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Experimental characterization of a small-scale solar Organic Rankine Cycle (ORC) based unit for domestic microcogeneration

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ABSTRACT

The integration of a Micro-Organic Rankine Cycle (ORC) power unit with conventional solar flat plate collectors ensures the simultaneous fulfillment of electricity and domestic hot water (DHW) demands. Due to the variability of the solar source, despite the introduction of a thermal storage unit, the plant is subject to severe off design operating conditions. A small-scale ORC-based was designed, built and fully tested, to experimentally assess the performance and operating robustness of the plant in steady and dynamic off-design condition. The unit is fed by hot water from a 135 L reservoir. Dedicated electric heaters (12 kW each one) reproduce the thermal availability from 15 m^2 of standard solar thermal collectors for domestic applications. The test bench underwent an extensive experimental assessment in both stationary conditions of the hot source and in presence of a variable thermal load at the evaporator. Due to the plant architecture and components, the control of the unit is based on the variation of the mass flow rate of the working fluid (R245fa) matching the thermal equilibrium at the evaporator in each operating condition of the system. The variation of the flow rate, in fact, must fit with thermal power available. The off-design steady state assessment allows the understanding of the wide operability of the plant (17–62 g/s), with power and efficiency varying between 150 and 500 W and 2.4–4%, respectively. The dynamic testing of the pilot unit points out the plant consistency and robustness to severe off-design operation, mostly due to the 1 kW scroll expander, very suitable for time-varying operating conditions. Both the option of a full discharge of the thermal energy of the reservoir and the option of a split discharge to the evaporator were investigated and provided a clear indication on the CHP feasibility when no addition of thermal energy takes place at the reservoir. It was observed that during a complete reservoir thermal discharge, the plant works for 3000–3300 s continuously, with a slow power decrease from 500 W to 100 W. Considering the thermal energy recharging time, the plant could be averagely operated up to 7 times during the day if a partial discharge was performed. Each plant activation lasts 900 s producing a power ranging from 500 W to 200 W. This operating strategy allows to cover up to 11.2% of the whole electric energy yearly required by an average European household.

1. Introduction

With respect to the 20/20/20 climate/energy targets, the EU has raised its short-to-mid-term goals, in terms of GHG emissions reduction (-40%), renewables share increase (+27%) and overall energy efficiency increase (+27%) by 2030 [1]. This calls for a shift in the energy paradigm towards more sustainable – namely, green – energy sources, particularly in the residential sector, where the technical feasibility of small-scale decentralized electricity generation combines with the growing sensitivity to the issues of environment protection.

The market of Organic Rankine Cycle (ORC) plants has known a rapid development over the last 20 years, up to 2.75 GWe cumulated installed capacity in 563 power plants by the end of 2016 [2,3]. Modeling and experimental activities can be retrieved in the scientific literature and prove that small-scale ORC-based plants allow to exploit the availability of solar thermal energy for Combined Heat and Power (CHP) generation to achieve the simultaneous fulfillment of electricity and Domestic Hot Water (DHW) demand in the residential sector [4–6]. Despite its relatively low market share, indeed, solar-based ORC plants featuring volumetric expanders – particularly scroll type - represent an appealing option for residential application, due to their fast response to the transient behavior of the heat source, low cost, large market availability of components, fail-safe operation and low vibration and noise

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Nomenclature

c_p	specific heat [kJ/(kgK)]
$\dot{m}$	working fluid mass flow rate [kg/s]-[g/s]
Q_1	Hot source thermal power [kW]
P	Power [W]
T	Temperature [K]
1	Condenser inlet
2	Condenser outlet/pump inlet
3	Pump outlet/evaporator inlet
4	Evaporator outlet/expander inlet
5	Expander output

Subscript

cw	cold water
in	inlet
out	outlet
exp	expander
hw	hot water
pump	volumetric pump
w	water
wf	working fluid

Greek Symbols

α	permeability [kg/(Pas)]
Δp	pressure rise [bar], [Pa]
η	efficiency

Acronyms

HRVG	Heat Recovery Vapor Generator
ORC	Organic Rankine Cycle
PHX	Plate Heat Exchanger
WF	Working Fluid
HW	Hot Water
CW	Cold Water

[7–12].

In domestic CHP applications, in which the power unit bottoms commercial flat plate collectors, the already scarce thermal energy gathered is partly employed to fulfill the demand of domestic hot water (DHW) that varies on an hourly, daily and seasonal basis. Consequently, the thermal energy availability to the ORC-based unit for electric power generation is hardly predictable, as well as the temperature level at which the thermal energy is transferred to the working fluid. These issues call for a control strategy to properly define the conditions for ORC activation and the optimal set of operating parameters for the power unit (e.g., working fluid mass flowrate, expander and pump RPM, operating pressures) in both design and off-design conditions [13,14].

For the application at hand, once the DHW demand has been met, the management of the unit can allow quite different scenarios in terms of electrical energy production. More specifically, a trade-off between the power of the bottoming unit and the time extent for its continuous operation must be sought as the former increases, a faster consumption of the residual thermal energy inside the reservoir takes place, forcing the power unit to stop until the thermal energy is restored. On the upside, the process of thermal recharge of the storage unit can start over and eventually results in a larger amount of ORC unit activations; on the downside, the plant operation is mostly intermittent, lower control on the global efficiency is allowed and the need to dampen the electricity fluctuations on the end user devices calls for the storage in a battery. The management of the thermal energy stored inside the reservoir is a complex issue and a model-based control strategy is needed to define a baseline for the electricity production. For such reasons, a small ORC-based power unit, featuring a 1 kW scroll expander was developed and fully instrumented, to experimentally assess its performance with large variations of the hot source condition and its suitability to off-design conditions. During the observation time, the variation induced on the hot source conditions reproduce either the effects of the DHW withdrawal on the available thermal energy in the storage unit or simulate the situation where the plant is driven exclusively by the hot water stored in TES tank without any further thermal reload from the solar thermal collectors.

The recovery unit can be also considered as a retrofit of the existing flat panel solar energy recovery systems since the thermal energy inside the tank often remains unused preventing any additional recovery.

