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Proceedings of the 7th International Seminar on ORC Power Systems

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Toward a Green Energy Community: Integration of micro-ORCs combined with renewable energy technologies in buildings.

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ABSTRACT

Distributed microgeneration is an alternative for aggregate energy integration into the electricity grid. Low-temperature heat recovery systems, such as ORCs, are particularly interesting given their compactness and safety for application in the residential sector, operating at moderate pressures and low heat source temperatures. Energy surpluses generated by renewable technologies commonly used in the building sector, such as photovoltaics or micro-wind, can be used to power systems that provide backup and add inertia to the grid. In this study, micro-ORCs (< 2 kWe) were integrated with different heat supply technologies in buildings, including storage with DHW water tanks or sensible heat in bedrock for heating. An overview of possible configurations and techno-economic optimization is provided, offering combined strategies with other installations and additional characterization of energy communities with a larger number of connected neighbors, determining optimized integrations for covering thermal and electrical demands.

1 INTRODUCTION

As global concerns regarding climate change and environmental degradation have increased, there is a growing need to transition to sustainable and renewable energy sources (IEA, 2022). Integrating energy communities in rural areas has emerged as a promising solution for increasing sustainability, promoting the use of renewable energy sources, and reducing carbon emissions (Koirala et al., 2016; Streimikiene et al., 2021). By leveraging local renewable energy resources and fostering cooperation between energy users and producers, energy communities can contribute significantly to achieving a sustainable energy future (Bassam, 2021). Furthermore, the integration of renewable energy technologies into residential buildings is a critical component of this transition (Klein & Coffey, 2016), and the cost-efficient implementation of cogeneration (CHP) systems in single-family homes represents a significant step towards achieving this goal (Ceglia et al., 2022a).

The integration of organic Rankine cycles (ORC) in single-family homes is presented as a promising option for the generation of electricity from residual thermal energy produced by, for example, the time gap between demand and the generation of domestic solar hot water (Ancona et al., 2022; Pereira et al., 2018a). (Rodriguez-Pastor et al., 2023) analysed the optimal sizing of ORCs for solar domestic hot water systems, depending on the demand and solar resources available at the site, and reported improvements in the efficiency of solar collectors owing to a lower fraction of cold-water mixing. (Braimakis et al., 2021) studied centralized scenarios incorporating district heating systems that further enhance the performance and feasibility of ORC systems. Using low-grade waste heat, such as solar domestic hot water systems (Bou Lawz Ksayer, 2011), the ORC system can produce electricity while simultaneously providing heat to the building through the District Heating network.

Energy communities are groups of households, businesses, or other entities collaborating to generate, consume, and share energy locally (Andoura et al., 2010). By leveraging surplus thermal energy from

systems such as domestic hot water with storage for electricity generation, ORC systems can contribute to the development of sustainable and self-sufficient energy communities (Alberto et al., 2022; Ceglia et al., 2022b). They can reduce dependence on the electric grid, promote energy independence, and enhance local resilience to power outages and disruptions (Dóci et al., 2015). They can also optimise the utilisation of surplus thermal energy, which would otherwise go to waste, by converting it into electricity, thus improving energy efficiency and reducing the environmental impact (Baral et al., 2015). Additionally, energy communities can promote social cohesion, participation, and empowerment among their members as they jointly participate in energy production and consumption decisions (Lowitzsch et al., 2020). However, there are also associated challenges and considerations, including regulatory and legal frameworks, technical complexities of power production system installation and operation (Loni et al., 2021; Pereira et al., 2018b), financial aspects such as investment costs and revenue sharing among community members (Busch et al., 2021), and potential disparities in energy demand and supply among different households or entities within the community (Frieden et al., 2020). Addressing these challenges requires careful planning, coordination, and stakeholder engagement (Mishra et al., 2022).
This study aimed to analyze the technical and economic feasibility of integrating ORC systems into single-family homes in southern Spain in decentralized and centralized scenarios. This study focuses on analyzing the potential for the use of waste heat from solar hot water systems to generate electricity and provide heating to buildings. A detailed techno-economic analysis of the ORC system and SDHW was conducted by considering different configurations and operating conditions. These results provide valuable information to policymakers, energy planners, and homeowners regarding the adoption and implementation of ORC systems in the residential sector.

