DECARBONIZATION OF DOMESTIC HOT WATER GENERATION IN SMALL ISLANDS USING PHOTOVOLTAIC SOLAR WITH A HYBRID ELECTRIC-THERMAL ENERGY STORAGE SYSTEM

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ABSTRACT

Small, isolated grids face an especially challenging task when dealing with the decarbonization of our society, as they cannot rely on the grid to compensate for peaks of demand and production.

On small Mediterranean islands, domestic hot water generation accounts for a particularly significant contribution to the energy demand, both in the residential sector and in the tourist industry. The case of the island of Lampedusa, where 40-50% of end users' electricity consumption can be attributed to DHW generation, provides a relevant example of how large the impact of domestic hot water demand can be on the local grid and on the overall energy demand.

With the aim of contributing to the decarbonisation of small island's energy systems, this study presents a system for the efficient generation of domestic hot water using renewable resources and analyses its performance by means of an experimental setup.

The proposed system is composed of three photovoltaic (PV) modules, for a total installed power of 1.74 kW, a hybrid inverter, a heat pump, and a combination of electric energy storage (3.6 kWh supercapacitor) and thermal energy storage (200 litres hot water tank). The combination of the PV and heat pump allows high efficiency in hot water generation; the combination of electric and thermal energy storage provides a cost-effective and flexible balance between the maximisation of self-consumption and the reduction of investment costs.

The system was installed at the ENEA research and monitoring centre in Lampedusa. The hot water energy demand was simulated using a dedicated system based on the typical consumption of a domestic user. The system's performance was estimated in terms of its self-consumption, self-sufficiency, and based on its ability to meet the domestic hot water demand at all times.

The results of the experimental campaign allowed verifying the system's ability to effectively generate hot water when needed, and to do so while shifting the electricity demand to periods of peak production and minimising the power exchange with the grid, allowing to self-consume up to 63% of the energy generated by the PV modules. The results of the tests also allowed to identify some elements in the system that can be further improved, especially with the objective of retrofitting the proposed control system to existing installations.

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1 INTRODUCTION

1.1 Background

Greenhouse gas emissions are the primary cause of global warming, a phenomenon closely related to issues of energy production, land use, changing in lifestyle and consumption patterns that have influenced the relationship between people, the planet, and its resources (IPCC, 2021). Therefore, the adoption of decarbonisation policies and the consequent reduction of emissions has become a global priority.

In this context, small islands represent a special case, that present specific opportunities and constraints. Renewable resources are often abundant on small islands, especially solar and wind energy; increasing the penetration of these intermittent energy sources, however, can be particularly challenging, as shown by their limited contribution to the electricity mix (Kuang et al., 2016).

First, the fact that many small islands are isolated from mainland grids makes it more difficult to achieve the correct balancing between supply and demand, both for the limited inertia of the system and because of the high level of correlation between the times of high and low contribution of different generation systems.

Compared to other energy systems, geographical conditions can also be particularly limiting. Small islands rarely present abundance of programmable renewable resources such as hydropower and biomass, which could otherwise help maintaining balance in the system. In addition, as many small islands rely on tourism as their main economic activity, landscape concerns become of high relevance: this can be a limitation for a more widespread adoption of wind power (Ciriminna et al., 2016), which normally integrates well with solar power, thus further increasing grid balancing issues.

On the other hand, the energy transition also constitutes an opportunity for small islands. Islands generally depend entirely on imported, expensive, fossil fuels to satisfy their energy needs, and relying on local renewable energy sources can improve energy while reducing energy costs (Sánchez et al., 2023).

This is particularly true in the case of domestic hot water (DHW) generation. While on land it is most often generated using cheap natural gas, this is not the case on small islands, often not equipped with a natural gas network, where it generally relies on electric boilers instead. These can take a significant share of the total electricity demand in small islands' households: in the case of Lampedusa, it was estimated that 40-50% of end users' electricity consumption can be attributed to DHW generation, something which has a high impact on the overall balance of the island (Pavanello et al., 2021).

This paper thus focuses on renewable DHW generation, with a specific attention to solutions that can combine high efficiency, low cost, and maximise self-consumption.

