International Journal of Sustainable Energy Planning and Management Vol. 38 2023 65–82

International Journal of Sustainable Energy Planning and Management

Heat pumps and thermal energy storages centralised management in a Renewable Energy Community

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ABSTRACT

This paper examines a Renewable Energy Community (REC) made up of 10 dwellings that collectively self-consume energy produced by a photovoltaic field connected to a water purifier. Each dwelling heat demand is satisfied by means of Heat Pump (HP) coupled with Thermal Energy Storage (TES), which can be managed to perform load shifting and increase collective-self-consumption (CSC).

Techno-economic analyses are performed accounting for HPs' COP variation with temperature and part load operations, as well as TES heat dispersion. A new centralised control strategy for HPs is proposed and a sensitivity analysis is performed to assess the impact of varying TES system capacity.

The results show that the centralised strategy can increase the CSC by 12-30%, with TES sizes of 100-1000 litres respectively. But the electricity consumption of HPs increases by 2-5% due to higher storage system temperatures causing worse average COPs by 2.3-0.6% and higher thermal losses by 29-58%. As a result, REC's energy independence rise, as does the amount of CSC incentives, but electricity bills also increase. Comparing these trends shows that CSC incentives should be adjusted according to energy prices to ensure cost-effective outcomes for all stakeholders and encourage the adoption of similar centralised control strategies.

Keywords

Renewable energy community;
Collective self-consumption;
Load shifting;
Heat pump management;
Thermal energy storages

http://doi.org/10.54337/ijsepm.7625

Abbreviations

COP	Coefficient of performance
CSC	Collective-self-consumption
DH	District heating
HP	Heat pump
LV	Low voltage
MV	Medium voltage
PV	Photovoltaic
REC	Renewable Energy Community
SC	Self-consumption
TES	Thermal energy storage

1. Introduction

Based on the European Directive 2008/2001 [1], the Italian Government has recently published the technical rules for accessing the service for valorisation and incentive of shared electricity [2]. The concepts of Renewable Energy Community (REC) and collective-self-consumption (CSC) have been introduced by the Regulatory Authority for Energy Networks and Environment [3], the ministry of economic development [4] and the ministry of justice [5]. A REC is defined as a legal entity composed of users belonging to the same

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low-voltage (LV) grid that decide to share the electricity produced by one or more systems powered by renewable energy sources. This “shared electricity” is called CSC (see 2.2), and the higher it is, the less dependent the REC is from the medium-voltage (MV) grid.

This article presents a method for increasing the CSC by centrally managing a group of heat pumps (HPs) and thermal energy storage (TES) devices. The aim of this management strategy is to shift the load and make use of surplus energy from a photovoltaic (PV) field. In simpler terms, we propose to manage everything from a central location to store and distribute heat more efficiently, using surplus energy from a PV.

This article analyses an Italian residential REC consisting of 10 dwellings that are powered by a combination of the national grid and a centralized PV field. The REC uses a decentralized heating system, where each dwelling has its own air-to-water HP and TES system. These technologies can be managed through a centralized monitoring and management system that tracks real-time data such as power production, demand, and TES temperature.

Given the growing importance of RECs, PVs, and HPs in the future energy system, this paper’s findings are relevant not only to researchers but also to industry players, including manufacturers and operators. In addition, it should be noted that the management strategy proposed in this paper can be easily replicated for other energy communities beyond the case study presented here.

The following literature review will start from district heating (DH) concepts and move on to the use of decentralised HPs and their management. Finally, the emerging RECs will be discussed and the role of this paper in research will be clarified.

1.1. Literature review

This paper does not deal specifically with district heating (DH); however, the technologies examined in this study are widely studied and used in DH systems. Therefore, it is appropriate to begin the discussion by framing it in relation to the district heating sector. Indeed, according with Figure *1* the system analysed in this study can be compared to a high efficiency 5GDH system. The obvious difference is that the decentralised air-to-water HP systems considered do not use the heat in the pipeline as in DH systems, but the heat available in the ambient air. For more on the classification and evolution of DH systems, see [7].

DH systems are more efficient than individual heating solutions in areas with high heating demand, especially in Central and Northern Europe and North America.[8].

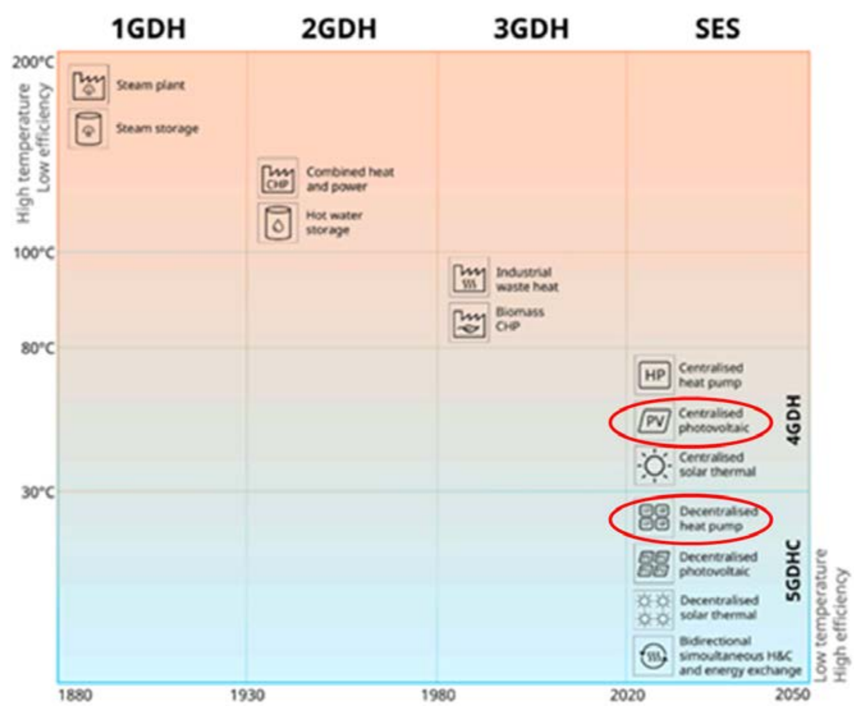

Figure 1: Evolution of DH systems over time [6] and case study placement.

However, conventional DH networks often suffer from high thermal losses through the pipelines due to high operating temperatures [9,10]. In case of low heat demand densities, losses in the distribution system are about 15% of the heat generated [11]. To address this issue, fifth generation DH (5GDH) systems operate at lower temperatures and integrate decentralized components, reducing thermal losses and enabling the use of renewable sources at low temperatures [6].

There are currently many studies on innovative solutions for DH [12]: One such solution is the integration of air-to-water heat pumps (HPs) and thermal energy storage (TES) systems with photovoltaic (PV) panels [13]. With smart management systems, TES can be heated during production peaks and the stored heat used during periods of high demand, contributing to load shifting and peak shaving [14]. While decentralized TES systems may offer better energy efficiency, they have higher investment costs [15], which can be offset through smart management systems that consider CO_2 emissions and increase energy independence from the grid [16].

The increasing use of HPs for heating homes [17] has led to a rise in the electrical load in the LV distribution grid [18] and put pressure on the grid's stability [19] and capacity [20]. The impact of a high penetration of HPs has been shown to be more problematic than a massive introduction of PV [21].