2 SYSTEM DESCRIPTION

In a decentralized system integrating ORCs in the residential sector, each household or residential unit has its own installed micro-ORC, which uses surplus thermal energy from its domestic hot water system with storage to generate electricity (**Figure 1**). This approach involves the installation of smaller capacity micro-ORC systems in each household or residential unit. Each micro-ORC can operate autonomously and generate electricity in individual operation (Physical System). The excess electricity produced can be injected into the grid, allowing the possibility of earning income by selling energy to the grid. This decentralized approach offers advantages in terms of energy autonomy for each residential unit. 714

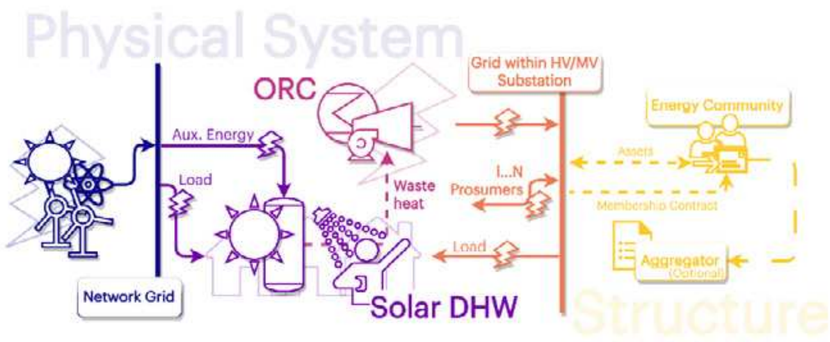

Figure 1. Conceptual diagram of the proposed decentralised ORC-SDHW system

In contrast, in a centralized system integrating ORCs in the residential sector, a higher-capacity ORC is installed in a central location, which can be a community facility or power generation plant (**Figure 2**).

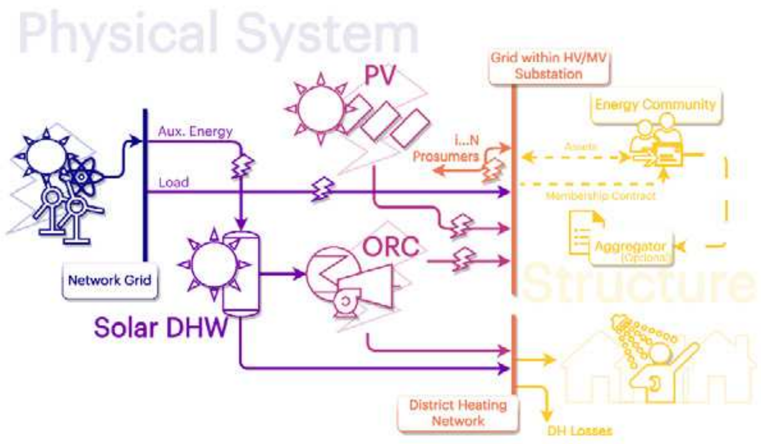

Figure 2. Conceptual diagram of the proposed centralised ORC-SDHW system

For the centralized approach presented, the central ORC system harnesses residual energy from industrial thermal processes or utilizes solar thermal energy for domestic hot water systems during periods of low demand or high solar resource, resulting in a decrease in the flow rate of the cold-water mix and a consequent increase in the performance of solar collectors. The central ORC can operate more efficiently and cost-efficiently because of its economy of scale, with a reduced kilowatt cost and better control and management of electricity generation. The produced electricity can be injected into the grid and distributed to households or residential units in a zone or community. This centralized approach offers advantages in terms of efficiency, economics, and management of electricity generation on a larger scale, as discussed. In a decentralized system, each household or residential unit has its own micro-ORC for local electricity generation, whereas in a centralized system, a higher-capacity ORC is used at a central location to harness surplus thermal energy from multiple households or residential units in a zone or community. Both approaches have advantages and challenges, and the choice between them depends on the specific needs and characteristics of the project or application under consideration, where the management of production/generation is provided by a contractual structure system (Structure). 715

