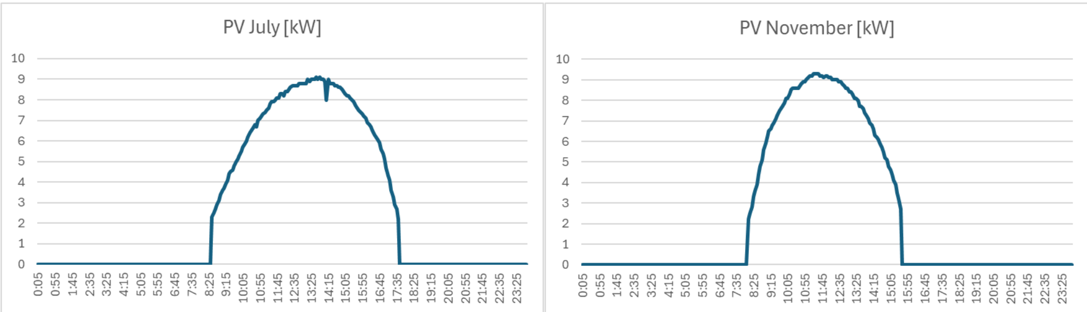


**Figure 4 Winter and summer photovoltaic generation curve.**

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 follows a pattern consistent with the climatic conditions at the location where the S.A.P.I.EN.T.E. system is installed.

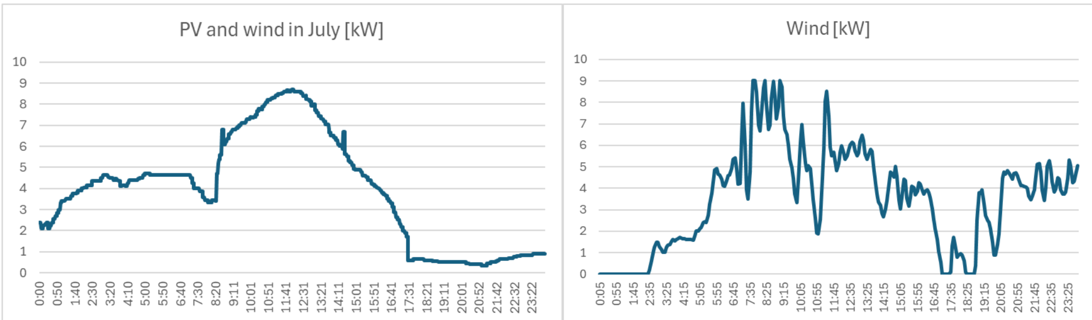


**Figure 5 Winter wind generation curve and summer photovoltaic and wind generation curve.**

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 in tables.

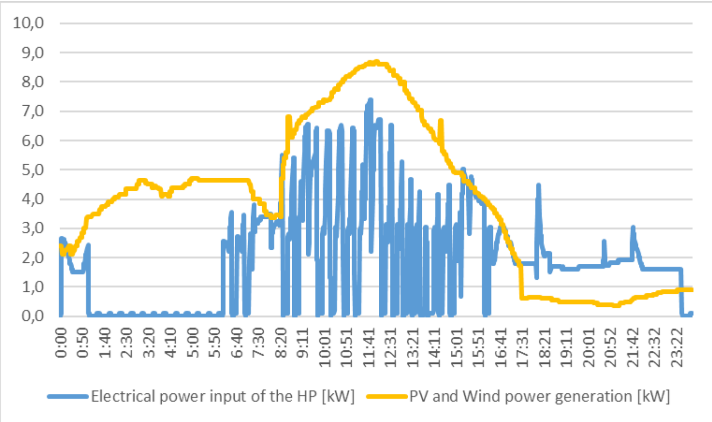
## 5. Experimentation

In the first test session, we focused on the summer season maximizing SC and SS while maintaining the necessary comfort for users. The test is on meeting the needs for hot water and cooling for the users inside the building. The building's electrical consumption was covered. The system was powered mainly by renewable energy sources (photovoltaic and wind power), and a smaller proportion of energy was taken from the grid. The overall results of the test in wind and PV mode are shown in the figure above with the electrical consumption curve of the HP required to meet the heat load. The HP follows the course of PV and wind power generation in a way that controls the power absorbed by the HP compressor to optimize and SC. Electricity and incentive costs for the month of July were considered according to regulations and fluctuations in the Italian electricity market.