2. Experimental layout

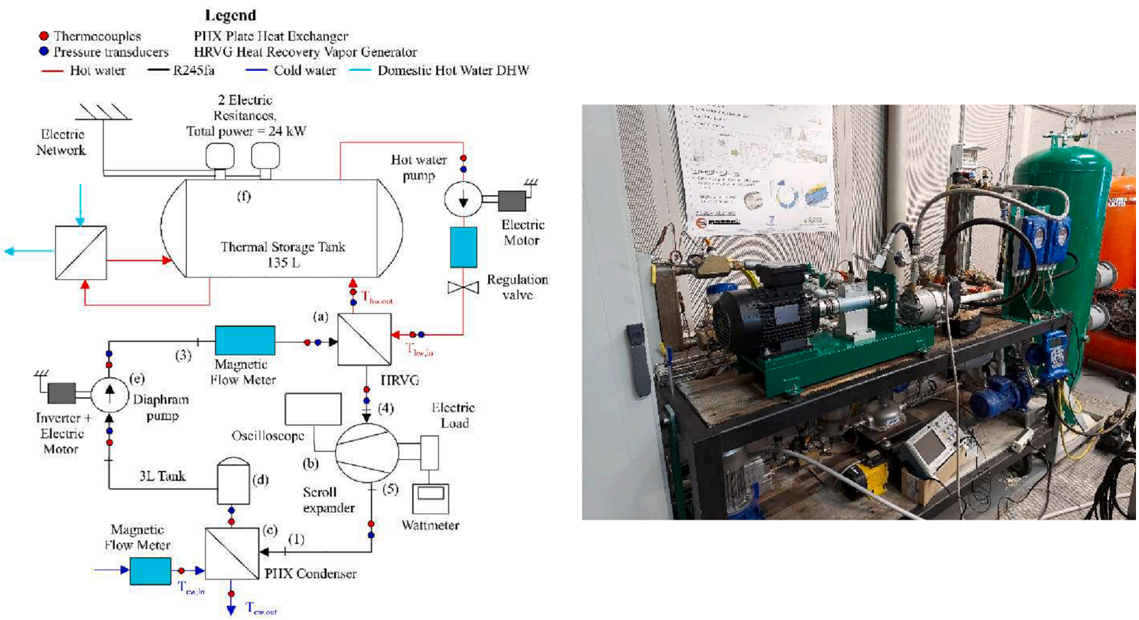
The present work deals with the experimental assessment of the performance of a micro-ORC plant that bottoms flat plate solar thermal collectors (15 m^2 surface), installed on a rooftop in typical climate conditions of central Italy. The design of the whole system was performed according to the comprehensive dynamic model developed by the Authors [15].

Fig. 1(a) reports the micro-cogenerative ORC-based set-up under investigation and Fig. 1(b) a picture of the plant itself. In addition to its suitability to the temperatures and pressures for application at hand [16,17], R245fa has high critical temperature, usually associated with high thermal efficiency [18]. In order to lubricate the pump and the expander, an ISO VG 68 POE oil was added to the working fluid in a share of 8% of R245fa charge (5 kg). A pair of 24 kW electric heaters warm up 135 L of water and simulate the thermal energy gathered by flat plate solar thermal collectors for residential application. The water is stored in a pressurized tank that damps the fluctuation of the hot source. The tank is pressurized by pre-charging it with air to prevent water from evaporating at the ORC-unit activation temperatures. The water is circulated by an electric motor-driven pump and a regulation valve allows the flow rate modulation to reproduce the thermal power availability at the ORC evaporator during actual operation. The electrical heaters, operated according to a preset activation map, reproduce the behavior of the solar collectors; similarly, the hot water extraction and replacement reproduces the use of DHW. The hot water flows in a plate heat exchanger heat recovery vapor generator (HRVG) (a) to heat the ORC working fluid up to a slight superheated vapor state. It then expands in a 1 kW hermetic scroll expander (b) thus producing mechanical power which is converted into electrical power through a generator. The electric power is dissipated on rheostat-adjustable electric load. The condenser (c), fed by tap water, brings R245fa back to its subcooled state. R245fa is gathered in a 3 L tank (d) prior to be recirculated by a diaphragm pump (e) with a 61.3 cm^3 volume displacement.

Pressure sensors and thermocouples, upstream and downstream each component, allow the cycle performance assessment. Magnetic flowmeters provide a real time reading of the flow rates of R245fa and water (Table 1). The expander power is measured through a wattmeter, while an optical probe inside the scroll casing allows the measurement of the revolution speed and the signal transmission to an oscilloscope. All quantities are actuated and measured by a PLC control bench.

In the following sections the results of different experimental analyses were reported, whose independent operating quantities are shown in Table 2.

The first experimental analysis concerns the steady off-design characterization of the unit. In this case, the working fluid mass flow rate was varied from 17 g/s to 62 g/s to follow the growth of thermal power availability at the evaporator, corresponding to a larger availability of



(a) (b)

Fig. 1. ORC-based power unit schematics (a) and experimental test bench (b).

Table 1
Measurement uncertainties.

Variable	Sensor Type	Measurement uncertainty
Temperature	Thermocouple	± 0.75 °C
Pressure	Pressure transducers	± 1.5% of full-scale
Mass flow rate (R245fa)	Magnetic Flow meter	± 0.15% measured value
Mass flow rate (water)	Magnetic Flow meter	± 0.5% measured value
Power	Wattmeter	± 1% measured value

Table 2
ORC and solar section operating quantities variation in the different experimental analysis.

Operating quantities	ORC section Mass flow rate of R245fa	Hot Water flow rate	Cold water flow rate	Solar section Solar Power (simulated by electric heaters)
Steady state analysis (Section 3)	17–62 g/s	20 L/min	30 L/min	12–24 kW
Transient analysis (Section 4)	0–62 g/s	6–20 L/min	30 L/min	12–24 kW
Analysis of discharge rate of the reservoir (Sections 5 and 6)	17–62 g/s	6–12-20 L/min	30 L/min	absent

solar thermal power, simulated by the growth of electric heaters power up to 24 kW.

The second experimental analysis regards the dynamic characterization, to assess the robustness of the plant when confronted with sudden variations of the available thermal power at evaporator. Such variation could be due to the daily, seasonal, and yearly variation of solar hot source and DHW requirements. The hot source power variation was simulated acting on the modification of hot water flow rate from 6 to 20 L/min and of the electric heaters between 12 kW and 24 kW. In order to address the variation of the thermal power available to the ORC-based unit., the working fluid mass flow rate was regulated in a range comprised between 0 and 62 g/s.