To address this, there is a need for greater flexibility in demand [22], which can be achieved through TES [23] or demand-side response schemes [24]. HPs can be used to heat the TES when energy is cheaper, which can significantly reduce operation costs [25]. To find the best strategy, factors like energy prices, COP, and thermal dispersion of the TES must be considered [26]. HP management strategies can be optimized based on daily forecasts [27], and the interaction between the HP, TES, and electrical storage should also be taken into account [17].

When comparing electricity and heat storage based on tariffs, there is a trade-off between prosumer benefits and grid impacts [28]. Both heat storage and batteries can have positive or negative effects on peak demand depending on the presence of capacity-based tariffs [29].

While research has shown that HPs can provide stability to the electrical grid in form of ancillary services and deliver cost savings, large-scale implementation is limited by the lack of aggregate control models [30]. The installation of a pool of HPs in a group of dwellings, as a REC, can significantly contribute to the reduction of issues connected to the extensive electrification of residential heating systems and will also make PV installation more cost-efficient [31]. In addition to PVs, HPs for RECs coupled with solar thermal or solar collectors [32] and hybrid systems with boilers [33] have been studied. However, the installation of a centralised heat pump management system requires accurate data collection and reliable weather forecasts, as well as smart HPs capable of receiving and implementing scheduling commands provided by a central supervisor [34]. Such a supervisor could be the manager of the REC itself, but currently, there is a lack of literature on methods that a manager of a REC could use to efficiently operate the REC and about the technical solutions that could be implemented.

Studies on RECs are focused on assessing the benefits that the establishment of a REC provides to all stakeholders, considering different REC configuration [35], different installed technologies [36] and business models [37]. The paper on the first REC created in Italy [38] merely shows the economic benefits to the REC participants provided by the current regulation, but concludes that the integration of REC can enhance energy efficiency and provide flexible services, which could be managed synergistically with the overall electricity system. A study [39] of a multi-criteria dimensioning of photovoltaics and batteries for REC was developed, taking into account different entities working together. In the conclusions it is suggested a potential benefit from thermal load management in a REC. Another study [40], deals with the impact of demand side management on REC as its composition varies. And again, the conclusions emphasise the importance of studying the electrification of thermal loads in RECs, in particular with a focus on the role of HPs. It has been demonstrated that centralised control of HPs can effectively address the challenges associated with the widespread adoption of electric heating in residential buildings and an optimisation algorithm for coordinating the operations of a pool of HPs has also been proposed [34]. However, this only aims to reduce peak absorption and does not perform an economic analysis that considers the point of view of individual stakeholders. Such an analysis was only conducted for the management of batteries in a REC, considering both role based method [41] and optimization method [42].

1.2. Paper novelty and structure

To the authors knowledge, no studies focused on the possibility to manage a pool of HPs through a centralised management system to increase RECs performances in both energy and economic terms. The aim of this paper is to evaluate such solution and to propose a centralised HP management system through the analysis of a real REC at the design stage. This study wants to prove that HPs and TESs can be used to store the surplus of PV production inside the REC, to increase CSC and decrease the dependence from the MV grid. This is a service for the national grid and so the grid operator should incentive it.

The study is structured as follows. Section 2 deals with the methodology and tools used to conduct the analysis. Firstly, a description of the case study (2.1) is provided, while the focus of subsection 2.2 is the Italian regulation on RECs and CSC. Load forecasting techniques (2.3) and the simulation tools employed (2.4) are then described. A specific focus on HP modelling is given in subsection 2.5 and on two different management strategies in subsection 2.6. Results are presented in Section 0. Subsection 3.1 shows the effects on REC energy balances of the two control strategies, while a sensitivity analysis is performed by varying the TES sizes in subsection 3.2, and the results of the economic assessment are presented in subsection 3.3. Finally, results are discussed, and conclusion is drawn in the last Section.

2. Materials and methods

In this chapter the reference study case is first presented (paragraph 2.1), followed by an explanation of the Italian regulations concerning collective self-consumption

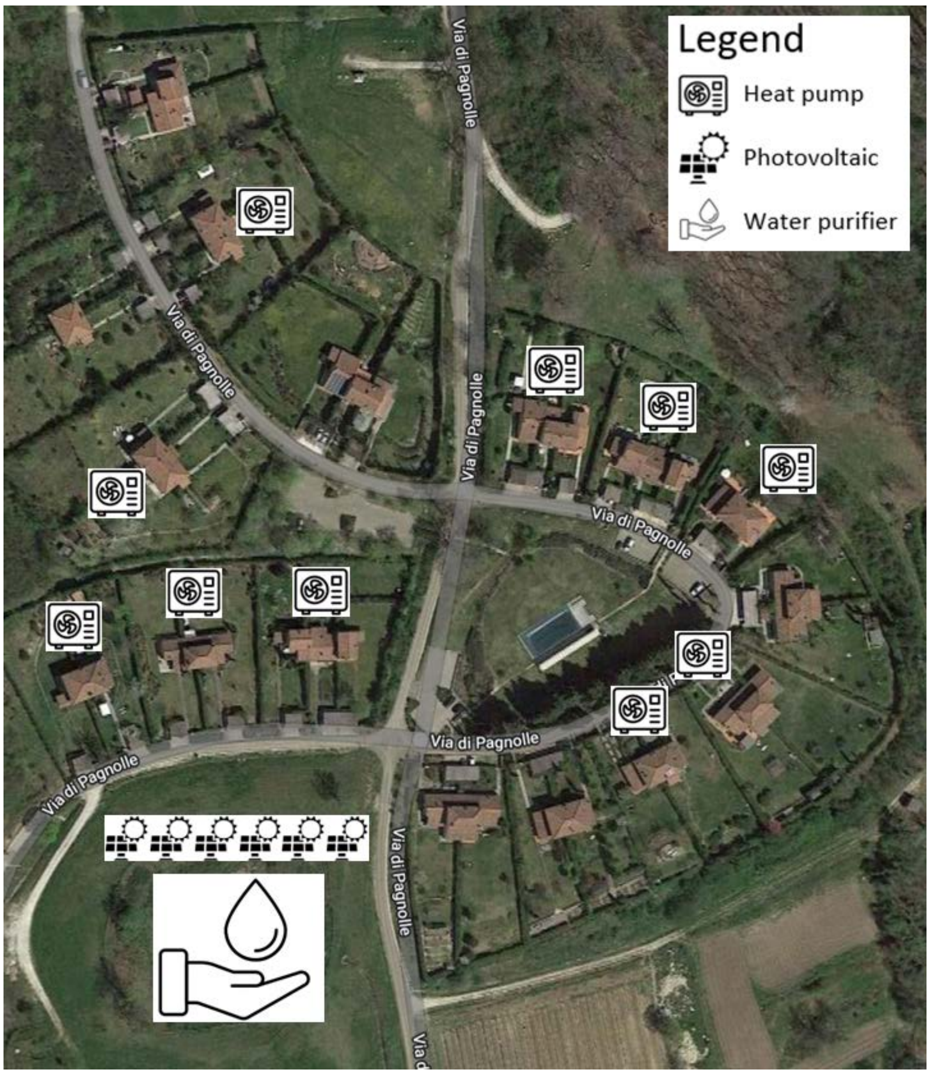

Figure 2: Case study: areal photo and installed technologies.