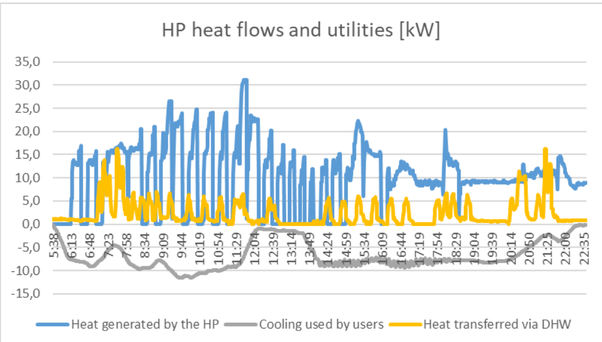
### 4.1. Summer test

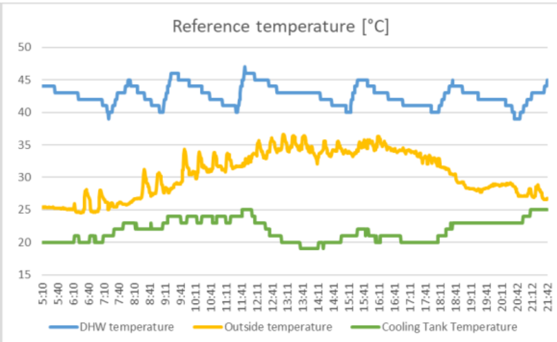
A summary table of the test carried out and the graph showing the trend of the main energy flows, the generation curve from renewable sources and the HP absorption curve is shown.

| Summer test | |
|---|---|
| Type of operation | DHW + Cooling |
| ACS Thermal Source | Heat Pump |
| RES PtH tracking | PV + Wind |
| Thermal profile | DHW + Cooling |
| Electrical profile | Building and utilities |
| Storage system | No |
| Self-consumption (SC) | 42% |
| Self-sufficiency (SS) | 80% |
| Net profit | 13,30 € |



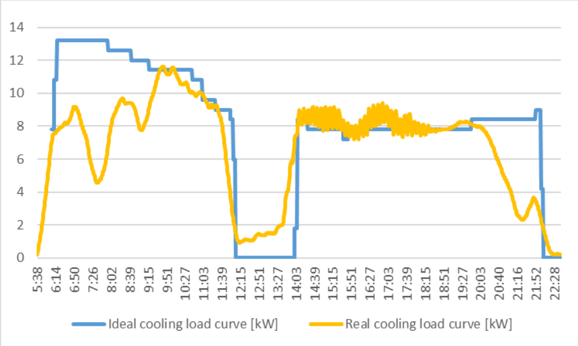

Energy flows are exchanged on an hourly basis. The hourly flow of energy consumed and energy produced considering all components are shown below. The graph on the left shows the total thermal energy produced by the heat pump, both that for DHW and cooling the building. The same graph shows the heat demand for DHW and for cooling. On the right is the temperature trend on the two dedicated storage tanks and the outdoor temperature.

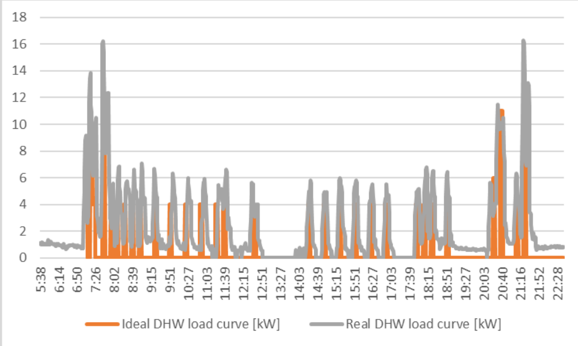



The DHW temperature varies between 40 and 45 °C and is therefore in an acceptable range. For cooling, the storage temperature ranges from 19 to 25 °C, also in an acceptable temperature range.

The ideal cooling load profile and the actual load profile are shown below. The adjacent diagram shows the ideal DHW load and the real DHW load. The graphs show a good overlap of the curves in the case of DHW. In the case of cooling the overlap coefficient is lower. This graph serves to realize how true to reality this test is. Below is a table with the thermal coefficients of the graphs shown.




In the following table the thermal coefficients are represented.

| Thermal performance | | |
|---|---|---|
| Average daily COP | 4,44 | - |
| HP distribution efficiency -> Utilities | 0,86 | - |
| Real DHW load divided by ideal DHW load | 0,97 | - |
| Real cooling load divided by ideal cooling load | 0,87 | - |

The following table outlines all major energy flows, which are also considered in the calculation of the daily net profit. Below is the graph representing divided on hourly intervals of the electrical energy consumed by the building and the electrical energy produced by the RES plants.

**Table 1 Energy flows during the day**

| Daily energy flows | | |
|---|---|---|
| Electricity consumed by the building (HP, lights, lifts, pump, garage) | 50,1 | kWh/day |
| Electrical energy absorbed only by HP | 43,7 | kWh/day |
| Thermal energy produced by HP | 194,2 | kWht/day |
| Daily heat requirement (cooling + DHW) | 166,6 | kWht/day |
| Electricity taken from the grid | 10,0 | kWh/day |
| Electricity delivered to the grid | 54,8 | kWh/day |
| Electricity produced by RES | 94,9 | kWh/day |
| Electricity in virtual self-consumption | 20,3 | kWh/day |
| Electricity in physical self-consumption | 36,7 | kWh/day |