The last analysis refers to a different operating mode, in which the ORC-based plant is fed exclusively by the hot water stored in the reservoir in absence of solar radiation (pure discharging phase). So, the thermal energy content of the hot water is not restored by the solar source (the electric heaters are switched off). As the test goes on, the thermal energy availability decreases inviting to a reduction of the thermal power absorbed. The mass flow rate of working fluid was progressively decreased from 62 to 17 g/s. The test was repeated considering three different values of hot water flow rate (6, 12 and 20 L/min) to observe the impact of its variation on discharge time. In all the performed tests, cold-water flow rate was kept constant to 30 L/min being independent from the solar section condition.

Depending on the goal of the test, either two electric heaters or only one are activated: the total 24 kW heating power is employed to initially heat-up the reservoir from ambient temperature up to 100–110 °C rated temperature. Main reason was to shorten of the thermal charging time of the reservoir with respect to the real case, where the heating process depends on the solar energy availability and, so, it requires a longer time. During the first and second test, the electric heaters power was reduced up to 12 kW (only one electric heater is activated), closer to the average value of thermal power provided by the solar source to the water. Therefore, the variation of the solar power has been simulated acting on the electrical heater which restore thermal energy inside the thank at a rate which is easily controllable. In this way, the robustness of the ORC-based power unit when steady and dynamic variations of the available thermal power take place has been assessed. The presence of DHW has been simulated as well, simply extracting hot water and replacing it with cold water.

A different approach was adopted for the evaluation of the performances of the ORC-based unit in absence of solar power or in presence of a limited contribution. Here the plant is fed by the hot water stored in the TES tank without heat restoring. The TES is discharged at variable rate (according to the power of the ORC-based unit). The shorter is the discharging time, the greater possibility is offered to the Sun when it is available to restore heat inside the thank. The number of recovery unit operations (ON-OFF) which can be performed in a day and their duration is an interesting knowledge to optimize the recovery from solar energy. This helps to define an optimum activation strategy of the ORC-based unit considering the dynamic model developed in [15].

3. Performance analysis

The testing of the unit in stationary operating points accounts for both the design point and off-design conditions, the latter very frequent

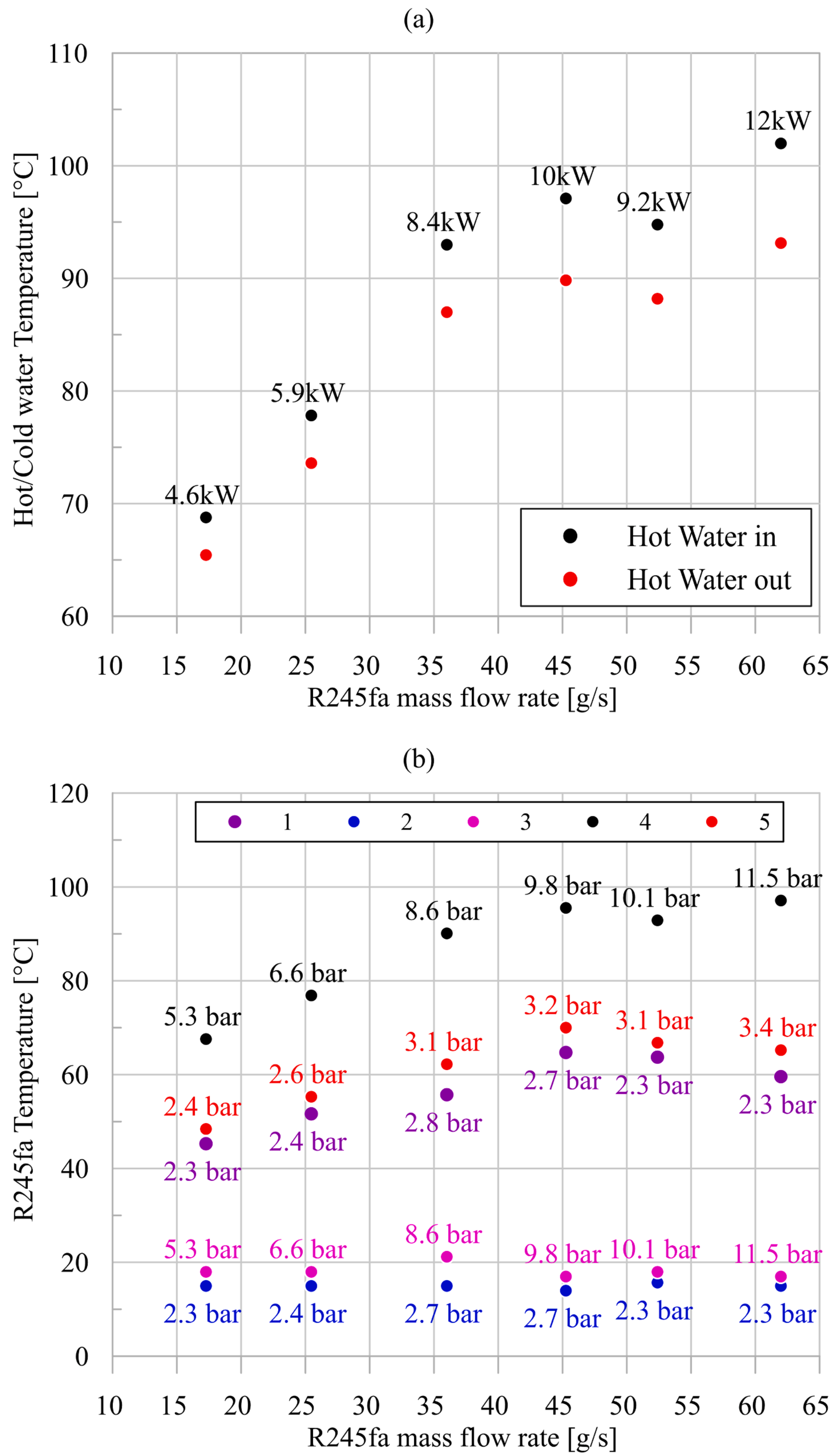


Fig. 2. Hot and cold water temperature and thermal power at evaporator (a) and pressures and temperatures at ORC stations (b).

in normal operation. The mass flow rate of the working fluid is adapted to the temperature of hot water at the evaporator inlet, via pump RPM modulation (Fig. 2(a)): due to the volumetric nature of the expander and its permeability, α in Equation (1) [19], it reflects on the pressure at the expander inlet (Fig. 2(b)). As Equation (1) shows, the permeability is represented by the ratio between the mass flow rate provided by the pump $\dot{m}_{wf}$ and the pressure difference between expander intake and exhaust side Δp_{exp}. In ORC plant with volumetric expanders, the expander intake pressure grows quite linearly with mass flow rate, [19]. So, the higher the permeability is, the larger the intake pressure increase is, for a given enhancement of mass flow rate provided by the pump. It is worth noticing that the expander permeability also affects the whole plant behavior being the expander intake pressure equal to the plant maximum one, net the head losses between the evaporator and the expander.

$$\alpha = \frac{\dot{m}_{WF}}{\Delta p_{exp}} \quad (1)$$

The lower the expander permeability is, the larger the pressure difference occurs across the expander, for a given flow rate. As a matter of fact, permeability affects the whole plant energy performance, since the expander intake pressure, net the low pressure drop between the evaporator and the expander itself, coincides with the plant evaporating pressure. This rebounds from the temperature trend at evaporator outlet, (Fig. 2(a)): a quite linear increase with mass flow rate occurs, due to the low superheating degree (5–10 °C) at expander inlet.