In this study, the R245fa fluid was selected based on the criteria of condensing at atmospheric pressure at temperatures on the order of ambient temperature. This allows for greater flexibility in installation, considering that the facility is applied in a residential environment.

3 SIMULATION

Figure 3 shows the proposed system. This was simulated using the commercial software TRNSYS (S.A Klein, 2017). For this purpose, an ORC type was created that modelled the ORC cycle based on the values of the parameters in **Table 1**.

Table 1. Thermodynamic considerations for power system simulation.

Variable	Value
Heat Exchangers approach temperature	20 K
Isentropic efficiency of pump	50%
Isentropic efficiency of expander	60%
Maximum refrigerant pressure	$0.85 \cdot p_{crit}$
Storage setpoint temperature for ORC start-up.	75 ºC

Refrigerant property calculations are performed through a subroutine that calls Coolprop (Bell et al., 2014), obtaining the associated power production in the expander at each time step. Several articles have employed this methodology, such as the studies by (Ancona et al., 2022). The following considerations and assumptions have been considered for the calculation of the power system in residential ORC systems with solar hot water systems. i) The minimum water outlet temperature of the ORC evaporator is 60°C to avoid penalizing the demand. ii) The mass flow rate of the refrigerant varied according to the waste heat power of the SDHW system to satisfy the energy balance in each case. iii) The calculations were performed in a quasi-dynamic regime. iv) The temperature of the cold fluid used for condensation is 25°C.

The TRNSYS simulations use Types 4 and 1 to represent the storage tank and collectors, respectively. The system equations will be simplified algebraically within TRNSYS, where the collector efficiency is described by three parameters (a_0, a_1, and a_2) in accordance with ASHRAE, SRCC, and CEN standards.

$$\eta_{coll} = a_0 - a_1 \frac{\Delta T}{I_T} - a_2 \frac{(\Delta T)^2}{I_T} \tag{1}$$

The collector area is determined by the volume/area ratio of 50 l/m^2, where the storage volume is designed to cover 1.5 times the total daily demand (Duffie & Beckman, 1991). The demand will be calculated according to the Spanish regulation standard, which is 28 l/s·person·day at a temperature of 60ºC (Ministerio de Fomento, 2019).

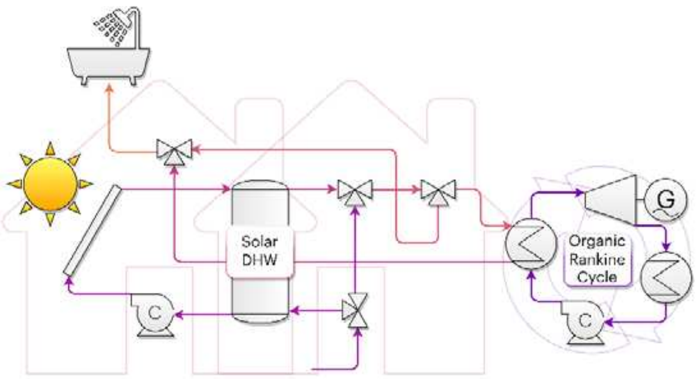

Figure 3. Flow diagram of the proposed SDHW-ORC system

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Meteorological data from Seville (-5.9731700º; 37.3828300°) were used, considering the variation in demand associated with the occupancy of the residence in the decentralized case and for several residences of four people in the centralized case. **Table 2** lists the thermodynamic parameters that describe the solar-loop components.