The main electricity tariffs are reported. According to Italian regulations, electricity produced from domestic renewable sources such as photovoltaics is sold to the reference entity, the Gestore dei Servizi Energetici (GSE) according to the tariff set by the energy market, the model used is called dedicated withdrawal (RID). The consumer continues to have a direct contract with the private supplier at a single-rate or time-based tariff. According to recent regulations related to European directives, the European and Italian electricity market is being transformed, there are new opportunities for consumers to take incentives for self-consumed electricity virtually. In this case, the consumer will continue to purchase electricity according to the rates set by the supplier but will benefit from some incentives on self-consume energy. An additional benefit comes instead from direct self-consumption of electricity, thus directly from generation to consumption. In this way there will be no incentives from the GSE but also no cost of energy taken from the grid. The gain will correspond to the electricity saved in case you purchased it.

**Table 2 Reference incentives and energy costs for the month of July.**

| Incentive tariffs and electricity costs for July | | |
|---|---|---|
| RID dedicated withdrawal tariff (July 2024) - average value F1, F2 and F3 | 0,10 | €/kWh |
| Savings from electricity not withdrawn (physical self-consumption) | 0,18 | €/kWh |
| Electricity purchase tariff (July 2024) | 0,18 | €/kWh |
| Virtual self-consumed electricity incentive | 0,14 | €/kWh |

**Table 3 Negative and positive costs and the total balance for the day.**

| Daily energy costs | | |
|---|---|---|
| Revenues from electricity sold and self-consumed virtually | 15,1 | € |
| Total building cost for DHW and cooling | -1,8 | € |
| Total balance | 13,3 | € |

The environmental coefficients associated with the use of renewable sources are summarized in this table, which shows the amount of energy saved, measured in tons of oil equivalent, and the related carbon dioxide equivalent emissions saved.

**Table 4 Environmental coefficients for the reference day**

| Environmental coefficients | | |
|---|---|---|
| Tonnes of oil equivalent saved by RES generation | 0,008 | TOE |
| Carbon dioxide equivalent emissions saved by RES generation | 40,9 | kg |

## 4.2. Winter Season

Winter tests are divided into four main trials the first two involve the use of PV plant. In the first case, no Pth logic is applied, while in the second case, Pth logics are implemented. In the third and fourth cases, a simulated wind power plant is used instead of the real PV plant differentiating the two cases according to whether P2h is used or not.

**Table 5 Boundary conditions used for winter tests.**

| Winter tests | | | | |
|---|---|---|---|---|
| Type of operation | DHW + Heating | DHW + Heating | DHW + Heating | DHW + Heating |
| ACS Thermal Source | Heat Pump | Heat Pump | Heat Pump | Heat Pump |
| Thermal profile | DHW + Heating | DHW + Heating | DHW + Heating | DHW + Heating |
| Electrical profile | Building and utilities | Building and utilities | Building and utilities | Building and utilities |
| RES | PV | PV | Wind | Wind |
| RES PtH tracking | No | PV | No | Wind |
| Self-consumption (SC) | 61% | 72% | 74% | 78% |
| Self-sufficiency (SS) | 32% | 44% | 75% | 82% |
| Net profit | -3,40 € | 0,40 € | 12,30 € | 14,10 € |

### 4.2.1 Photovoltaic without renewable energy source power-to-heat tracking - Baseline

The first figure, on the left, shows the instantaneous trend of the HP's absorption for heating and DHW generation and the PV generation curve. These two curves are not linked in any way. The curve on the right shows the curves with hourly average values, the PV generation curve is the same, while the consumption curve also includes the building's consumption of common areas, such as lights, lift and pumps.

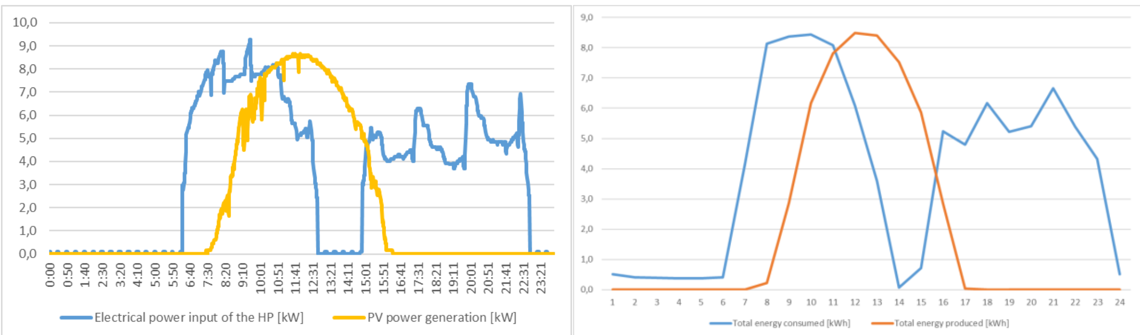
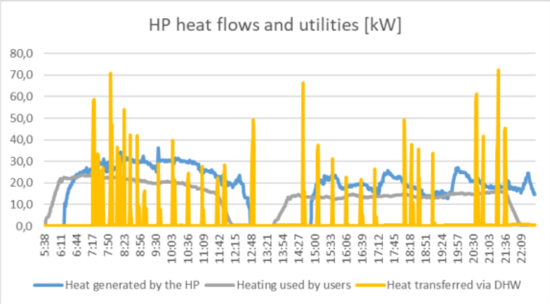
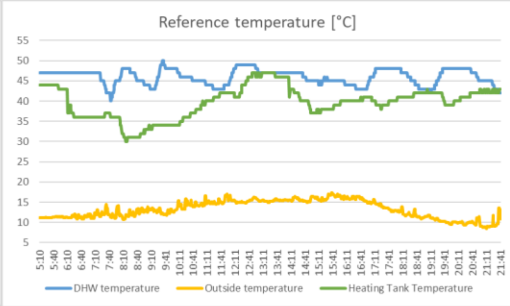