1.2 Literature review

Pomianowski et al. (2020) provide an excellent overview of sustainable and energy-efficient DHW systems. Clearly, the study highlights the potential synergy of two main technologies: heat pumps (HP), and photovoltaic (PV) solar panels.

There is extensive literature on the combined use of PV panels and HPs for DHW generation, a solution that is also starting to become common commercially. Aguilar, Aledo, et al. (2016), for instance, monitored a PV-HP system in Alicante (Spain) for one year, showing that the heat pump could contribute to more than 60% of the total DHW demand with only 470 W of PV panels installed, in spite of the relatively simple control system. The same authors tested a slightly different setup, where the energy generated from the PV system when the HP is off is used in an electric resistance instead, so that all the energy from the PV is used to generate DHW and not injected to the grid (Aguilar, Crespí-Llorens, et al., 2019); this configuration showed to be particularly efficient in reducing CO_2 emissions (82% compared to a traditional boiler), maximising self-consumption (100%) and reducing electricity demand peaks from the system.

Compared to electric boilers, HPs have limits in the degree of self-sufficiency and/or self-consumption that they can achieve if coupled with PV panels because of their limitation to ON/OFF operations. One solution can be that of operating the heat pump at variable speed; while the results reported by Szreder

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and Miara (2020) are promising, this solution is still not available commercially, and it could result in additional wear of the heat pump. For this reason, earlier work by the authors (Ballistreri et al., 2022) and by Zhang et al. (2024) proposed coupling the heat pump with an electric energy storage (EES) system, that can be used to compensate load and PV generation fluctuations.

This type of hybrid system features high levels of energy savings and reasonable economic performance, if sufficient incentives are available (Beccali et al., 2020). Detailed, yearly simulations performed in Matlab-Simulink environment (Ballistreri et al., 2022) showed that this configuration allows a more optimal trade-off between self-sufficiency, self-consumption and comfort when compared to a similar system without EES; a grid-connected, hybrid system allows achieving above 90% self sufficiency with only 740 W of PV installed ("M" DHW load as defined by the EN 50440:2015 norm).

1.3 Aim

Given the promising performance showed in computer simulation, this paper focuses on the experimental implementation of the system.

2 METHOD

2.1 System description

The hybrid system used in the tests is showed in Figure 1 and is installed at the ENEA observatory in Lampedusa. It is composed of the following components:

- a 490 W HP for DHW, rated COP = 3.071, integrated 200-litre storage (Figure 2c);
- a 1740 W_p PV system (Figure 2a);
- a hybrid inverter (1.5 kVA, 94% rated efficiency), able to recharge the electric storage from the grid with a four-phase adaptive technology, feed into the grid the PV electricity, and cover the load with energy from the grid and PV at the same time (Figure 2b);
- a 3000 Wh EES system based on supercapacitor technology (Figure 2b).

The simulation of the DHW demand is allowed by a closed hydraulic circuit connected to the HP that includes a 5000-liter tank, whose thermal capacity allows the system to operate at an approximately constant supply temperature.

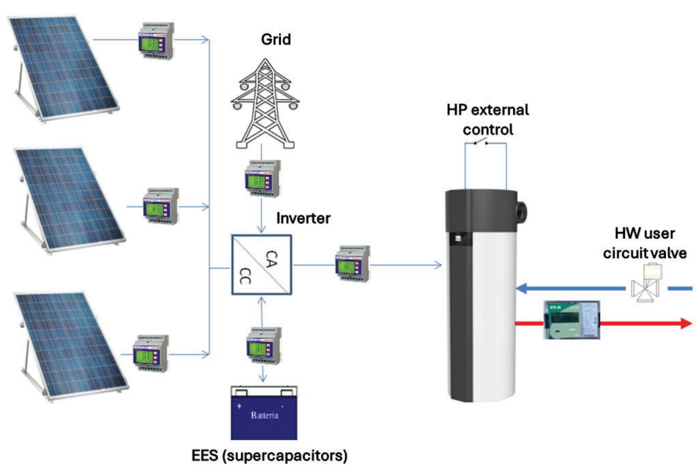

Figure 1: System diagram of the hybrid PV-HP-EES HW generator system

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(a) PV plant **(b)** Inverter and EES **(c)** Heat pump

Figure 2: Photos of the system components installed at the ENEA research centre in Lampedusa