Table 2. Thermodynamic parameters of the solar collectors

Parameter	Value	Units
Fluid specific heat	4.19	*kJ/kg.K*
Tested flow rate	0.011	*kg/s.m^2*
Intercept efficiency (a_0)	0.801	-
Efficiency slope (a_1)	3.93	*W/m^2.K*
Efficiency curvature (a_2)	0.026	*W/m^2.K^2*
1st-order IAM	0.2	-

These values were used to evaluate the technical and economic feasibility of the installation and its integration in an energy community context. No subsidies or grants were considered in the analyses. The objective is to provide correlation coefficients for evaluating the system based on the number of people participating in the energy community, proposing simple expressions that may be valuable for organizations such as governments or municipalities that intend to implement ORC-based energy communities. The expressions have the following forms (Equations 2 and 3):

$$E_{DHW}^{d} = a_{DHW}^{d} + b_{DHW}^{d} \cdot Persons + c_{DHW}^{d} \cdot Persons^{2} \tag{2}$$

Where E_{DHW}^{d} is the annual thermal demand for domestic hot water of the household in kWh.

$$E_{ORC}^{d} = a_{ORC}^{d} + b_{ORC}^{d} \cdot Persons + c_{ORC}^{d} \cdot Persons^{2} \tag{3}$$

And E_{ORC}^{d} is the annual ORC production for the decentralised case in kWh. When forming a community considering a centralized system that supplies several residences, the expressions are as follows (Equations 4 and 5).

$$E_{DHW}^{c} = a_{DHW}^{c} + b_{DHW}^{c} \cdot Households + c_{DHW}^{c} \cdot Households^{2} \tag{4}$$

Being E_{DHW}^{c} is the annual thermal demand for domestic hot water of the households in kWh.

$$E_{ORC}^{c} = a_{ORC}^{c} + b_{ORC}^{c} \cdot Households + c_{ORC}^{c} \cdot Households^{2} \tag{5}$$

And E_{ORC}^{c} is the annual ORC production for the centralised case in kWh. On the other hand, the Internal Rate of Return (IRR) will be evaluated from Equation 6.

$$IRR = r \ when \sum^{n} \frac{CF_k}{(1+r)^k} = 0 \rightarrow IRR^{i} = a_j^{i} + b_j^{i} E_{DHW}^{i} + c_j^{i} {E_{DHW}^{i}}^{2} + d_j^{i} E_{ORC}^{i} + e_j^{i} {E_{ORC}^{i}}^{2} \tag{6}$$

For a useful life (n) of the installation of 20 years and a discount rate (r) of 5%. Similarly, to evaluate the cost of energy, the Levelized Cost of Energy (LCOE) is used, as expressed in Equation 7:

$$LCOE = \frac{CAPEX + \sum_{k=1}^{n} \frac{OPEX_k}{(1+r)^k}}{\sum_{k=1}^{n} \frac{E_{ORC}^{i}}{(1+r)^k}} \tag{7}$$

$CAPEX$ being the initial investment cost of the plant, $OPEX_i$ is the annual operation and maintenance cost and E_{ORC} the annual energy produced in the ORC in kWh. Investment and maintenance costs were estimated using CEPCI (Jenkins, 2014) indices. The energy cost is determined by the wholesale price in Spain in 2022 (OMIE, 2022).