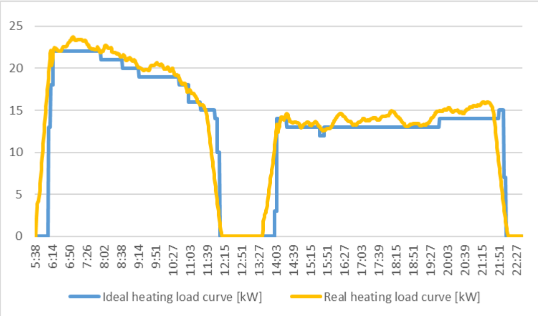

**Figure 6 On the left PV generation curve and HP consumption; on the right PV generation curve and total consumption**

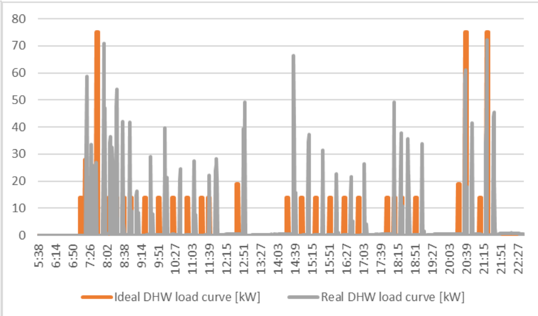
The graph on the left shows the total thermal energy produced by the HP, both that for DHW and heating. The same graph shows the heat demand for DHW and for heating. On the right is the temperature trend on the two dedicated storage tanks and the outdoor temperature.




The DHW temperature varies between 40 and 50 °C and is therefore in an acceptable range. For heating, the storage temperature ranges from 30 to 47 °C. At least 40 °C should be ensured for this type of building.




The ideal cooling load profile and the actual load profile are showed. The adjacent diagram shows the ideal DHW load and the real DHW load. The graphs show a good overlap of the curves in the case of DHW. In the case of heating the overlap coefficient is good too.

**Table 6 Thermal coefficients of the test**

| Thermal performance | | |
|---|---|---|
| Average daily COP | 3,80 | - |
| HP distribution efficiency -> Utilities | 0,89 | - |
| Real DHW load divided by ideal DHW load | 0,92 | - |
| Real heating load divided by ideal heating load | 1,06 | - |

The following table summarizes the main energy flows used to calculate energy coefficients, system efficiencies and profits.

**Table 7 Main energy flows for calculating energy coefficients**

| Daily energy flows | | |
|---|---|---|
| Electricity consumed by the building (HP, lights, lifts, pump, garage) | 93,8 | kWh/day |
| Electrical energy absorbed only by HP | 83,5 | kWh/day |
| Thermal energy produced by HP | 317,7 | kWht/day |
| Daily heat requirement (heating + DHW) | 283,6 | kWht/day |
| Electricity taken from the grid | 63,4 | kWh/day |
| Electricity delivered to the grid | 19,8 | kWh/day |
| Electricity produced by RES | 50,2 | kWh/day |
| Electricity in virtual self-consumption | 2,9 | kWh/day |
| Electricity in physical self-consumption | 30,0 | kWh/day |

Below are the rates considered for the winter tests.

**Table 8 The incentives and energy costs for November**

| Incentive tariffs and electricity costs for November | | |
|---|---|---|
| RID dedicated withdrawal tariff (November 2024) - average value F1, F2 and F3 | 0,12 | €/kWh |
| Savings from electricity not withdrawn (physical self-consumption) | 0,19 | €/kWh |
| Electricity purchase tariff (November 2024) | 0,19 | €/kWh |
| Virtual self-consumed electricity incentive | 0,14 | €/kWh |

The cost trend for the day was negative.

**Table 9 Negative and positive costs and the total balance for the day.**

| Daily energy costs | | |
|---|---|---|
| Revenues from electricity sold and self-consumed virtually and physically | 8,7 | € |
| Total building cost for DHW and heating | -12,1 | € |
| Total balance | -3,4 | € |

The environmental coefficients associated with the use of renewable sources are summarized in this table, which shows the amount of energy saved, measured in tons of oil equivalent, and the related carbon dioxide equivalent emissions saved.