(paragraph 2.2). Next, a methodology for generating hourly load profiles in the absence of actual data is presented, using aggregated information from utility bills and surveys (paragraph 2.3). Paragraph 2.4 illustrates the tool used for the simulation of energy balances, while 2.5 focuses on HP modelling. Finally, paragraph 2.6 describes the two types of control strategies used to manage HPs and TESs: the standard one and the centralised one, which allows load shifting and the increase of CSC.

2.1 Reference cases study

The REC studied consists of 10 single-family homes in the Florence countryside and water purifier system, which provides clean water for houses (see Figure *2* and Table *1*). The electrical demand of the water purifier is 34.4 MWh per year and can be shifted to daylight hours by rescheduling the activity of the water pumping and purification systems. For these reasons, the homeowners decided to invest together in a centralised 50 kW_p PV system connected behind the meter of the water purified. The PV production is used primarily by the water purifier, yet the surplus of electricity can be used to cover the power demand of the dwellings. In each house, an air-to-water HP coupled to a TES system is installed for heating and domestic hot water, to cover the thermal demand which was previously satisfied with a gas boiler (Table 1 second column). A centralized HP management system is installed to better exploit the PV surplus and increase REC independence from the grid by increasing its CSC.

Table 1: Case study: electrical demand

Building	Electric demand home appliances [MWh/year]	Thermal demand heating and DHW [MWh/year]
Residential 1	2.4	8.7
Residential 2	5.1	21.4
Residential 3	1.5	8.8
Residential 4	6.2	15.9
Residential 5	4.5	14.7
Residential 6	2.6	21.3
Residential 7	1.8	22.8
Residential 8	9.2	5.2
Residential 9	9.8	33.9
Residential 10	5.5	18.6
Water purifier	34.4	-
Total	74.8	171.4

2.2. Collective-self-consumption under the Italian regulation

Figure 3 shows how REC works and what CSC is according to the Italian regulation. The REC is composed by 11 users: 10 residential buildings and the water purifier. Each user is connected via a meter to the LV grid and pays the bill for the electricity it withdraws from it (red arrow). Dwellings take all the energy they need from the grid. The water purifier, on the other hand, only withdraws part of the energy it needs from the grid because a good part of it is produced and self-consumed thanks to the photovoltaic panels installed behind its meter (green arrow).

In order for the electricity to be considered self-consumption, the consumption must be simultaneous to the

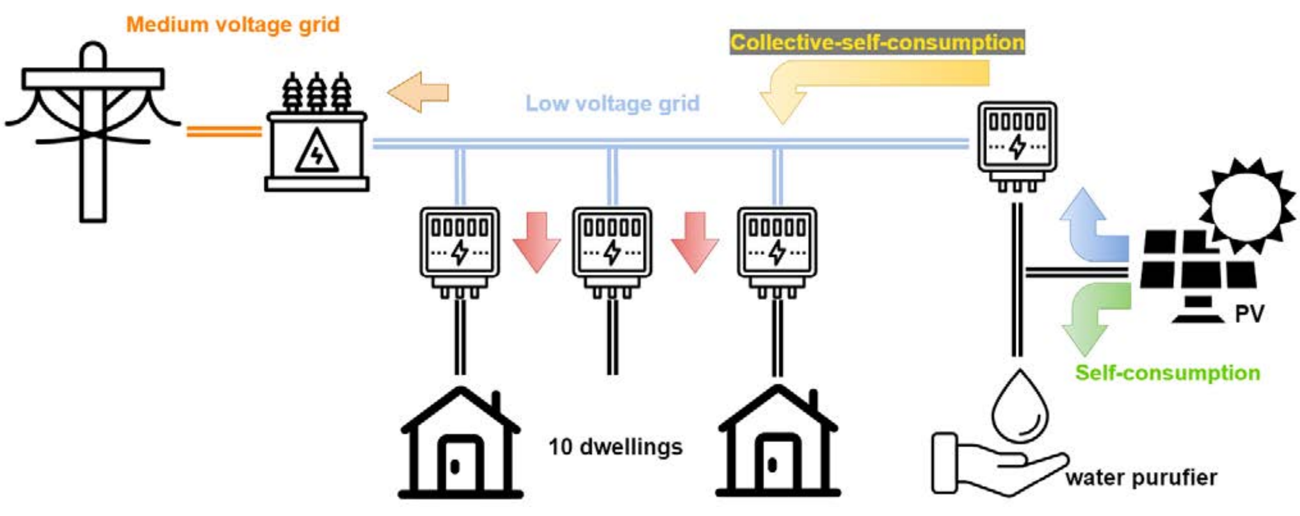

Figure 3: Case study: simplified electrical diagram to explain the Italian regulation.

production. When this does not happen or the production is greater than the consumption, the surplus of energy is fed into the grid via the meter and the Italian grid operator remunerates it (blue arrow) [43]. Part of the electricity fed into the grid does not leave the LV grid if there are users under the same LV grid who are withdrawing it (in this case study, the residential buildings). Only the electricity that is not consumed at the LV level is fed into the MV grid (orange arrow). According to the Italian regulation, if the user that feds electricity into the grid and the users that withdraw the electricity are part of the same REC, the part of electricity that remains within the LV grid is defined as CSC (yellow arrow). For each kilowatt-hour of CSC, an incentive of about 120 €/MWh is paid by the grid operator to the REC representative, who then redistributes the money among REC members according to the rules that each REC defines during its constitution [44].

CSC is incentivised because the higher the CSC, the lower the electricity exchanged between the LV and MV grids. Converting electricity from MV to LV and vice versa, as well as the transport through the grid, involves losses. In addition, the feed-in of PV-generated electricity might cause grid instability issues, due to the natural discontinuity of generation from this source. For these reasons, the possibility of increasing CSC must be studied.

2.3. Load profiles generation

Load profiles are one of the main inputs for an energy system simulation. For this analysis, one-year hourly load profiles of the 10 detached houses and of the water purifier are needed, electrical and thermal for the first, and only electrical for the second. These are not available, because the installed meters are old generation, so they must be simulated. Techniques to generate load profiles can be divided in two typologies: bottom-up and top-down approaches.

Bottom-up methods are based on modelling all the appliances of a building and simulating their use through stochastic algorithms [45–47]. These approaches have the advantage of reproducing detailed load profile and allow to assess load shifting impact of each single appliance [48]. On the other hand, they require a large amount of input data, which must be hypothesized or collected through surveys. This makes the results of simulations dependent on the quality of the collected data or on the researcher's assumptions [36]. In addition, using this approach for many buildings can be unpractical and time-consuming.