The upper cycle pressure – i.e., pressure in 4 - varies from 5 bar to 12 bar when mass flow rate ranges from 17 g/s to 62 g/s, while maximum temperature raises from 70 °C to 110 °C in the same interval. This proves that the plant works properly with mass flow rates well below the 62 g/s design value, even if great attention must be paid to the penalty on the power generation. The ORC produces a power close to 500 W in design condition (Fig. 3(a)) and as the mass flow rate reduces, the power generation exhibits a slightly sublinear trend: for a 40 g/s mass flow rate (- 35% from the design value), the power generation drops to 300 W (-40%). With larger mass flow rate decreases, the ORC-based unit is still able to produce power and the power decrease slows down even more: the power generation decreases from 300 W to 100 W (-67%) when the mass flow rate diminishes from 40 g/s to 17 g/s (-58%).

The ORC-based plant presents a promising trend also in terms of plant efficiency, evaluated according to Equation (2):.

$$\eta_{ORC} = \frac{P_{ORC}}{Q_1} = \frac{P_{exp} - P_{pump}}{\dot{m}_w c_{p,w} \left(T_{hw,in} - T_{hw,out}\right)} \quad (2)$$

The ORC plant efficiency η_{ORC} is expressed as the ratio between the net power produced by the unit P_{ORC} and the thermal power made available by the hot water Q_1. More in details, P_{ORC} can be obtained subtracting the pump power to that produced by the expander. For what concerns Q_1, it is obtained multiplying the mass flow rate of hot water $\dot{m}_w$, its specific heat at constant pressure $c_{p,w}$ and the difference between the temperature of hot water at evaporator inlet $T_{hw,in}$ and outlet $T_{hw,out}$.

The efficiency of the ORC-based unit decreases from 4% to 2.5% when mass flow rate varies in the 17 g/s to 62 g/s range (Fig. 3(b)), in accordance with the best literature on the topic. The decrease of efficiency as function of mass flow rate is due principally to the lower growth slope of power of the unit with respect to Q_1. Another important cause of the efficiency trend is the decrease of expander efficiency with mass flow rate, further proving that the expander is the component which affects the whole ORC performance the most.

4. Assessment of ORC-based unit performance under variable availability of hot source power

In addition to the large range of operation, already assessed via steady state testing of the plant, an ORC-based plant for solar application shall exhibit robustness to the time-variability of the available thermal power. Indeed, despite the installation of a thermal storage tank to overcome the hourly variability of solar energy, the power available to the unit varies with the DHW withdrawals. Model-wise this can be dealt with, by simply accounting for an aleatory disturbance against which the plant must be robust and reliable, in the prototype testing the hot source variability is reproduced over a 2750 s time domain (i) by modulating the mass flow rate of hot water to the evaporator and (ii) by arming the electric heaters according to the profile in Fig. 4(a).

The R245fa flow rate is regulated to ensure at least the full vaporization of the working fluid at the expander inlet Fig. 4(b), even if dual-phase expansion is admissible. Based on the shift of the hot water mass flow rate, up to 7 sections can be appreciated.

During the starting phase of the unit (0 s – 50 s), the expander intake pressure and the flow rate are proportionally related (Fig. 5(a) and (b)), while the temperature variation does not follow a proportional trend: at first it spikes to 90 °C but subsequently a typical first order dynamical growth is observed (Fig. 5(c)). The expander starts producing power already with an 8 L/min hot water flow rate and 110 °C at evaporator inlet (Fig. 5(d)), proving the expander ability to establish a pressure growth proportional to the mass flow rate.

In section 2 (15 s – 550 s) the hot water flow rate is kept to 8 L/min (Fig. 4(a)). During the first 130 s, the mass flow rate of R245fa is increased from 54 g/s up to 60 g/s, to keep the superheating degree below 10 °C and prevent a sudden vaporization of the working fluid, inside the evaporator. During the remaining 370 s of section 2, R245fa mass flow rate stabilizes at 60 g/s, corresponding to an 11.7 bar expander intake pressure (Fig. 5(b)), and the superheating degree drops along with the temperature of the hot water (Fig. 5(c)). The generated power grows linearly between 200 W and 400 W, until the superheating degree starts dropping (Fig. 5(d)).

In section 3 (550 s – 980 s), a hypothetical reduction of DHW requirement is simulated via an increase in the hot water flow rate (18

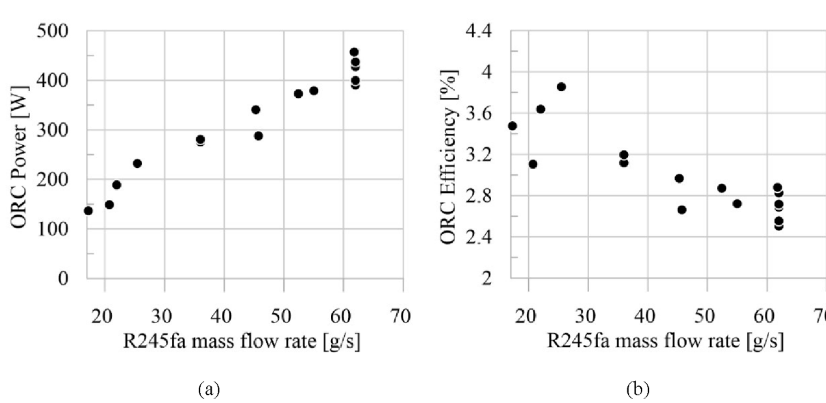


Fig. 3. ORC power (a) and ORC efficiency power trend (b) as function of mass flow rate.