**Table 10 Environmental coefficients for the reference day**

| Environmental coefficients | | |
|---|---|---|
| Tonnes of oil equivalent saved by RES generation | 0,004 | TOE |
| Carbon dioxide equivalent emissions saved by RES generation | 21,6 | kg$CO_2$ |

## 4.2.2 Photovoltaic with renewable energy source power-to-heat tracking

It can be seen in the curve on the left that the heat pump's absorption falls into the PV curve during the central hours and then exits the Pth logic to meet the comfort of the users. On the right-hand side, the total consumption of the building is displayed over and above the PV generation. In this mode, a good SC coefficient of 72% is obtained.

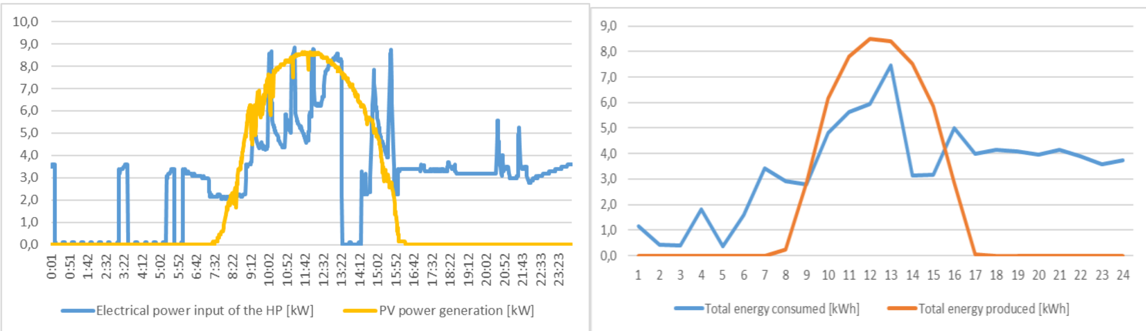
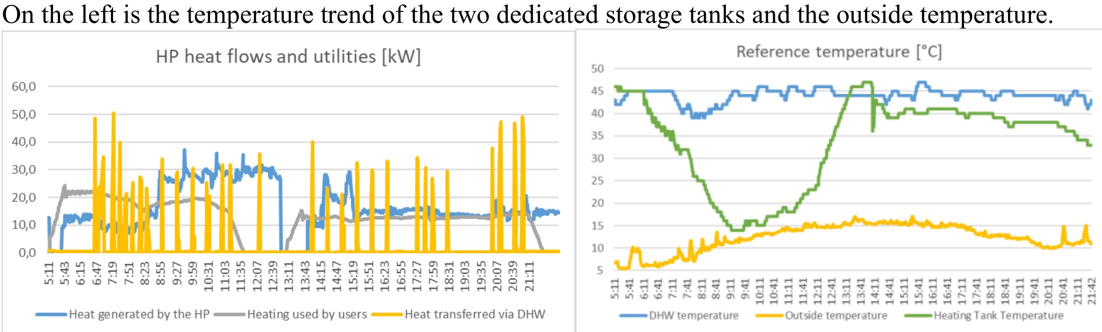
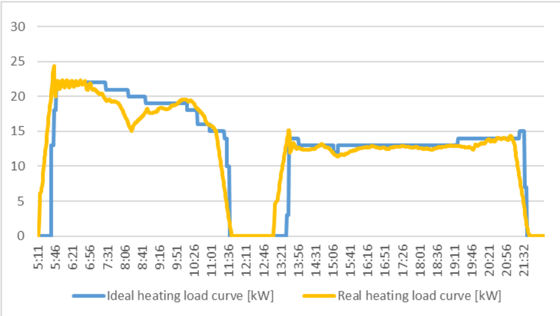


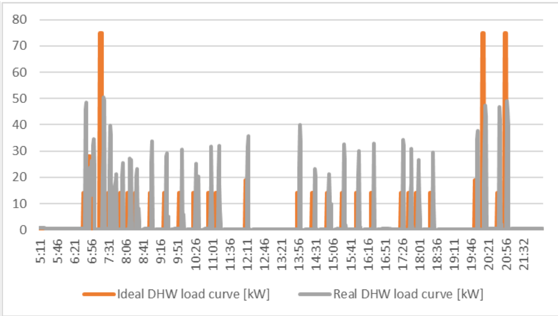

**Figure 7 On the left PV generation curve and HP consumption; on the right PV generation curve and building consumption**

The graph on the left shows the total thermal energy produced by the heat pump, both for heating and DHW. On the same graph are the load emitted by the dry coolers for DHW and for heating the consumers.
On the left is the temperature trend of the two dedicated storage tanks and the outside temperature.