4 SUBMISSION OF MANUSCRIPT

4.1 Decentralized systems

In decentralized systems, the trend of irradiance is crucial for the correct operation of the ORC and an increase in production. This variable is directly related to the number of people living in the house, as it requires a larger solar loop size (larger area and storage) to meet the demand. The ORC production for months of high irradiation will practically double (450 kWh) for the case of maximum occupancy (six people), owing to the lack of demand and a higher thermal level than in other cases (**Figure 4, left**). On the right side of **Figure 4**, the points are displaced according to the number of people and associated demand for domestic hot water. This shows that, in many solar DHW systems, there is a significant excess of energy that is not used and is lost when hot water is mixed with cold water from the main source. This was deduced from the amount of energy produced in the ORC from the waste heat in solar DHW systems. For a setpoint temperature of 60 °C, according to the regulations governing these systems, there is a thermal resource at the outlet that can be used in a simple way through the ORC evaporator, designed such that it does not affect the demand in this case, and that the consumer receives domestic hot water at the temperature that he/she establishes.

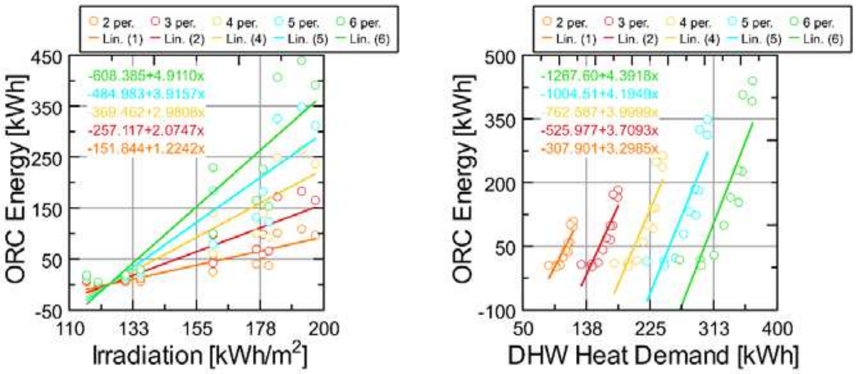

Figure 4. Monthly ORC energy production as a function of the number of people in the household and left: monthly incident irradiation (kWh/m^2) and right: monthly domestic hot water demand (kWh)

From an economic point of view, ORCs still have challenges to be fully competitive on a small scale, with costs of 45 cents/kWh, more than twice that of photovoltaic systems without storage, and even above those with batteries (Lazard, 2023). Cost reductions may occur with a greater number of people to supply and optimised management of the available heat. An increase of 500 kWh in the ORC production per year may decrease the associated LCOE by 10 cents until it stabilizes (**Figure 5, left**). This also applies to the net present value (NPV), which reaches a maximum of five people (2300 €) and then decreases. Therefore, there is a strong correlation between the demand and annual production (**Figure 5, right**), which can take advantage of almost half of the energy applied to the demand in ORC production. As the heat demand increases, the net present value will eventually stabilize, as the sizing of the ORC will have to increase, and the cost correlations will be different from those considered in the micro-ORC field. In this sense, it is of interest to opt for centralized configurations, as discussed in the next section.

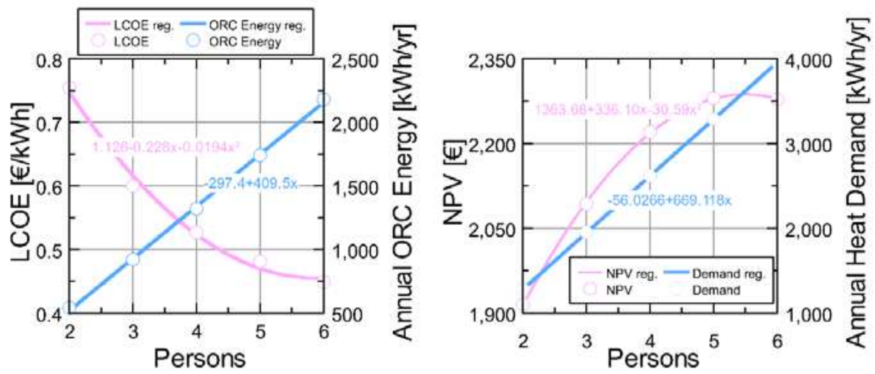

Figure 5. Regressions as a function of the number of people living in the house for the left, LCOE (€/kWh), and annual energy produced by ORC (kWh/yr); and right, net present value (€) and annual heat demand (kWh/yr).