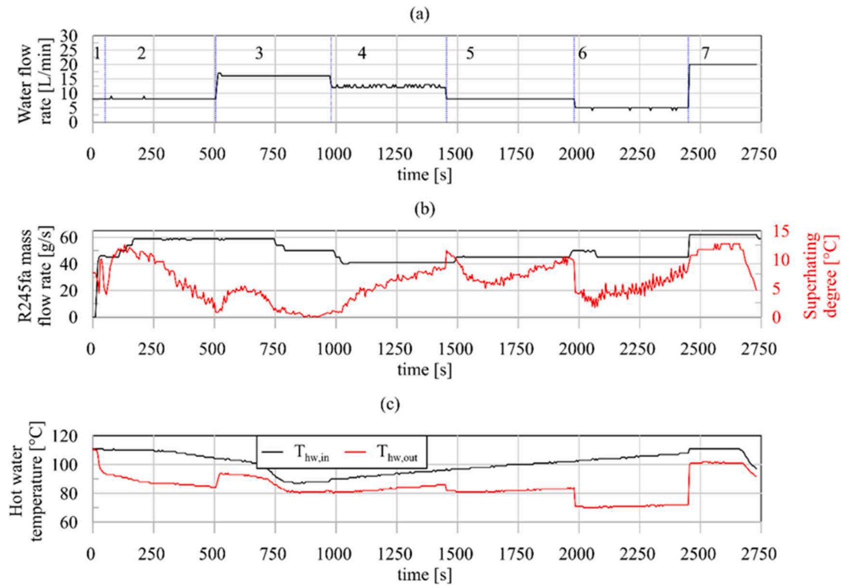


Fig. 4. Flow rate of hot water (a). R245fa flowrate and superheating degree (b) and hot water temperature (c).

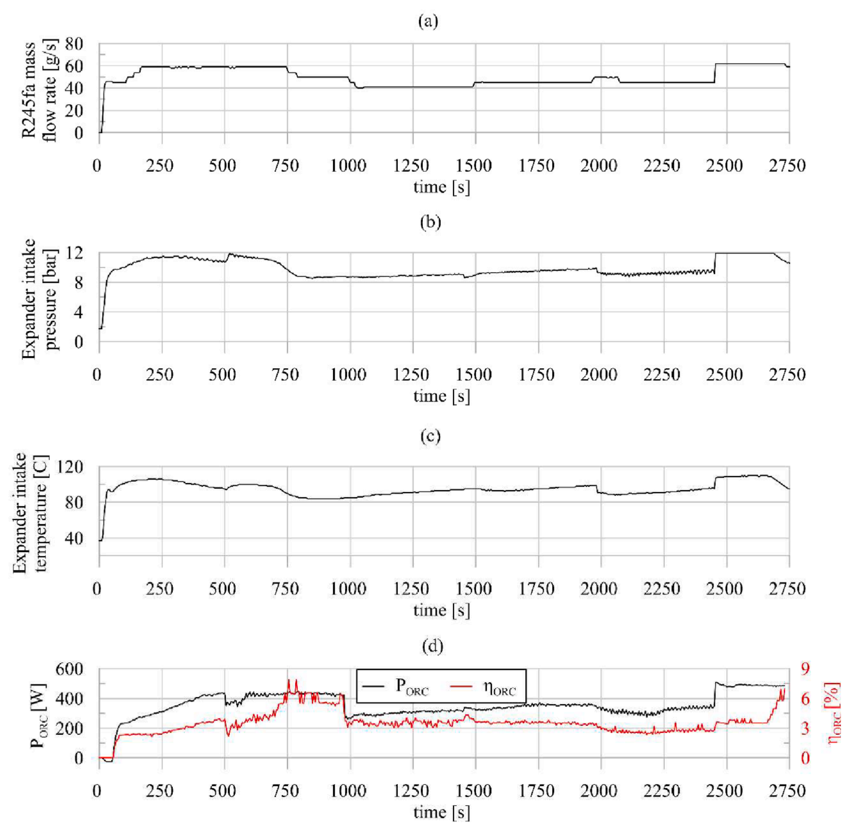


Fig. 5. R245fa flow rate (a), expander pressure (b) and temperature (c), power and efficiency of the ORC unit (d).

L/min). In order to exploit a larger superheating degree, the mass flow rate of R245fa is reduced down to 54 g/s, at about 800 s: during the remaining 180 s of section 3 an only marginal increase is appreciated on the R245fa superheating degree (Fig. 4(b)) and thus on the expander intake pressure (Fig. 5(b)). Nonetheless, the expander works in better conditions: the higher efficiency prevails on the relatively unvaried superheating degree and the unit power increases (Fig. 5(d)).

Conversely, section 4 (980 s −1420 s) accounts for an increased DHW requirement, simulated by the reduction of the water flow rate down to 12 L/min. The R245fa flow rate drops to 40 g/s to prevent the superheating degree from decreasing with the hot water mass flow rate: values close to the rated one (10 °C) assure larger power outputs from the unit.

In section 5 (1420 s − 2000 s) the hot water flow rate is further reduced to 8 L/min. For superheating control purposes, the R245fa mass flow rate is slightly increased. Whereas the R245fa mass flow rate increase is too little to slow down the water temperature increase, it makes the expander intake pressure growing with a linear trend (Fig. 5(b)) and the superheating degree sink to 7 °C (Fig. 4(b)) at 1450 s. From that point on, the temperature at the expander intake starts rising again, pushing the superheating degree up to 10 °C. The power of the ORC unit is relatively unaffected by the mass flow rate and grows continuously until 2000 s (Fig. 5(d)).

A further increase in DHW request is simulated in section 6 (2000 s – 2200 s), in which a 6 L/min hot water flow rate is considered. The subsequent reduction in the R245fa flow rate (40 g/s) - and eventually in the expander intake pressure – is compensated via an increased superheating degree (above 10 °C) in order not to depress the overall plant performance.

In section 7 (2200 s – 2800 s) flow rate of hot water is raised to 20 L/min, according to a sudden decrease in the DHW demand. In order to keep a superheating degree below 13 °C, the flow rate of R245fa is pushed to 62 g/s: a 12 bar pressure is reached at the expander intake (Fig. 5(b)) and the ORC unit provides 500 W power.