The temperature of the heating and DHW storage tank is show. The DHW temperature varies between 40 and 46 °C and is therefore in an acceptable range. For heating, the storage temperature ranges from 15 to 47 °C. The temperature for the heating tank dropped from 45 °C to 15 °C in three hours, the load was considerable and the heat pump did not deliver enough heat to meet the load, which resulted in the tank cooling down and a rise in the tank temperature to 45 °C at around 13:00, which was also due to a higher power output from the HP and a decrease in the load delivered by the HP






The ideal heating load profile and the actual load profile are shown. The adjacent diagram shows the ideal DHW load and the real DHW load. The graphs show a good overlap of the curves in the case of DHW, while in the case of heating the overlap coefficient is lower. In this case, the load simulation went very well for both DHW and Heating. Below is a table with the thermal coefficients of the graphs shown.

| Thermal performance | | |
|---|---|---|
| Average daily COP | 4,27 | - |
| HP distribution efficiency -> Utilities | 0,88 | - |
| Real DHW load divided by ideal DHW load | 0,96 | - |
| Real heating load divided by ideal heating load | 0,99 | - |

The following is a table with all major energy flows. In these energy flows are the flows also considered for the calculation of daily net profit.

| Daily energy flows | | |
|---|---|---|
| Electricity consumed by the building (HP, lights, lifts, pump, garage) | 81,5 | kWh/day |
| Electrical energy absorbed only by HP | 71,2 | kWh/day |
| Thermal energy produced by HP | 304,1 | kWht/day |
| Daily heat requirement (heating + DHW) | 269,1 | kWht/day |
| Electricity taken from the grid | 45,5 | kWh/day |
| Electricity delivered to the grid | 14,2 | kWh/day |
| Electricity produced by RES | 50,2 | kWh/day |
| Electricity in virtual self-consumption | 4,9 | kWh/day |
| Electricity in physical self-consumption | 34,5 | kWh/day |

Below is the table with the negative and positive costs and the total balance for the day.

| Daily energy costs | | |
|---|---|---|
| Revenues from electricity sold and self-consumed virtually and physically | 9,1 | € |
| Total building cost for DHW and heating | -8,7 | € |
| Total balance | 0,4 | € |

The environmental coefficients associated with the use of renewable sources are summarized in this table, which shows the amount of energy saved, measured in tons of oil equivalent, and the related carbon dioxide equivalent emissions saved.

| Environmental coefficients | | |
|---|---|---|
| Tonnes of oil equivalent saved by RES generation | 0,004 | TOE |
| Carbon dioxide equivalent emissions saved by RES generation | 21,6 | kg$CO_2$ |

### 4.2.3 Eolic without renewable energy source power-to-heat tracking – Eolic baseline

The curve on the left shows the HP absorption and wind generation curve. On the right the total building consumption trend and the wind generation curve on hourly average

The reference day is the same as for PV, the HP's electrical and thermal load trends are the same, as are the storage temperatures and the correspondence of ideal and real loads such as thermal performance. The only substantial difference is the generation curve.

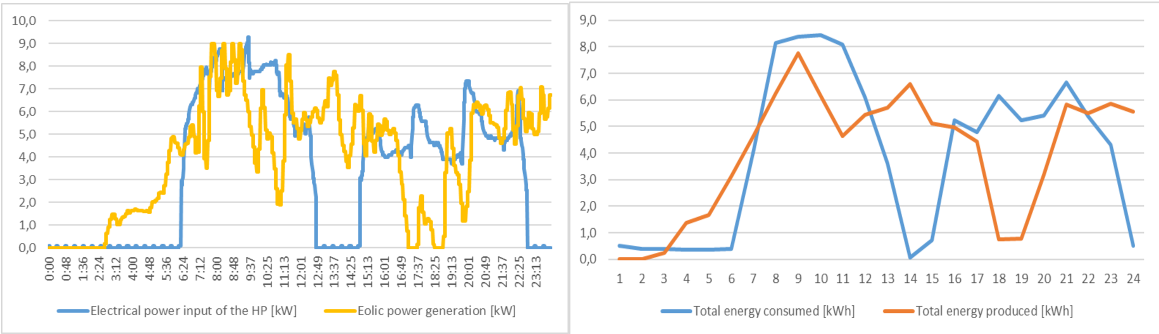



**Figure 8 On the left Eolic generation curve and HP consumption; on the right Eolic generation curve and building consumption**

Below is the table with the main energy flow. The daily wind generation curve has a higher contribution of energy from RES than from PV.

| Daily energy flows | | |
|---|---|---|
| Electricity consumed by the building (HP, lights, lifts, pump, garage) | 93,8 | kWh/day |
| Electrical energy absorbed only by HP | 83,5 | kWh/day |
| Thermal energy produced by HP | 317,7 | kWht/day |
| Daily heat requirement (heating + DHW) | 283,6 | kWht/day |
| Electricity taken from the grid | 23,5 | kWh/day |
| Electricity delivered to the grid | 25,3 | kWh/day |
| Electricity produced by RES | 95,6 | kWh/day |
| Electricity in virtual self-consumption | 7,7 | kWh/day |
| Electricity in physical self-consumption | 66,9 | kWh/day |