Top-down methods start from aggregated data, such as monthly energy consumptions, which can be read from electric and gas bills, and proceed to redistribute the consumption over different days and hours. The advantage is that the total demands are real, while the reliability of the daily profiles depends on the technique chosen to redistribute consumptions. This redistribution can be done by assumptions on the hours when people are present in the buildings or by using typical curves and existing bench-mark building energy profiles, which are then scaled to total consumptions [49,50]. Using typical curves to simulate multiple buildings could lead to a poor representation of the non-contemporaneity of the consumption of the members of a REC, which is what guarantees CSC. For this reason, a new top-down simulation method is proposed for this study and summarised in Figure *4***.**

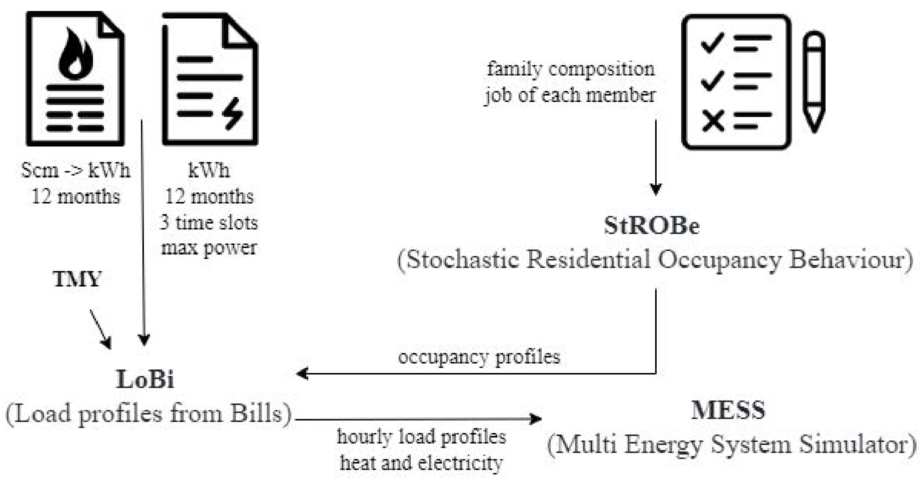

Figure 4: Load profiles generation workflow diagram.

This method consists of gathering one-year electricity and gas bills from each REC member and to have each of them fill out a survey. From the electricity and gas bills it is possible to read the consumptions for each month. For the electricity they are also divided into three timeslots, and the maximum power withdrawn is available. Electricity demand is in kWh, while gas demand is in Sm^3 and has been converted to thermal kWh considering a conversion factor of 10.69 kWh/Sm^3. The survey is used to collect data about occupants age and job status, which is then used as input for "StROBE" [51], an open-source tool using Markov chains to simulate occupancy profiles. These hour-by-hour profiles tell if people in the building are awake, sleeping or outside.

"LoBi" (Load profiles from Bills [52]) generates hourly load profiles. Monthly electricity demand is redistributed on hourly base considering time slots and using occupancy profiles as weights. Randomness is added by extracting values from a distribution that has as minimum the refrigerator power, as maximum the maximum power withdrawn from the grid, and an average that matches the total amount read on the bill.

To estimate heat demand, average hourly air temperature from a Typical Meteorological Year (TMY) [53] is used as weight to redistribute consumption.

Thermal and electrical load profiles of each building are then used as input for the simulation tool. Some examples of the generated profiles (electricity and heat demand of one of the ten dwellings) are shown in Figures 5 and 6. Since thermal demand was estimated from gas bills, it is not possible to know the exact breakdown of demand between heating and domestic hot water. However, a rough idea can be observed in Figure 6 considering that in summer the heating systems are turned off.

Cooling demand is not considered in this study because deals with hilltop country cottages which do not need it. Load shifting for heat demand can be achieved using TES, which increases the temperature from 40°C to 60°C. However, load shifting for cooling demand is not feasible in residential applications due to the limited temperature range. The cooling system requires 12°C, while the minimum achievable temperature by the HP is 5°C. This would require more powerful and costly HPs, as well as the use of glycol.

2.4. Simulation tool

MESS (Multi Energy System Simulator) is an open-source simulation software [54–56] that allows to assess the potential of an energy system by simulating hour by hour its energy balances. In a previous study [36] the model was validated by comparing its results with those of the model developed by Vrije Universiteit Brussel [31].

MESS inputs are the load profiles of each building, REC composition, geographical position and technical parameters. In this study MESS is used to calculate the REC energy independence from the MV grid by considering PV production, water purifiers and dwellings' demand, amount of SC, CSC, the electricity withdrawn

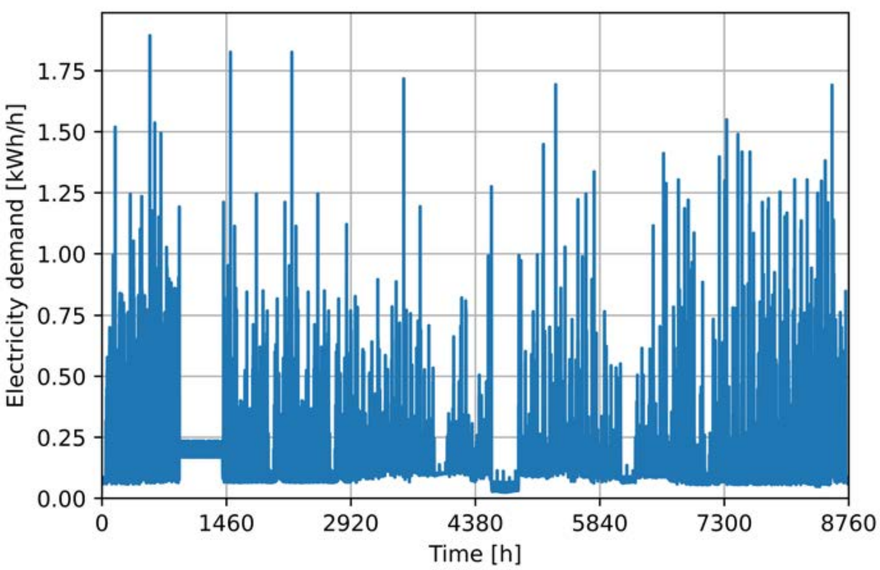

Figure 5: Hourly electricity demand of a residential building: a ppliances.

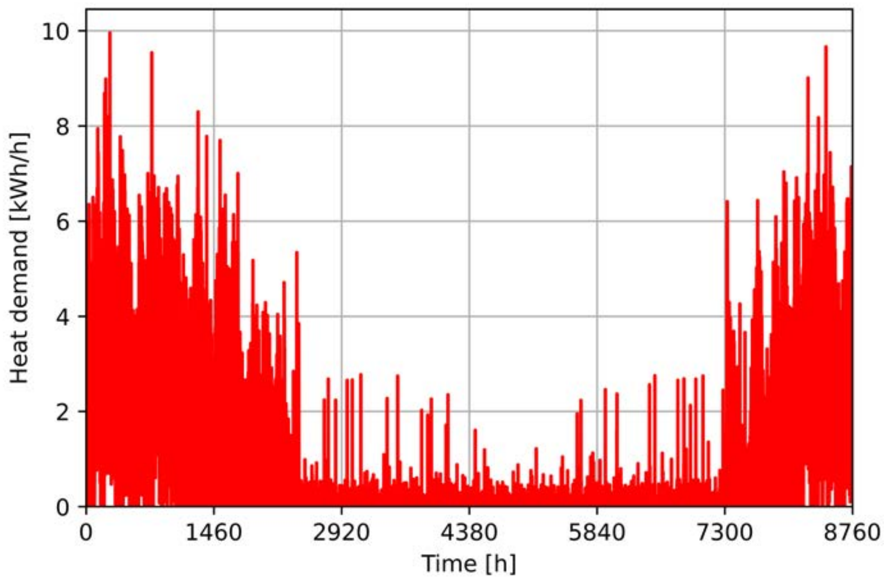

Figure 6: Hourly heat demand of a residential building: heating and DHW.