Algorithm 1 HP control algorithm implemented in the PLC

measure $\dot{W}_{PV}$ and T_{HP}
if $\dot{W}_{PV} > \dot{W}_{PV}^{min}$ **then**
  if HP is OFF **then**
    if $T_{HP} < T_{HP}^{min}$ **then**
      turn ON the heat pump
    end if
  else if HP is ON **then**
    if $T_{HP} > T_{HP}^{max}$ **then**
      turn OFF the heat pump
    end if
  end if
end if

2.2 System management and control

The inverter is controlled based on the following principle: the priority goes to the load(s) connected to the inverter: if the power from the PV panels is not sufficient, additional power is drawn first from the EES, and then from the grid. If the PV panels generate more power than required by the load, the excess power is fed to the EES, until the maximum SOC is reached. At this point, extra power is fed to the grid. The inverter can also be operated in island mode, but this possibility was not employed in this study. The inverter also controls voltage settings to the PV panels, based on a MPPT logic, thus maximising conversion efficiency.

The HP, all throughout the duration of the tests, was operated based on its "solar" control mode: while the HP ensures that a minimum temperature of 40°C is maintained at all times, a dry contact allows to send an "activation" control signal to the HP. As long as the dry contact is closed the HP is switched on, until it reaches a maximum temperature, defined by a control logic within the HP itself as a function of the ambient temperature, in the range of 55°C to 60°C.

The activation control signal is implemented through an external programmable logic controller (PLC) and is based on measurements of the PV DC power output and on the HP hot water storage temperature. The control is rule-based, and defined by Algorithm 1 which is, in turn, based on the three parameters $\dot{W}_{PV}^{min}$, T_{HP}^{min} and T_{HP}^{max}. These parameters represent, respectively, the minimum PV output power for forcing the HP pump activation, the minimum HP storage temperature below which the HP is activated, and the maximum storage temperature above which the HP is deactivated.

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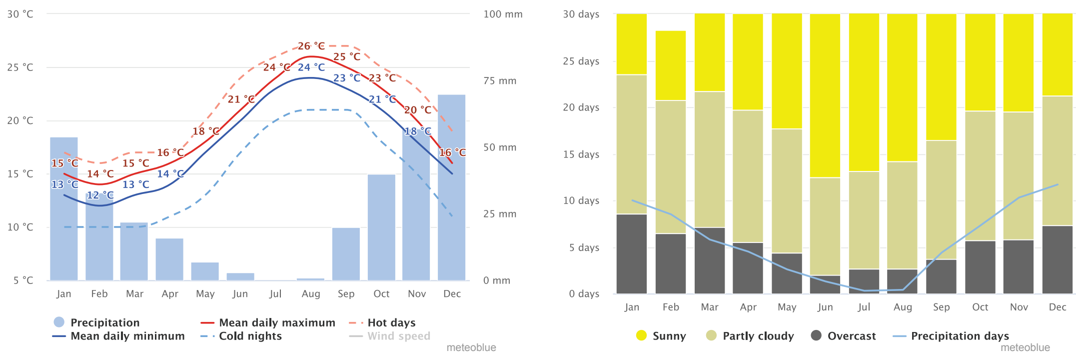
Type	Unit	Description
T	HP	Inlet water temperature
T	HP	Outlet water temperature
$\dot{m}$	HP	Water mass flow
T	HP	Inlet air temperature
T	HP	Outlet air temperature
$\dot{W}$	Inverter	Power to HP
$\dot{W}$	Inverter	Power to/from grid
$\dot{W}$	Inverter	Power to/from EES
$\dot{W}$	Inverter	Power from PV

Table 1: Full list of monitored measurements



(a) Monthly average temperatures

(b) Solar irradiation

Figure 3: Climate in Lampedusa

The DHW demand from the users is simulated using a closed hydraulic circuit, whose control is ensured by an electronically-controlled flow valve. The PLC's interface allows defining the open/close profile of the valve, thus allowing to simulate the DHW demand.