Incentive tariffs and electricity costs for November are the same in the case of PV. Below is the total balance sheet with the costs and gains explained.

| Daily energy costs | | |
|---|---|---|
| Revenues from electricity sold and self-consumed virtually and | 16,9 | € |
| Total building cost for DHW and heating | -4,5 | € |
| Total balance | 12,4 | € |

The environmental coefficients associated with the use of renewable sources are summarized in this table, which shows the amount of energy saved, measured in tons of oil equivalent, and the related carbon dioxide equivalent emissions saved.

| Environmental coefficients | | |
|---|---|---|
| Tonnes of oil equivalent saved by RES generation | 0,008 | TOE |
| Carbon dioxide equivalent emissions saved by RES generation | 41,2 | kg$CO_2$ |

### 4.2.4 Eolic with renewable energy source power-to-heat tracking

The wind generation curve with Pth tracking with instantaneous trend is shown on the left. The electrical absorption curve of the HP compressor matches for the most part, although it could be better. Overall, the trend over the day is good, also considering the overall consumption of the building, as shown on the curve on the right, we get a good SC coefficient (78%) on the day.

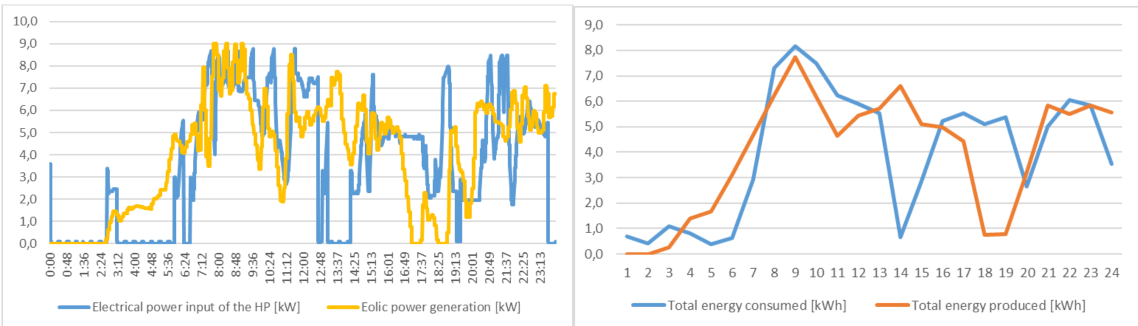
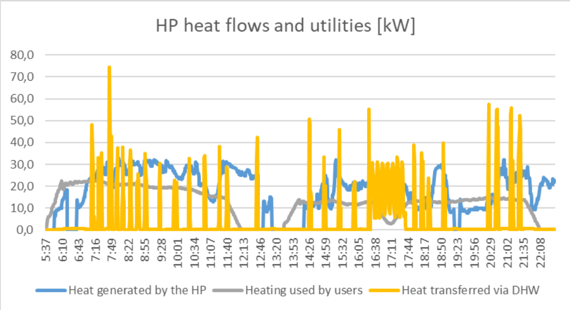
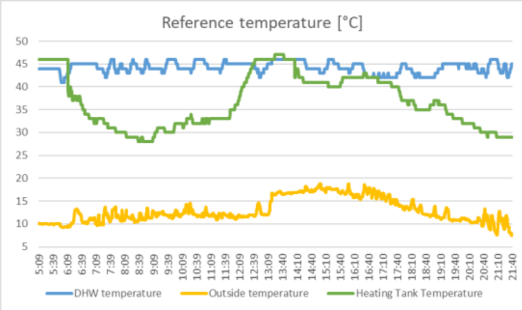



**Figure 9 On the left Eolic generation curve and HP consumption; on the right Eolic generation curve and building consumption**

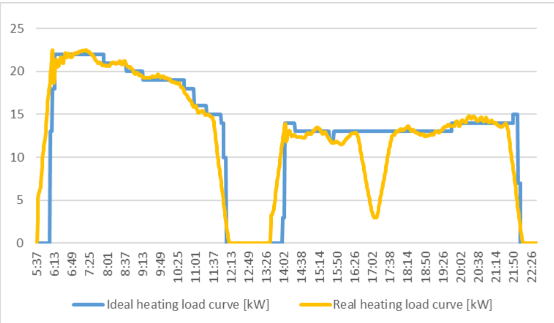
The graph on the left shows the total thermal energy produced by the HP so both that for heating and DHW, and the single output of the two dry cooler side loads in the same graph. On the right is the temperature trend on the two dedicated storage tanks and the outdoor temperature.