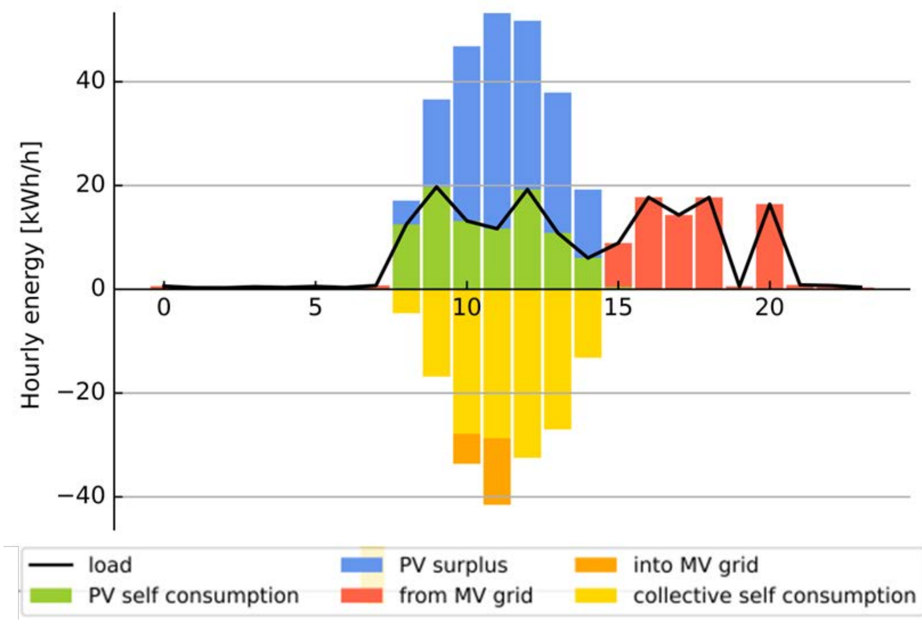

Figure 7: One day water purifier energy balance.

from the MV grid and the one fed into it (Figure *7*). Hourly balances are then aggregated to evaluate the annual amount.

2.5. Heat pump modelling

A function with one-minute time step, which simulates an air-water HP coupled with an TES, is introduced within MESS. The function inputs are the user's heat demand and the PV surplus and returns HP's electrical consumption. Two different control strategies are implemented: the HP follows the heat load, or the HP follows the PV production (paragraph 2.6).

Regardless of which strategy is used, the coefficient of performance (COP) is calculated as a function of ambient temperature, temperature of input water and load condition.

The HP model is developed starting from the performance of a scroll compressor from the Danfoss catalogue [57]. A compressor designed to produce 10 kW of thermal energy at nominal condition is taken as a reference. The Danfoss software gives the compressor performance as function of the evaporation and condensing temperature. A pinch point of 3°C on the water side and of 10°C plus 5°C of superheat on the air side have been assumed.

$$COP = f\left(T_{evap}, T_{cond}, load\right) \tag{1}$$

$$T_{evap} = T_{amb} - 15°\text{C} \tag{2}$$

$$T_{cond} = T_w + 3°\text{C} \tag{3}$$

Figure 8 shows the operating range. These values are implemented within the code in order to calculate the maximum water temperature achievable by the HP, given the ambient temperature. The requested water temperature, at each time step, is compared with the maximum allowable and the COP at design condition (6000 rpm) is hence calculated from regression curves supplied by the producer of the compressor (Figure *9*). In this way the design conditions of the machine are calculated for a size of 10 kW thermal. A corrective coefficient is then applied to the electric and thermal power, in order to consider HP of different sizes. Indeed, each dwelling in this case study has a different HP, sized according to its peak heat demand.

The HP can be regulated thanks to the inverter between 900 and 6000 rpm, allowing the HP to be used following thermal demand or PV surplus. In the former case, part load is defined as the ratio between thermal demand and the heat the HP provides at 6000 rpm, while in the latter, as the ratio between the electricity it uses and the electricity it would use at 6000 rpm. COP

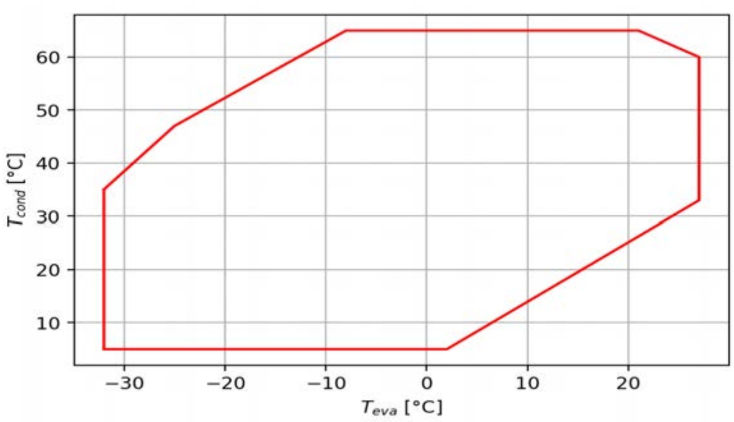

Figure 8: HP operating range.

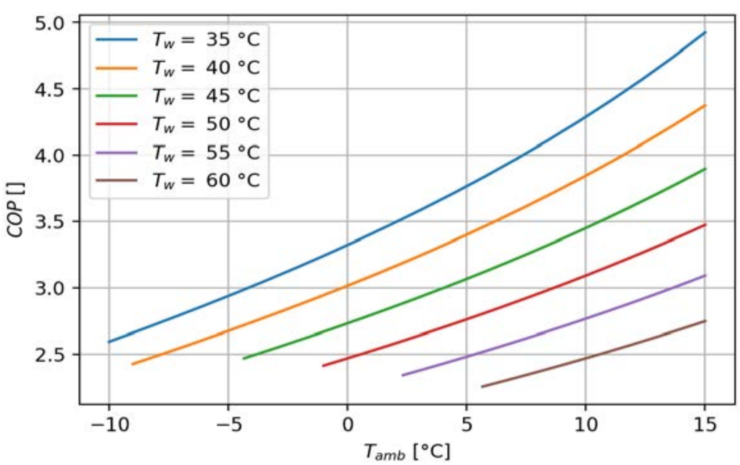

Figure 9: Design COP trend at 6000 rpm for the reference compressor.

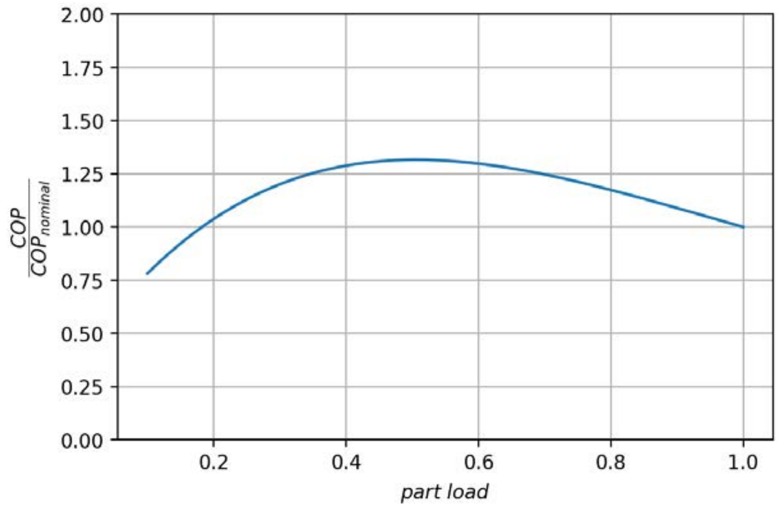

Figure 10: COP variation under partial load conditions.