The ORC plant proves its own ability to constantly reset its own equilibrium to properly follow the hot source drift. Apart from the first 50 s, needed to the pump to start circulating the working fluid right after the unit is started, the generated power ranges between 300 W and 500 W for the total analyzed time domain, with a regular efficiency trend (between 3% and 6%). The smoothness and robustness of plant operation, despite the severe fluctuations of temperatures, pressures and mass flow rate of working fluid, point out the suitability of scroll technology for the expansion device in the application at hand.

5. Assessment of ORC-unit performance under thermal energy storage temperature drift

The energy merit of the micro-cogenerative unit under investigation is associated with the possibility it assures to continuously operate when fed with the thermal leftovers from DHW fulfillment and thus exploit low grade thermal energy, wasted otherwise. The operating flexibility of the power unit, already proven in transient off-design conditions, is checked against a progressively decreasing TES thermal availability (Fig. 6(a)), recurring in real operation whenever no addition of thermal energy from the solar thermal collectors takes place. A dedicated experimental analysis focuses on (i) the assessment of the ORC unit performance with low R245fa flow rates and (ii) on the plant responsiveness to sudden flow rate variations, via the modulation of the pump RPM, to assure the best possible trade-off between a proper superheating degree - or, at least, the full vaporization of the fluid at the expander intake - and the optimal pressure at the expander intake.

As soon as the hot water in the TES tank reaches 110 °C, the electric heaters are turned off and the ORC pump activates. On the hot side of the evaporator, the water flow rate is kept constant (20 L/min) across the whole test duration, while on the cold side of the evaporator the R245fa flow rate is continuously adapted to ensure a proper superheating degree (Fig. 6(b)). The experimental test runs until the useful power produced by the unit is above 100 W.

Until 300 s, the plant operates in design conditions, i.e., 62 g/s flow rate and 10 °C superheating degree. From that point on, the thermal drift of the hot source starts affecting the mass flow rate of the working fluid, progressively reduced until 1200 s, when the superheating degree does not exceed 1 °C (Fig. 6(b)). Generally speaking, in this phase, the flow rate modulation aims at maximizing the expander intake pressure, rather than at assuring the design superheating degree.

The need to prevent a dual-phase expansion becomes the priority at 1200 s, when the superheating degree spikes to 5 °C (Fig. 6(b)) as the expander intake pressure adapts to the mass flow rate variation of R245fa (Fig. 7(a) and 7(b)): the instantaneous variation of intake pressure when mass flow rate varies is the key to the fast adaptability (and controllability) of the unit despite the slower trend of the temperature (Fig. 7(c)).

After 1200 s the mass flow rate is gradually reduced down to 17 g/s when the hot water temperature is equal to 65 °C. The plant proves to be flexible throughout the whole 3200 s test duration and able to follow the thermal drift of the TES unit, with 450 W power generation, up until 500 s and more than 200 W until 1600 s (Fig. 7(d)). In the remaining part of the test (1600 s – 3200 s), the power produced is above 100 W, despite the very low values of mass flow rate entering the expander. The global efficiency stays in the 2% − 4% range, confirming the plant effectiveness in addressing the TES thermal drift that occurs when the consumed thermal energy cannot be restored by the solar thermal collectors. Moreover, some margin for further improvement could be gained through the modulation of the hot water mass flow rate, according to an optimized discharge strategy.

6. Assessment of TES discharge rate

The optimized discharge strategy should rely on the assumption that as the flow rate of hot water to the evaporator decreases, the ORC unit can be continuously fed for a longer time span. Of course, the downside is that the thermal equilibrium of the ORC unit fixes lower characteristic mass flow rates of the working fluid, i.e., lower generated power.

A dedicated experimental campaign assessed the impact that the TES discharge rate, associated with various mass flow rates of hot water (12 L/min and 6 L/min), has on the ORC unit performance (Fig. 8). By analogy to the test cases discussed above, the test was over when the ORC unit power drops below 100 W.

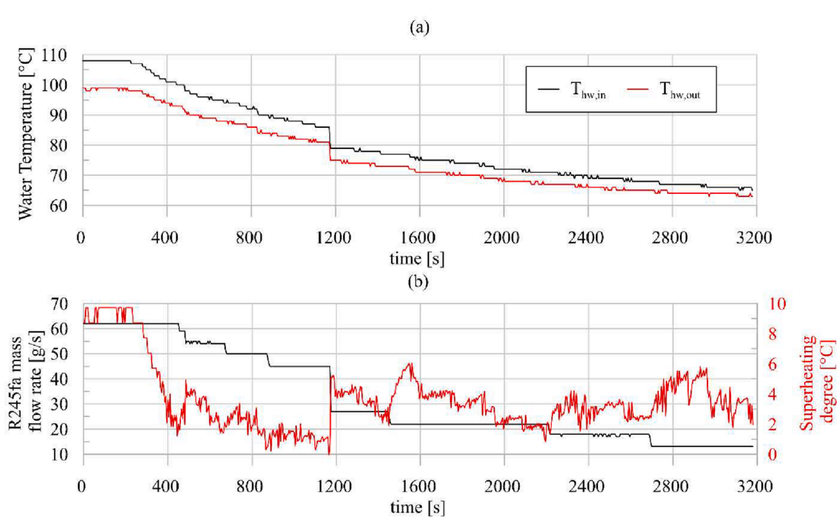


Fig. 6. Water inlet and outlet temperature (a) and R245fa mass flow rate and superheating degree (b).