2.3 System monitoring and data acquisition

The PLC, in addition to providing system control, also allows monitoring and data acquisition. The full list of available measurements is provided in Table 1. All electric power measurements are acquired by the inverter, while all other measurements are acquired by the PLC; the HP inlet and outlet water temperature and the mass flow are acquired by an Isoil energy meter, which in turn is made of two PT500 thermistors and an ultrasonic flow meter; HP inlet and outlet air temperatures are measured by two PT100 thermistors;

Data logging for all the measurements acquired by the inverter is managed through the inverter's web portal; other measurements are logged by the PLC with a frequency of one point per minute.

The list in Table 1 lacks the measurement of the temperature of the HP hot water storage. This type of measurement would require intrusive operations on the HP, an operation that would be impossible to apply to real-life retrofits due to safety and insurance concerns. For this reason, the control was implemented by using the temperature measured at the HP outlet as proxy for the HP internal storage temperature.

2.4 Location

The experimental facility is located in the ENEA research facility on Lampedusa, a small island in the Mediterranean Sea located approximately 200 km South of Sicily (35.5086° N, 12.5929° E). The location

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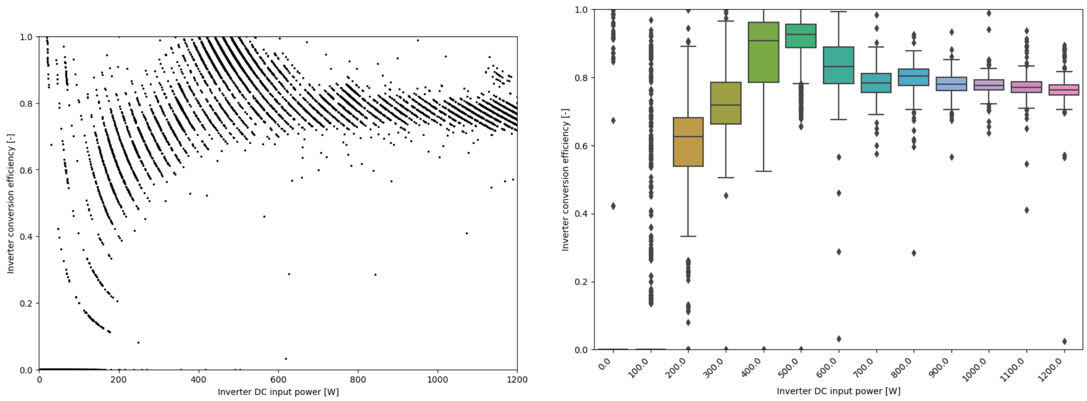

(a) Scatter plot

(b) Box plot

Figure 4: Inverter efficiency vs load

is representative of the climate of Sicilian small islands and enjoys a relatively mild climate, as shown in Figure 3.

2.5 Characterisation of system components

System components where characterised before and during the system tests.

In the case of the inverter, its instantaneous efficiency was calculated as shown in Equation 1 for each data point. The results are shown in Figure 4: while the strong fluctuations of the measurements generate similar fluctuations in the calculated inverter efficiency, the measurements confirm the expected overall correlation between inverter load and efficiency, with peak efficiency seen at around 30% of the maximum inverter load. Overall, however, the inverter operates at a relatively low efficiency (approximately 80% at medium to high load) most of the time.

$$\eta^i_{inv} = \frac{\dot{W}^i_{DC,in}}{\dot{W}^i_{AC,out}} = \frac{\dot{W}^i_{PV} + \dot{W}^i_{EES}}{\dot{W}^i_{HP} + \dot{W}^i_{grid}} \tag{1}$$

The HP's COP was instead estimated based on daily aggregated values, based on Equation 2. The COPs for all tests during which the difference between the initial and the final temperature of the HP internal storage was lower than 2°C are shown in Figure 5. Apart from Test 6, that seems to represent an outlier, the overall COP of the HP was calculated in the range of 3.1 to 3.7.

$$COP_{HP} = \frac{\sum_i \dot{m}^i_{user}(T^i_{HP,out} - T^i_{HP,in})\Delta t_i}{\sum_i \dot{W}^i_{HP}\Delta t_i} \tag{2}$$

Finally, the round-trip efficiency of the supercapacitors that are used as EES system was evaluated in dedicated tests, which resulted in a round-trip efficiency of 94%, 94% and 92%, respectively.