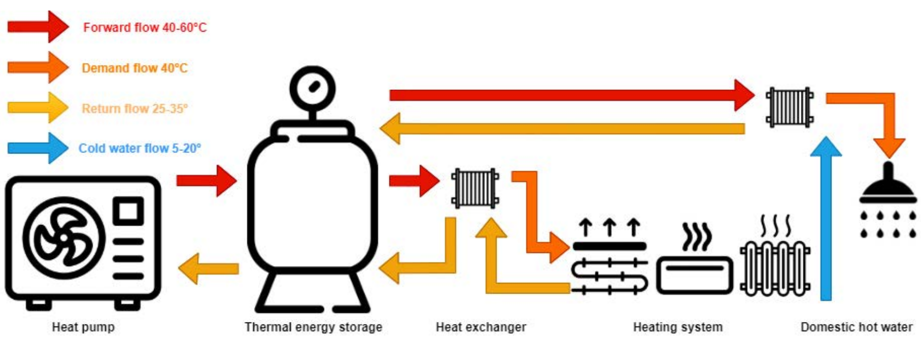

Figure 11: Simplified diagram of the heating system.

correction under these conditions is estimated according with [58] as shown in Figure *10*. This curve is the result of considering the effect of load regulation on the main HP components: heat exchangers, inverter, and compressor. The reduced flow rate causes the exchangers to be oversized, thus causing a reduction in the pinch points and therefore a benefit in terms of COP. On the other hand, when further decreasing the load, the efficiency of the inverter decreases. Therefore, the compressor has an optimal behavior in the middle of the machine's operating range. For high power, friction losses are high, while, for low power, leakage losses prevail.

There is a limit below which the machine cannot operate, approximately 15% of nominal load.

2.6 Heat pump and TES control strategies

TES is modelled considering U-values of 0.36 W/m^2K [29], corresponding to rigid polyurethane insulated commercial tanks. A stratification of 5°C between top and bottom is imposed To calculates the dispersing surface a geometry of a cylinder with a height three times its diameter is considered. The above are the only heat losses as the dispersion inside the pipes has been neglected, since these are inside the dwellings.

Interaction between HP, TES, heat demand and PV surplus is implemented in MESS. Two different control strategies are simulated and compared. Figure *11* shows a schematic representation of the system.

Standard strategy: HP follows heat demand.

When the building is to be heated or domestic hot water is required, hot water inside the TES circulates in the heat exchangers to heat return water from the heating system or cold water from underground. Demand flow temperature depends on the heating system type (fan coil, floor heating or radiator). For the simulation in this study a temperature of 40° is considered, but the results can be generalised to other working temperatures.

HP switches on to maintain a constant temperature inside TES, so HP must produce at each time step the same heat required by the heating system and by domestic hot water: HP follows heat demand.

If the heat required is lower than the heat generated by the HP at minimum load, the excess of heat produces an increase in the TES temperature. So, thanks to the TES the HP does not have to be switched off. If the temperature inside the TES reaches the maximum temperature that the HP can provide (above 60°, but depending on ambient temperature), the HP switches off. Before switching on again the HP, the heat demand is satisfied by the thermal energy stored inside the TES.

This strategy uses the TES only as inertial TES to reduce the number of HP switch-on events. Doing so, its efficiency and life-time increase [59].

Centralised strategy: HP follows REC PV surplus.

TES can also be used to store the energy produced by a PV system, which would otherwise end up on the grid. In this case the control strategy follows the PV surplus instead of thermal demand. If the thermal demand is lower than the thermal energy produced by the HP, the TES temperature increases. This mechanism goes on as long as there is a PV surplus or until maximum temperature is reached. Afterwards, the HP switches off and, if heat energy is required, it is taken from the TES.

If the TES is properly sized, this strategy allows to shift the load from evening to daily hours increasing SC.

This study deals with REC and CSC, one PV field and ten HPs. Therefore, to implement a control strategy able to harness REC PV surplus using HPs and TES, a centralised management is needed. The MESS operates as follows: if there is PV surplus, the HP with TES at the lowest temperature is switched on, in order to use the surplus and charge the TES. If there is more surplus, another HP is used. Using this selection criteria, the average temperature of all TESs is kept low. Consequently, COP are higher and heat dispersion lower.

3. Results

In this chapter the effect of using a centralised management on CSC and REC independence from the grid are shown in comparison with the standard management strategy. A sensitivity analysis is then carried out as the volume of TESs varies, followed by an economic assessment.

3.1. Centralised vs standard heat pump management

The following simulation considers TESs of 200 L, that is a standard size that can be found in market for residential applications. The three graphs in Figure 12 are the monthly balances of energy production (P) and demand (D). The former is in part self-consumed by the water purifier, and in part collectively self-consumed by the dwellings. The remaining part ends out of the REC, likely fed into the MV grid (it is assumed for simplicity that there are not utilities in the same LV grid of the REC that are not part of it). On the other hand, the demand is met by energy produced by PV which is SC or CSC and by energy withdrawn from the MV grid. It is clear how production and demand have an opposite trend over the year, the first is higher during summer while the second in winter, when heat demand is higher. Because of this, the surplus of energy that could be valued by a centralised HP management system is limited, yet should be considered.

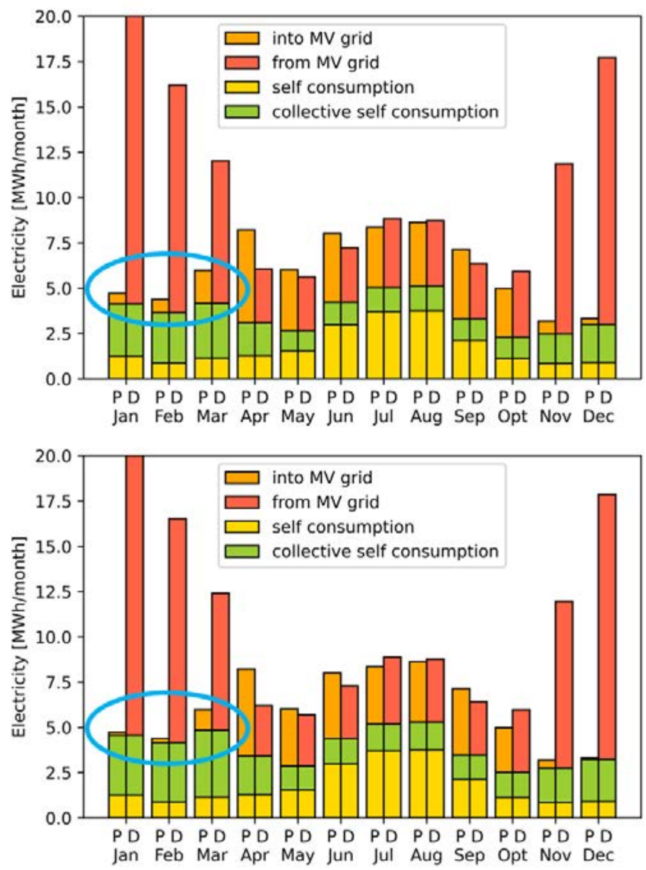

Figure 12: REC monthly energy balances: standard (above) vs centralised (under) management.