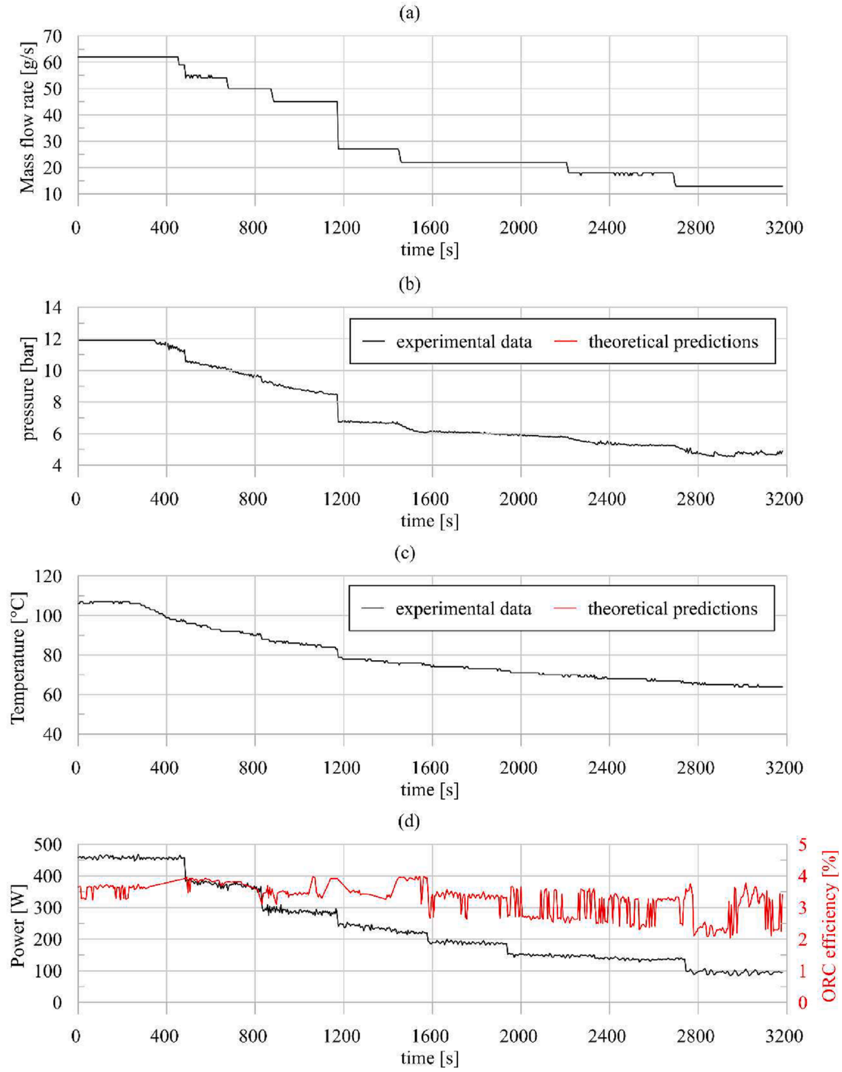


Fig. 7. R245fa mass flow rate (a), theoretical and experimental profiles of pressure (b) and temperature (c), power and efficiency of the ORC unit (d).

As expected, with a 6 L/min flow rate, the hot water temperature decrease is slower than with a 12 L/min flow rate (Fig. 8(a)): the 90 °C threshold temperature is reached within 1400 s in the former case, within 800 s in the latter one. With reference to the 12 L/min case, the temperature reduction trend approaches the one associated with 6 L/min flow rate after 800 s: as the hot water temperature drops, the thermal balance at the evaporator calls for a lower R245fa flow rate fed to the cold side of the evaporator. An only marginal effect of the different hot water flow rates is appreciated on the overall duration of the ORC unit operation, that tops 3335 s with 6 L/min flow rate and 3100 s with 12 L/min. Way more interesting the effect of the different discharge rates on the power generated by the plant (Fig. 8(c)): once the plant is started, the unit provides more than 300 W up until 1000 s and 1700 s, in the 12 L/min case and 6 L/min case, respectively. The gap between trends is filled up after 1700 s, due to the larger flow rate of R245fa in the 6 L/min case.

In the 12 L/min case, the plant reaches higher efficiency values (between 4% and 6%), than in the 6 L/min scenario (between 3% and 4%). The 6% efficiency peak limited to the 1400 s – 1700 s time span, appreciated in the 6 L/min test case, suggests that, with low flow rates of hot water, lower average efficiencies should be expected, with a negligible extension of the operating time of the ORC unit.

At the end of the TES tank discharge, the unit power production ranks at 767 kJ, 739 kJ and 761 kJ electric energy with a 20 L/min, 12 L/min and 6 L/min flow rates of hot water, respectively (Fig. 9): larger flow rates of hot water provide the best trade-off between the duration of the ORC operation (close to one hour), the generated power and the efficiency level of the ORC unit.

It is worth noticing that, in case the TES is completely discharged, the ORC unit cannot be operated until the thermal energy is restored: considering 135 L of water stored in the TES tank, whose temperature is raised from 65 °C (at discharge completed) to 108 °C (ORC unit activation threshold), 24300 kJ are needed. On the test bench, the two 12 kW electric heaters take 17 min to complete the water heating. Such power, though, is hardly attainable in real applications, hence a longer time-to-charge should be expected: for a preliminary evaluation, an average 10 kW power is transmitted to the hot water by the solar collectors [15], leading to 41 min wait until the TES thermal availability is restored. Hence, in the 20 L/min hot water flow rate scenario, the time between two consecutive ORC activations is 94 min: a conservative estimate of 5 h duration for the solar radiation results in 3 complete discharges per day, if the energy stored in TES tank is used to drive exclusively the ORC unit. In this case, a whole energy equal to 2300 kJ per day can be produced, with a production of 233 kWh per year, i.e., a 9% share of the 2700 kWh overall electric energy demand per household in Europe [20]. In the actual cogenerative set-up, the TES thermal availability is split between the DHW fulfillment and the feeding of the ORC-unit, preventing the complete discharge of the TES for electricity