3 RESULTS

Figures 6 and 7 show the results of the test performed on the 02/11/2023, with the control parameters $\dot{W}^{min}_{PV}$, T^{min}_{HP} and T^{max}_{HP} respectively set to 800 W, 50°C and 51°C.

Figure 6 shows the relevant power flows measured during the test, whose sign is based on the balance at the inverter (positive values mean power flowing into the inverter, negative values mean power flowing out of the inverter). The horizontal dotted line is used for convenience to show the 800 W setting. The figure shows the system behaving as intended. During the initial part of the day, the PV power is uniquely

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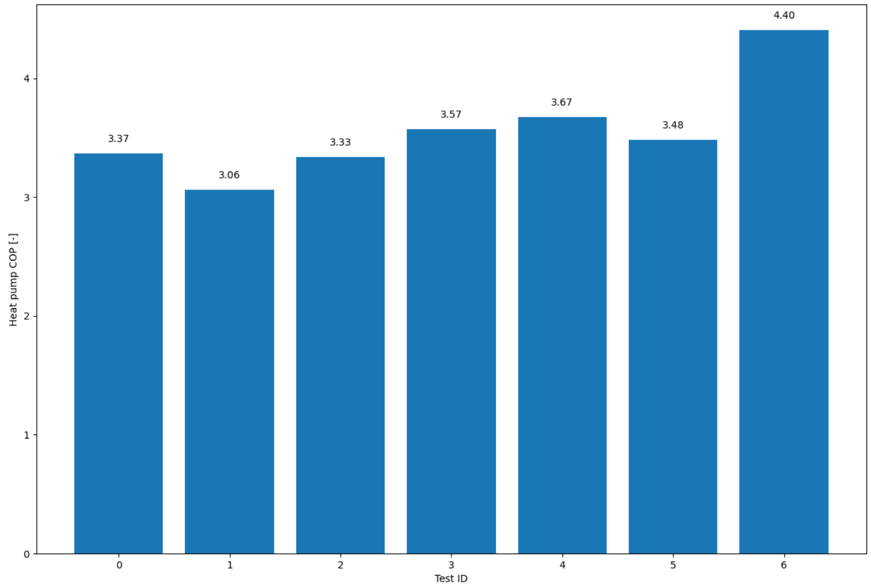

Figure 5: Heat pump COP for different tests

used to charge the EES; as soon as the output power reaches 800 W, the HP is activated and part of the PV generation is rerouted to power it; this allows to reduce the power flow to the grid during most of the day, with the exception of the period from 13:02 to 13:37, when the HP is turned off and a relatively high power is injected to the grid.

The analysis of the temperature profile highlights however the limitations related to using the HP hot water outlet temperature as proxy of the HP internal hot water temperature. As the outlet temperature is often lower than the actual internal temperature (aside from when the user valve is open), the heat pump actually heats up beyond the 51°C setpoint temperature; as soon as the user hot water flow is opened at