Looking at the winter months, it is possible to see that the energy fed into the MV grid with the standard strategy decreases and becomes CSC using centralised strategy. The same happens for the energy withdrawn from the MV grid, also if the total demand slightly increase. Effect on summer months is small because the HPs are used only for domestic hot water.

Table 2 summarise the REC annual balances comparing results of the two control strategies. The centralised one leads to a rise of CSC by 2.4 MWh. This amount of energy is produced and consumed inside the LV grid, so that the annual energy fed into the MV grid decrease by exactly 2.4 MWh. Charging the TESs using this energy, means not having to switch the HPs on again using energy from the MV grid when heat is required. Nevertheless, the reduction in electricity withdrawn from the MV grid (–1.0 MWh) is smaller than the reduction in the fed in one, due to the total demand increment (+1.4). This is caused by the increase of average temperature inside TES and the resulting deterioration in COPs and increase in heat losses.

Table 2: REC annual energy balances: standard vs centralised HP management.

	Standard	Centralized	
Production [MWh/year]	72.9	72.9	
Water purifier SC [MWh/year]	21.5	21.5	
Cottages CSC [MWh/year]	21.1	23.5	+ 2.4
Into MV grid [MWh/year]	30.3	27.9	– 2.4
From MV grid [MWh/year]	82.0	81.0	– 1.0
Demand [MWh/year]	124.6	125.0	+ 1.4

3.2 Sensitivity analysis

The previous paragraph has proven that a centralised management strategy can boost the REC energy independence from the MV grid, providing a service to the grid operator. This paragraph deals with a sensitivity analysis varying TES size from 100 litres to 1000 litres.

Figure 13 shows that increasing storage capacity, the possibility to perform load shifting using PV production surplus raises. In this way CSC grows decreasing the amount of energy the REC exchanges with the MV grid. From this point of view, the grid operator should promote the purchase of large TESs. Moreover, without a centralised system, HPs could not be switched on when there is a PV surplus of energy inside REC. In this case, it does not make sense to invest in large TES. Indeed, inertial TES of up to 200 litres are currently used and not larger TES useful for load shifting.

Figure 14 shows that heat generated by HPs is not dependent on TES size if no heat dispersions are considered (green lines). This is true for both the control strategies because the heat generated must be equal to the heat required by the users. But in real condition a higher TES means larger dispersing surface. For that reason, heat generated by HPs raises with TES size. Comparing standard with centralised management, the latter leads to higher medium temperatures inside TES and a consequently increase of losses and thermal energy needed.

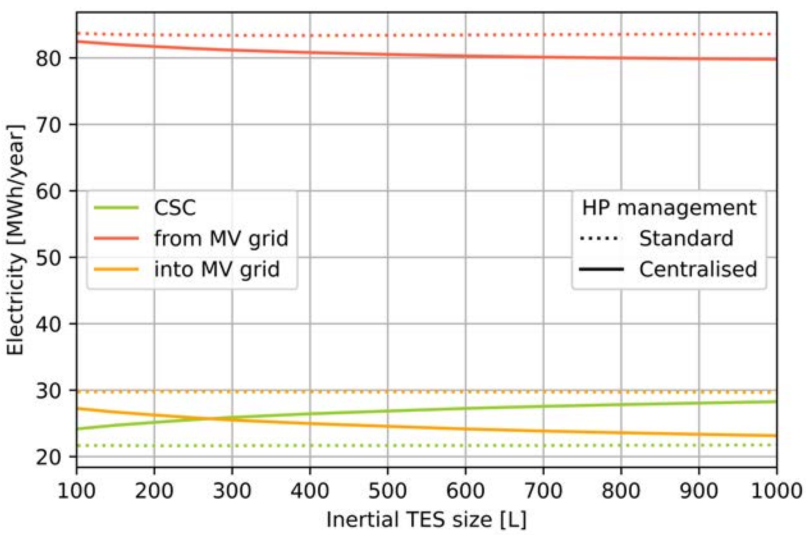

Figure 13: REC energy balances varying TES size.

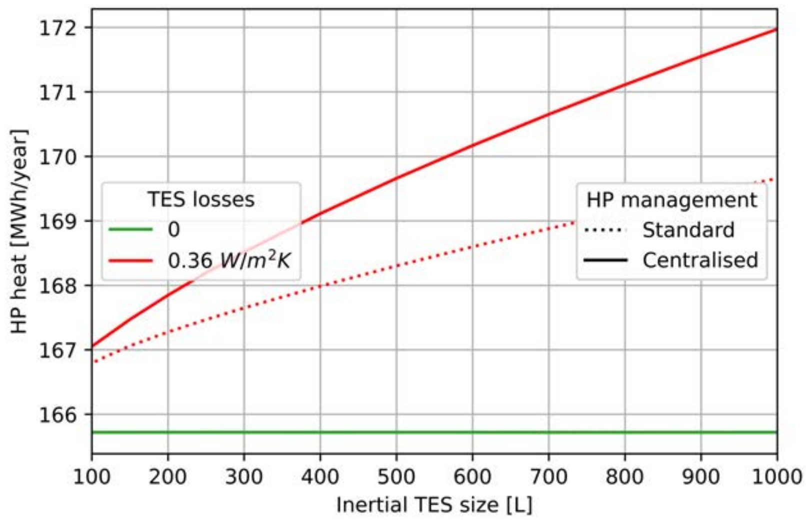

Figure 14: Heat produced by HPs varying TES size.

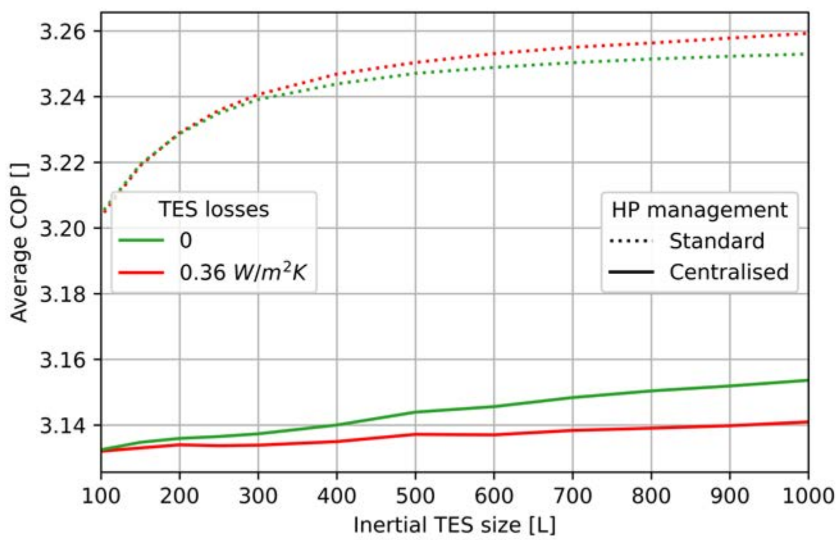

Figure 15: Average COP at which HPs work over year.

Looking at yearly average COP (Figure *15*), it is higher with the standard management because temperatures remain lower. With both strategies COP raises with thermal storage capacity because the medium temperature over the year inside TES goes down, but the trend is different. This happens because as the thermal storage capacity increases, so does the possibility to harness the energy produced by the PV with the centralised strategy. Doing so, TES temperatures rise. In the standard case, dispersion promotes COP by decreasing temperature. With the centralised control strategy, this consideration is no longer true because thermal losses involve more energy to be produced at high temperature and low COPs.