4.2 Centralized systems

For centralized systems, the investment cost associated with the Rankine cycle is lower because of economies of scale as well as the establishment of different energy production strategies and better power cycle efficiencies. Thus, as occupancy increased, the technical and economic feasibility became more notable (**Figure 6**). Thus, for the centralised case, the LCOE can already be competitive (€0.25/kWh), including both storage and joint production of domestic hot water, with some community photovoltaic installations (€0.18/kWh) provided by (Lazard, 2023). From 10 houses (40 persons) in the energy community, integration became viable from the point of view of IRR>r, where net present values (NPV) became greater than the investment cost (**Figure 6, bottom**).

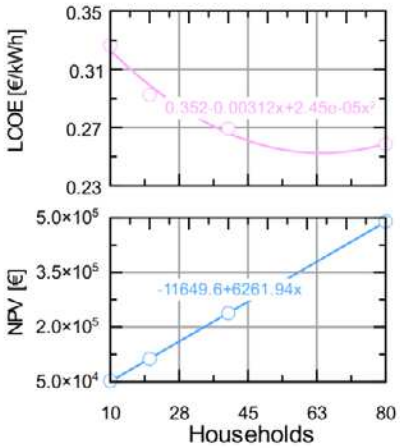

Figure 6. Regression of the LCOE and NPV as a function of the number of households associated with the energy community.

These levelized cost values indicate a great interest in the proposed configuration, as it proposes a system that can be competitive with solar photovoltaic energy communities (<35% difference compared to energy communities based on photovoltaics), where a system with storage (water tank) and a dual use of energy both in thermal form (DHW) and in electrical form through the ORC is also proposed. High cogeneration efficiencies were obtained for the central plant with the solar ORC, reaching their maximum for 66 houses for the studied configuration. Beyond this point, the cost of storage increases exponentially, and its average temperature decreases. Therefore, it is recommended to section the installation into several smaller ones that offer better performance (**Figure 7**). However, the trend of the IRR is linearly upward as more electrical energy is produced and the investment is returned in less time.

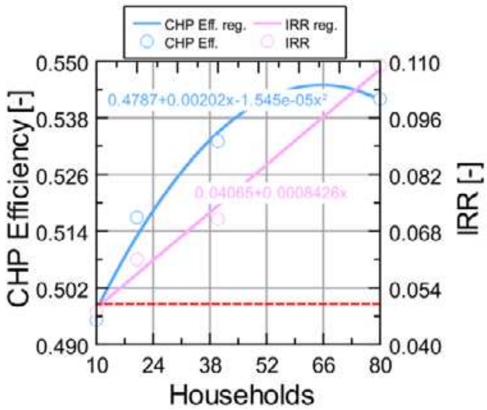

Figure 7. Cogeneration efficiency and internal rate of return as a function of the number of houses in the energy community

It is also noted that for the economic cost-effectiveness baseline (red dotted line in **Figure 7**), where IRR>r, the minimum number of dwellings to be covered by the community energy modality with SDHW-ORC will be at least 10-12 dwellings. In the case of lower associated demand or lower

occupancy in the energy community, smaller ORC equipment and decentralised modular configurations should be chosen.
To establish simple mathematical relationships for the technical-economic evaluation of the configurations studied, statistical correlations with a high coefficient of determination (R^2>90%) have been carried out, which allow different hot water demand scenarios to be adapted to the associated design output in the ORC. The results obtained from the statistical fitting of the simulation are listed in **Table 3**, where they can be implemented according to the building occupancy to be applied in **Table 4** to obtain the economic feasibility of the ORC-SDHW integration. A linear trend of demand with respect to occupancy is observed, mainly given by regulatory norms in Spain and the expression of water consumption used.