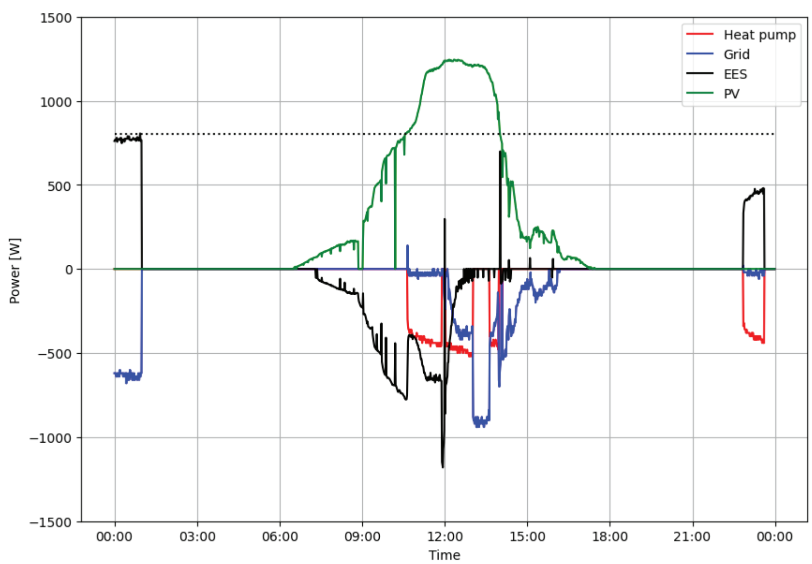

Figure 6: Power flows in the proposed system during the 02/11/2023 test

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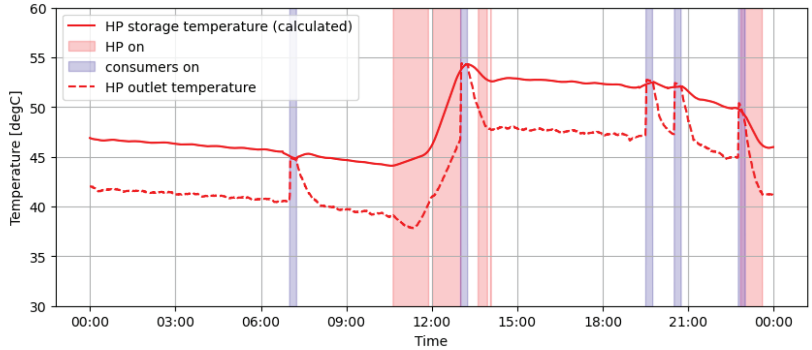

Figure 7: HP storage and outlet temperature in the proposed system during the 02/11/2023 test

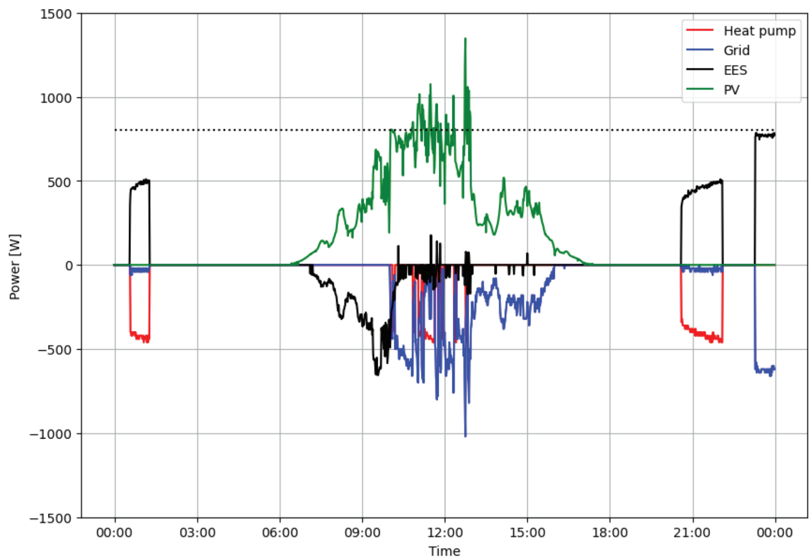

Figure 8: Power flows in the proposed system during the 01/11/2023 test

13:00, the measured outlet temperature increases rapidly to the actual internal temperature, prompting the deactivation of the HP. A few minutes after the valve is closed, as the temperature measured at the HP outlet decreases faster than the HP internal temperature, the temperature reaches 50°C and, thus, prompts the re-activation of the HP.

These control settings, especially $\dot{W}_{PV}^{min}$ = 800 W, are particularly suitable for sunny days. This can be seen when looking at the results of the test of the 01/11/2023 (Figure 8), which can be classified (based on the PV generation profile) as a relatively cloudy day. In this case, the HP only activates for a few minutes during the day, and thus requires an additional heating period later in the evening (between 20:36 and 22:05). While this is not an optimal behaviour, it should be noted that the need to reduce the amount of energy injected in the local grid during sunny hours is less important during cloudy days, when overall solar generation is lower.