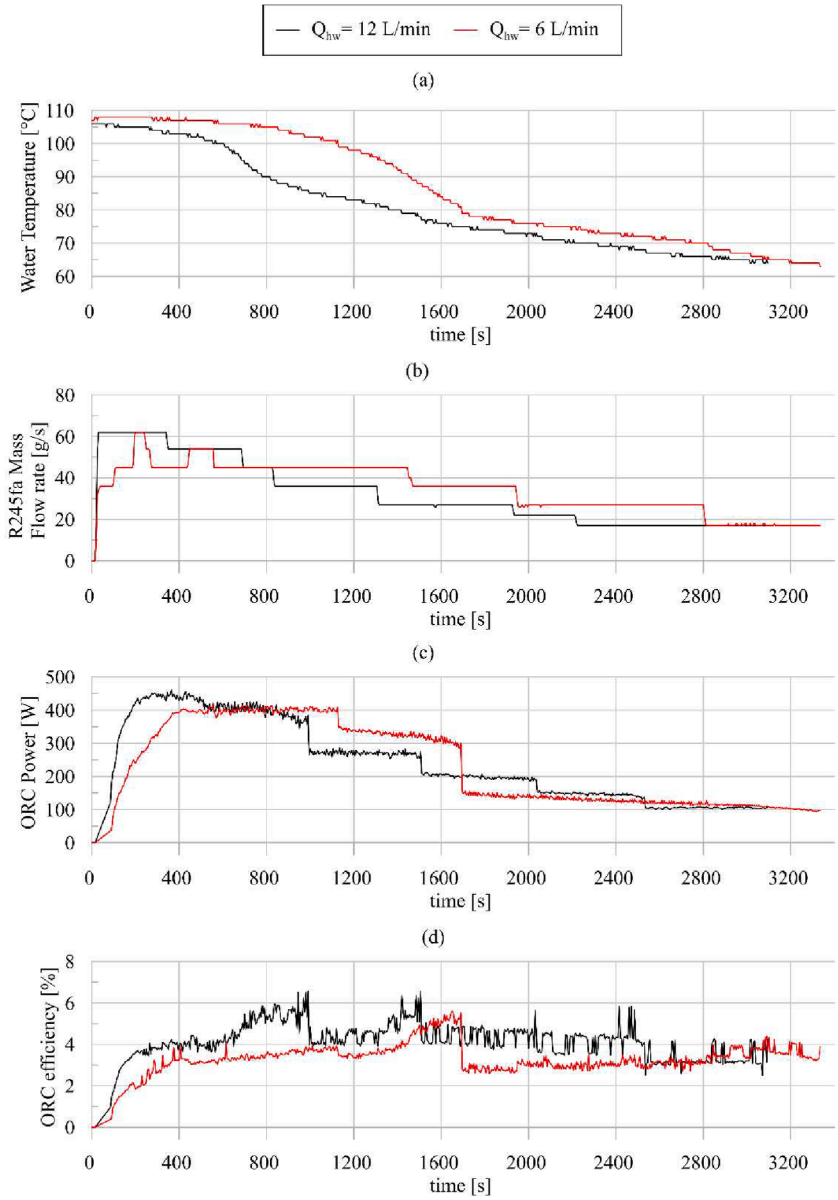


Fig. 8. Dynamic profile of hot water temperature (a), R245fa flow rate (b) ORC power (c) and efficiency (d).

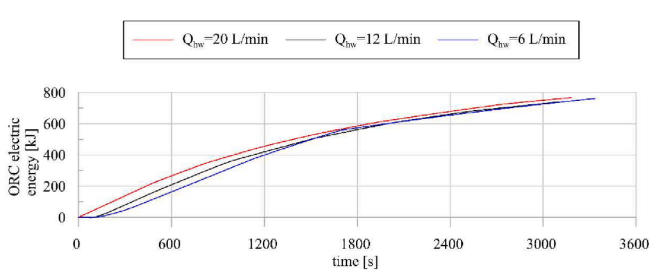


Fig. 9. Cumulated electric energy produced by the ORC unit.

purposes. Plus, the large time for TES recharge can easily prevent multiple ORC activations.

The theoretical analysis by the Authors in [15] accounts for the simultaneous fulfillment of DHW and electricity generation: if the lower threshold on the hot water temperature for ORC-based unit activation is pushed down to 90 °C, the optimal timespan for the unit continuous operation is 15 min (900 s). Such result is aligned to the experimental evidence, that proves that the after 900 s continuous operation of the ORC-based unit the hot water temperature drops to 90 °C. Moreover, during the first 1000 s of operation, the ORC unit provides power in the 300 W – 500 W range, larger than any other output generated during the remaining 2000 s.

Consequently, an alternative option to the TES full discharge is a withdrawal of thermal energy, split in multiple phases, in order to allow, for each value of hot water temperature imposed by the thermal equilibrium at the TES, 15 min continuous operation of the ORC unit. In such case, the average amount of ORC activations per day tops 7: in the best-case scenario of 20 L/min flow rate of hot water at the evaporator, 370 kJ per ORC activation are generated (Fig. 9), leading to 2590 kJ daily production and 262 kWh generated per year.

The residual thermal energy in TES during the queue of the DHW demand is available for conversion in the ORC unit: the seventh and last discharge could exploit such energy availability and last until the TES is completely discharged (roughly 3200 s). The daily production of electricity ranks at 2987 kJ that cumulated over a year leads to 303 kWh, i.e., an 11.2% share of the annual electricity demand per household in Europe.

7. Conclusions

Decentralized power generation via ORC units is among the most promising techniques to increase the sustainability rate in the residential sector. The selection of a proper control strategy assures a huge margin for performance improvement of the ORC unit, often operated far from the design point. A fully instrumented ORC unit was conceived to bottom 15 m^2 of solar thermal collector surface mounted on a rooftop in central Italy. The ORC unit was developed and experimentally assessed, in both design and off design conditions. The thermal energy provided to 135 L of water by flat plate solar collectors during normal operation and the hot water withdrawal for DHW purposes were reproduced, via dedicated electric heaters and by regulating the flow rate of hot water from a TES tank, respectively. The expander revolution speed was not constrained to any target value: it results from the dynamic equilibrium between the driving and resisting torque on the machine shaft.

The assessment of the plant in stationary conditions confirms the expectations on the ORC unit flexibility: as the working fluid flow rate varies between 17 g/s and 62 g/s, the generated power ranges from 100 W to 500 W. The efficiency ranges between 2.4% and 4%, mostly affected by the expander response to different processed flow rates of working fluid.

The effect of the DHW withdrawals on the thermal availability to the bottoming ORC unit was analyzed over a 2800 s time domain: the flexibility of the scroll expander, whose intake pressure varies linearly with the processed mass flow rate, assures proper operation in non-stationary conditions and a faster start of the unit (50 s). The ORC unit generates power in the 300 W – 500 W range, with an efficiency between 3% and 6%.

If operated during the TES thermal drift (3200 s), i.e., without any thermal energy addition to the TES, the ORC generates more than 200 W during the first 1600 s and the efficiency is in the 2% – 4% range. Preliminary experimental evidence suggests that the effect of a reduction in the hot water flow rate on the timespan of ORC unit continuous operation is negligible.

Based on different durations of the ORC-unit run and the time needed to restore the TES thermal availability, if no DHW production is considered, an average amount of 3 discharges per day is feasible: over the year, this corresponds to a 9% share of the overall domestic electricity demand. When the subtraction of thermal energy for DHW purposes is considered, the splitting of the TES discharge over multiple ORC unit activations (15 min ORC run duration) should be preferred: 7 ORC unit activations per day assure a yearly generated power corresponding to a 9.7% share of the yearly European electricity demand per household. Such datum ranks at 11.2% if the seventh and final ORC unit activation is run to the full discharge of the residual energy in the TES unit.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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