Table 3. Regression coefficients for the demand for domestic hot water (kWh) and associated ORC production (kWh) as a function of occupancy in each case.

Variable	a_j^i	b_j^i	c_j^i
E_{DHW}^{dec}	1.36367779E+03	3.36101028E+02	-3.05942581E+01
E_{ORC}^{dec}	-4.15466000E+01	6.60843314E+02	1.03428571E+00
E_{DHW}^{cen}	-2.58935167E+02	2.72777354E+03	6.79019086E-02
E_{ORC}^{cen}	-3.67802467E+03	2.34557525E+03	5.83261022E-01

Table 4. Regression coefficients for obtaining IRR for each case studied.

Variable	a_j^i	b_j^i	c_j^i	d_j^i	e_j^i
IRR^{dec}	9.05291474E+02	-1.59023221E-02	4.68049936E-05	-9.55433309E-02	1.34798619E-05
IRR^{cen}	3.41658317E-02	1.70048237E-06	-	-1.58635444E-06	-

5 CONCLUSIONS

This study proposes the integration of an ORC into domestic hot water systems to evaluate its techno-economic viability. It studied a decentralised case with micro-ORC and low annual thermal demand and another case in which a group of houses are grouped into an energy community, thus establishing a central ORC system and production of DHW with solar collectors. Several important conclusions can be drawn from the results and analysis presented in this paper.

- First, it shows that the integration of the ORC in solar domestic hot water systems can be technically and economically viable, especially in centralised systems with higher thermal demand (>40 persons).
- In the decentralised case, it was found that the micro-ORC can be an interesting option for small demands, but economic viability may be limited (IRR<2%). In the centralised case (energy community), it was demonstrated that the integration of the ORC and solar collectors could result in a significant decrease in energy cost (IRR>10%) and an increase in cogeneration efficiency (>51%).
- Competitive LCOE values were obtained compared to energy communities based on photovoltaics with <35% difference, adding to our case a storage system and thermal power generation.
- In addition, the number of homes in an energy community significantly impacts the economic viability of ORC integration, with a minimum of 10 homes necessary for the project to be sufficiently profitable. Domestic hot water demand and ORC production are highly correlated, suggesting that the integration of these systems can be highly efficient because there is a large thermal resource that can be harnessed with ORC (almost half of the thermal demand for domestic hot water) instead of mixing with cold water to reach the 60 °C required by regulations.

NOMENCLATURE

E	energy	(kWh)
CF	cashflow	(€)
η	efficiency	(–)
CHP	combined heat and power	
ORC	organic Rankine cycle	
DHW	domestic hot water	
IRR	internal rate of return	(-)
NPV	net present value	(€)
LCOE	levelized cost of energy	(€/kWh)

Subscript/superscript

cen	centralised
dec	decentralised
coll	collector

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The ORC conference, organized biennially, stems as the only conference that is specific to ORC technology, therefore gathering a diverse community whose affiliation spans across all the interested stakeholders, not only in this particular technology but also and in a broader context, in the energy transition. Original equipment manufacturers, professional associations, end-users, investors, policy makers, academics, scientists feel at home at ORC 2023.

The almost 100 proceedings in this book cover a wide variety of topics, from fundamentals to system integration through component design, accounting for thermodynamic performance as well as component design. In addition to this, and as a new track in 2023, works on heat pump technology were also accepted in order to raise awareness of the strong ties between both technologies, specifically in energy storage applications.

This book provides an excellent overview of the current maturity of power systems based on Organic Rankine Cycle technology for applications as diverse as geothermal and waste heat recovery in industry or downstream of other prime movers (e.g., marine applications). It is also an excellent source of information to understand the current challenges faced by the technology, stemming from a very competitive market and increasingly stringent environmental regulations.

The organizers of ORC 2023 hope that the reader finds this work as exciting as the attendees to the conference and, maybe, make the decision to join the 8th edition to the conference in 2025.

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