The consequence of thermal energy and COP trends is shown in Figure 16: without dispersion electricity consumed by HPs decrease with TES size because of the COP increase. Considering dispersion and standard control strategy, a minimum can be found. This is the result of two opposite effects: increasing TES volume, the COP increases due to decreased temperatures, but heat losses also increase due to increased surface area. With the centralised management the COP improvement is not sufficient to cope with the increase in thermal energy

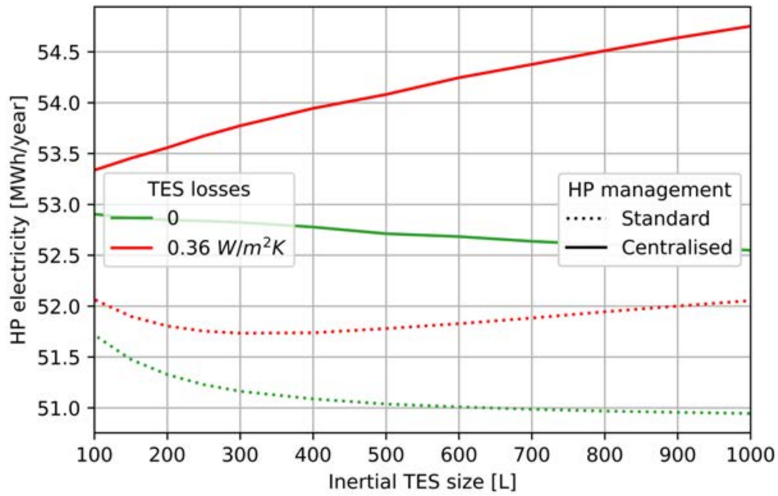

Figure 16: Electricity consumed by HPs varying TES size.

required due to heat losses. Therefore, the demand for electricity rises.

Analyses conducted thus far have shown that using a centralized management and increasing the size of TESs allows for increased collective self-consumption and energy independence of the energy community. Unfortunately, doing so also increases the electricity consumed by the HPs. The economic impact of these consequences is evaluated in the next section.

3.3 Economic assessment

Previous paragraphs have shown that the centralised HPs management allows to increase CSC, but at the same time increases electricity consumed by HPs. The PV field it is not under the same meter of the dwellings in which HPs are installed but is connected to the meter of the water purifier. For that reason, all the energy used to power the HPs has to be withdrawn by the grid and paid (doesn't matter if it comes from the LV or from the MV grid). This means that an increase in the energy consumed generates an increase in the electricity bill of the members of the REC which depends on the price of energy (See [60,61] to observe energy prices in the Italian market). This increase is offset by incentives on CSC of 120 €/MWh [44]. As Figure *17* shows, not to have an economic loss requires a scenario with low energy prices and large TES. The latter, by the way, costs more.

Considering that, a member of a REC would allow the REC manager or the grid operator to centrally manage its HP in order to increase REC energy independence from the MV grid only in scenario with low energy price. Hence, it's clear that, in order to make such system become real, an update of the regulation is needed to provide specific incentives for those who buy a TES and decide to make it available to provide a grid service.

4. Conclusions

This study assesses the possibility to use HPs and thermal energy storages inside a Renewable Energy Community to increase its collective-self-consumption and its independence from the medium voltage grid.

A REC consisting of ten dwellings sharing electricity generated by a 50 kWp photovoltaic field connected behind a common water purifier is considered. Their hourly load profiles are generated using a top-down simulation method from electricity and gas bills. Demand profiles are then used as inputs to an energy simulation software to perform techno-economic analysis. An HP model is used that considers the variation of COP as a function of ambient temperature, water temperature, and part-load conditions. Thermal losses within the TES are also considered.

Two different control strategies for managing the HPs of the ten cottages are compared. In the standard one, the HPs follow the thermal demand without considering whether the electricity used is produced by PV or must be withdrawn from the medium-voltage grid. On the other hand, a centralized strategy is proposed that allows the HPs to use the PV surplus to store energy within the TESs and use it when it is required later.

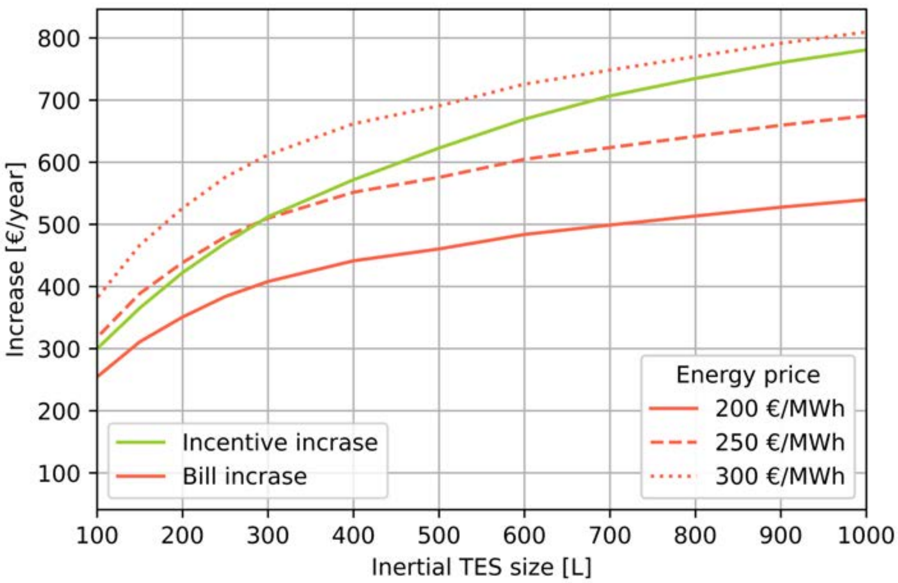

Figure 17: Economic assessment of centralised management varying TES size and energy price.

The centralized strategy leads to an increase in REC CSC, which corresponds to an equal decrease in energy fed into the MV grid. It also allows the energy withdrawn from the MV grid to decrease, but to a lesser amount. This happens because the total energy required by HPs increases, as the centralized strategy causes an increase in the average temperature of TESs over the year. As a result, COPs decrease, and thermal losses increase. By increasing the size of TESs, both collective self-consumption and electricity demand further increase.

Economic analyses show two opposing effects of using centralized management: an increase in electricity bills and an increase in incentives on collective self-consumption. The first is a cost, while the second is a revenue. The former depends on energy prices while the latter does not, since it is considered to be fixed. In a scenario with high electricity prices, centralized HP management is not competitive, yet it becomes so with low costs and large TESs.

In conclusion, the proposed solution can provide a service to the grid, but for its deployment to be favoured, it would be advisable to revise the incentives on CSC according to energy prices. Alternatively, or additionally, the purchase of large TESs with low dispersion coefficients could be incentivized.

The results of this study should be of interest not only to researchers, but also and especially to HPs developers, who could provide them with smart remote control systems, and to those who develop and use management systems for RECs. Implementing the solutions proposed would help the stability of the grid and also the earnings of REC members.

Future research could address centralized strategies for managing HPs that consider limiting values on temperatures and integration with other storage systems, such as latent heat technologies or electrochemical storage. Cold storage for cooling demand could also be investigated by introducing the use of heat pumps for sub-zero degree cooling.

In addition, the results simulated in this study will be compared with data collected from monitoring of the REC under study, which will be established soon.

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