Decreasing the T_{HP}^{min} control setting could potentially be beneficial for the operations of the system. First, by lowering the average operating temperature of the heat pump, a higher COP can be expected; second, by enlarging the difference between the activation and deactivation temperatures, fewer HP starts and stops are expected, which can promote a longer lifetime. While the results of the test performed

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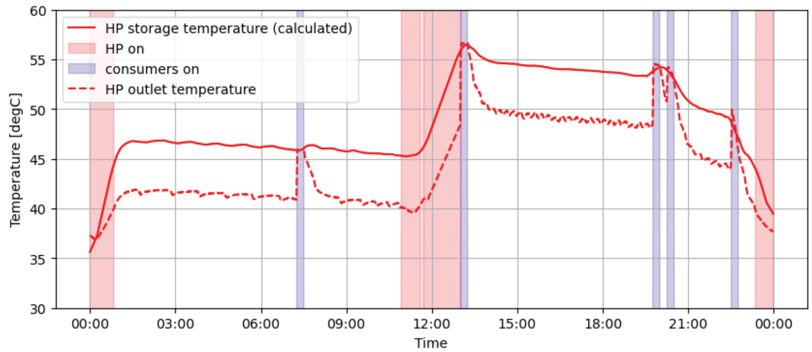

Figure 9: HP storage and outlet temperature in the proposed system during the 03/10/2023 test

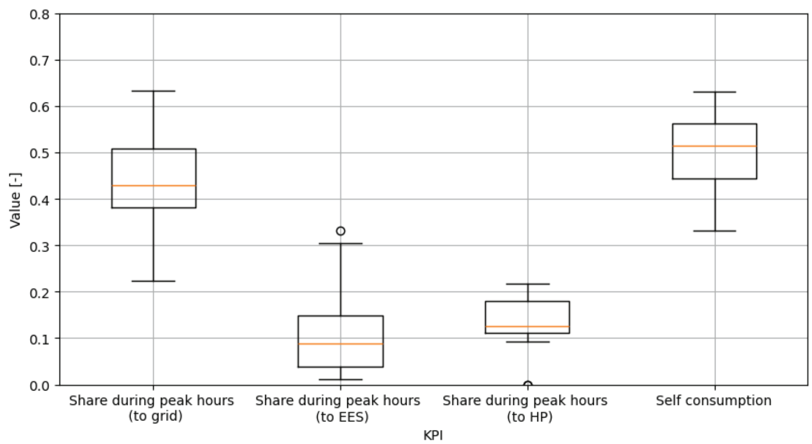

Figure 10: Share of energy flows during peak hours by final user and self-consumption index across the different tests

lowering the T_{HP}^{min} and T_{HP}^{max} control settings to 41°C and 55°C, respectively, seem encouraging, it can be seen (Figure 9, referred to the 03/10/2023 test) that this is at least partly due to the difference between the HP hot water outlet temperature and its internal water temperature: if the latter had been used as the actual control variable, the HP would have presumably been activated later (possibly after the 13:00 to 13:15 DHW user activation).

Looking at all the tests performed, the results shown in Figure 10 represent the share of the PV energy going to the three different potential users (HP, grid, EES) during "peak hours", here defined as the time frame between 10:30 and 16:30. The share of generated energy going to the grid during peak hours still represents the largest share in almost all tests, a large spread can be observed and values as low as 23% could be achieved.

Also in Figure 10 the system's self consumption is shown. The most promising results were obtained during the 02/11/2023 and 06/11/2023, both tests having the same settings ($\dot{W}_{PV}^{min}$ = 800 W, T_{HP}^{min} = 50°C and T_{HP}^{max} = 51°C) and with a degree of self-consumption achieved of 63% and 59%, respectively.

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4 DISCUSSION

4.1 Relevance

The experimental work presented in this paper confirmed the validity of the system's concept and overall structure. The system behaved substantially as expected and according to the system modelling, thus confirming its validity. It should be noted, however, that the results showed in the simulations presented by Ballistreri et al. (2022) reported a self consumption of 72% for the system, compared to a maximum of 63% achieved in the experimental results presented in this paper. As the tests reported in this paper where performed between the end of October and the beginning of November, while the simulations referred to one year of operations, solar irradiation conditions should have been more favourable in the tests than in the simulation; this suggests that, while the experimental system mostly fulfils its duty, there is room for further optimisation.

The concept as presented in this paper and by Ballistreri et al. (2022) was originally conceived having in mind the specifics of isolated contexts, where often DHW generation makes a larger contribution to overall electricity needs compared to other contexts, and where balancing the electrical grid can be more challenging due to its small size. It should be noted, however, that both needs also exist in standard grids. The work presented by Zhang et al. (2024) is related to the application of a similar system on the island of Kyushu, in Japan. Despite being a larger island and connected to the rest of the Japanese electricity grid, Kyushu is already suffering from renewable energy curtailment issues (Dumlao and Ishihara, 2021).