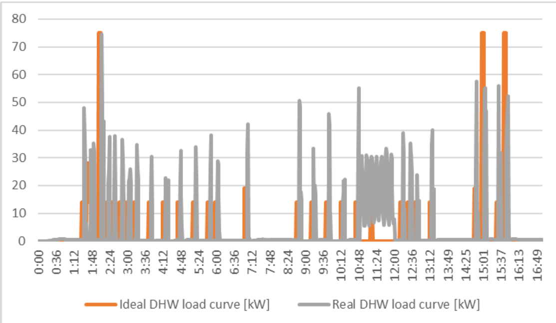



The temperature of the heating and domestic hot water storage tank is given below. The domestic hot water temperature varies between 40 and 47 °C and is therefore in an acceptable range. For heating, the storage temperature ranges from 29 to 47 °C. The morning load led to the tank cooling down and the HP brought the load to the correct temperature around 1pm.

As can be seen from the following graphs there was a technical problem on both the DHW and heating side in the afternoon at around 17:00




The ideal heating load profile and the real load profile are shown. The adjacent diagram shows the ideal DHW load and the real DHW load. The load is not a good match due to the technical problem in the afternoon. The overlapping of the graphs in the case of heating is better but not perfect. Below is a table with the thermal coefficients of the graphs shown.

| Thermal performance | | |
|---|---|---|
| Average daily COP | 3,88 | - |
| HP distribution efficiency -> Utilities | 0,90 | - |
| Real DHW load divided by ideal DHW load | 1,56 | - |
| Real heating load divided by ideal heating load | 0,98 | - |

The following is a table with all major energy flows.

| Daily energy flows | | |
|---|---|---|
| Electricity consumed by the building (HP, lights, lifts, pump, garage) | 95,4 | kWh/day |
| Electrical energy absorbed only by HP | 85,1 | kWh/day |
| Thermal energy produced by HP | 330,5 | kWht/day |
| Daily heat requirement (heating + DHW) | 298,4 | kWht/day |
| Electricity taken from the grid | 17,7 | kWh/day |
| Electricity delivered to the grid | 17,9 | kWh/day |
| Electricity produced by RES | 95,6 | kWh/day |
| Electricity in virtual self-consumption | 7,4 | kWh/day |
| Electricity in physical self-consumption | 74,0 | kWh/day |

Below is the total balance sheet with the costs and gains explained.

| Daily energy costs | | |
|---|---|---|
| Revenues from electricity sold and self-consumed virtually and | 17,3 | € |
| Total building cost for DHW and heating | -3,4 | € |
| Total balance | 13,9 | € |

### 4.2.5 Profit Indicator

I have calculated the profit indicator for the winter tests of PV and wind power in the case of heat pump utilization with tracking of renewable energy sources. It turns out that in the case of PV the profit is very large (112%), whereas in the case of wind power the profit margin is smaller (15%). This is because wind power has a more varied daily pattern than PV and the overlap between energy generation and use is more likely. Furthermore, the amount of energy can also vary the coefficient. In the case of PV, less energy is generated, so it is important to try to utilize it all through demand management logic.
In this situation, we can say that in the case of using a PV generation plant, the profit margin by applying demand management logic is a very good opportunity.

| | | |
|---|---|---|
| Profit Indicator (PI) | 112% | PV |
| | 15% | Eolic |

## 6. General Analysis of the Considered Variables and Conducted Tests

The tests carried out are highly complex due to the number of variables involved. A broader analysis reveals the following aspects:

1. The most profitable electricity is, and will always be, the electricity not consumed; Pth strategies will be effective only if electricity demand does not increase, or even decreases, compared to scenarios that do not adopt this approach .
2. Efficiency strategies aimed at reducing energy demand, such as improving the building envelope or installing high-efficiency systems like next-generation HP, will prove to be the best solutions for increasing the sustainability of an energy system.
3. Particular attention must be paid to the thermal energy distribution system and its intrinsic losses to adopt the most effective strategies.
4. Final consumption, or more precisely, the final comfort level associated with the user's consumption, will remain a fundamental parameter. It will only make sense to compare the efficiency and sustainability of different systems if the final comfort level is the same.
5. The variables involved in these dynamics are numerous and depend on the characteristics of the building and systems, user behaviour and presence, external conditions, and the renewable energy systems considered. Furthermore, some consumption strategies will be more effective than others depending on the national electricity market. To draw general conclusions, the variables must be standardized and boundary conditions formulated, keeping in mind that individual cases may behave entirely differently from the analysis developed in this set of tests.
6. Some results obtained from this group of tests can be related to the gains, by RES, achieved through the application of electricity demand management strategies.
7. SC of energy produced from RES proves to be particularly advantageous in summer, more than in winter, due to the different incentive values of the dedicated withdrawal mechanism.

## 7. 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 PtH and load shifting strategies. Moreover, we demonstrated how diversifying generation capabilities, making power production available throughout the whole day, can have a beneficial impact. We also show how converting electrical power into thermal power by means of a HP can enhance the energy coefficients, while also warranting thermal comfort to the RECs users. Finally, we have shown that the application of the described strategies can have a higher impact when involving PV plants respect to wind power plants.

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