4.2 Limitations and future work

From the point of view of the technical implementation of the system, there are certainly some improvements that could be made.

First, the experimental implementation of the system showed that the loss of accuracy when using the HP outlet temperature as a proxy for the HP internal storage temperature is significant. Thanks to the part of the control connected to the PV output measurement, the overall behaviour of the system is retained: in spite of the inaccuracy in the temperature measurement, the HP is turned on at the right times. However, the increased performance of the control algorithm that could be achieved is only partly unlocked because of this inaccuracy. Future work on the system will be focused on improving this aspect.

A better insulation of the outlet pipe from the HP, until the temperature measurement, would definitely lead to a more accurate behaviour. There are however uncertainties related to how such intervention could help in catching the temperature increase in the HP internal storage when the HP is on, which would require further investigation.

Including the correction of the temperature measurement as part of the control algorithm could also provide improved control performance. Here, efforts should focus on finding the best compromise between the accuracy of the correction and the complexity of the related model, as it would need to be implemented in systems with limited computational power. Future work on this system will also include further investigation of this possibility.

While rule-based controllers are still the most common today and often allow achieving consistent results, there is also room for improvement in the adoption of more advanced control strategies. Optimisation-based controllers, such as those based on the principle of model control, or energy management systems can provide improved performance with respect to rule-based controllers. In this case, an optimisation-based controller could improve the control of the system by taking advantage of forecasts of user hot water demand and PV generation, and by taking into account efficiency profiles of the HP, the inverter, and the EES system.

The work in this paper is based on the system that was modelled in Ballistreri et al. (2022). Further work on the system should also focus on the identification of the best compromises in terms of installed sizes of all the components of the plant, including the number of PV panels, the maximum power output of the inverter, the capacity and type of the electric storage system and the thermal storage of the heat pump. Conceptually, the control logic of the system could be applied to a situation where different parts

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had already been previously installed, without an integrated design optimisation effort; however, the economic performance of the system is strongly influenced by the capital cost of its components, and there is room for identifying the most relevant trade-offs between different solutions.

5 CONCLUSIONS

In this paper, we presented the results of the experimental evaluation of a hybrid system for fulfilling domestic hot water demand from renewable sources made of a PV system, an inverter, a heat pump and a supercapacitor. The tests were performed between the 06/10/2023 and the 06/11/2023, and led to the following conclusions:

- the system's concept, originally proposed and simulated by the authors in Ballistreri et al. (2022), is able to achieve its purpose also once the concept is translated into an experimental system; self-consumption values as high as 63% were achieved, compared with 72% predicted by the system's simulation;
- the control system's main parameters, namely the minimum PV output power for HP forcing the HP pump activation, the minimum HP storage temperature below which the HP is activated, and the maximum storage temperature above which the HP is deactivated, should be optimised in order to maximise the system's performance. An initial attempt was performed during the tests, which led to the provisional conclusion that $\dot{W}_{PV}^{min}$ = 800W, T_{HP}^{min} = 50°C and T_{HP}^{max} = 51°C is a good starting point;
- the system implemented in this work uses the HP outlet temperature as proxy of the HP internal storage temperature for the system's control; this choice was made to ensure that the system's implementation represented realistic conditions, where the HP's internal storage temperature cannot be read by external control systems unless major modification are made. This choice did not prevent the system to achieve its purpose, but contributed to a non-optimal system control.

NOMENCLATURE

The nomenclature should be located at the end of the text using the following format:

Abbreviations

COP	Coefficient of performance
DHW	Domestic hot water
EES	Electric energy storage
HP	Heat pump
PLC	Programmable logic controller
PV	Photovoltaic

Latin Symbols

$\dot{m}$	Mass flow, kg/s
T	Temperature, $^{\circ}C$
$\dot{W}$	Power, W

Greek Symbols

Δ	Difference, –
η	Efficiency, –

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Superscripts and Subscripts

AC	Alternated current
DC	Direct current
in	Inlet
inv	Inverter
max	Maximum
min	Minimum
out	Outlet

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