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Multi-Country Analysis on Energy Savings in Buildings by Means of a Micro-Solar Organic Rankine Cycle System: A Simulation Study

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Abstract: In this paper, the smart management of buildings energy use by means of an innovative renewable micro-cogeneration system is investigated. The system consists of a concentrated linear Fresnel reflectors solar field coupled with a phase change material thermal energy storage tank and a 2 kWe/18 kWth organic Rankine cycle (ORC) system. The microsolar ORC was designed to supply both electricity and thermal energy demand to residential dwellings to reduce their primary energy use. In this analysis, the achievable energy and operational cost savings through the proposed plant with respect to traditional technologies (i.e., condensing boilers and electricity grid) were assessed by means of simulations. The influence of the climate and latitude of the installation was taken into account to assess the performance and the potential of such system across Europe and specifically in Spain, Italy, France, Germany, U.K., and Sweden. Results show that the proposed plant can satisfy about 80% of the overall energy demand of a 100 m^2 dwelling in southern Europe, while the energy demand coverage drops to 34% in the worst scenario in northern Europe. The corresponding operational cost savings amount to 87% for a dwelling in the south and at 33% for one in the north.

Keywords: renewable technologies; combined heat and power production; organic Rankine cycle; buildings; energy savings

1. Introduction

The energy consumption in the residential sector represents a high share of the total energy use in Europe [1]. In order to accomplish the European Union's 20-20-20 energy and climate targets [2], design of more energy-efficient buildings and integration of renewable energy technologies in buildings, to supply their energy demand, are the recommended actions to be taken [3]. In particular, the uptake of renewable heat technologies is encouraged to support the ambition of 12% of heating coming from renewable sources by 2020 [4]. At present, there are several renewable technologies that could be coupled with buildings to provide thermal and/or electric energy demand, such as biomass boilers, thermal solar panels, photovoltaic panels, and heat pumps. Among them, because of its worldwide diffusion, solar energy is considered one of the most promising forms of renewable energy and a rapid expansion of its utilization has been taking place during the last few decades. Moreover, the use of solar energy as a prime mover of small scale combined heat and power (CHP) systems is considered very interesting for residential applications [5] and several works deal with this topic. For example, Quoilin et al. [6] analyzed the thermodynamic performance of low cost solar organic Rankine cycles considering different working fluids, expansion machines, and system configurations. Cioccolanti et al. [7], instead, investigated the performance of a small scale low temperature organic Rankine cycle (ORC) prototype plant for trigenerative purposes. Furthermore, considering that the thermodynamic efficiency of the organic Rankine cycle is increased by high inlet temperature at the expander, the use of concentrated solar power (CSP) technologies is recommended. Among CSP technologies, mostly parabolic trough collectors (PTC) are coupled with ORC systems. He et al. [8] modelled a PTC system coupled with an ORC and they studied the effect of selected parameters (such as the size of the thermal storage tank) on the system performance. However, linear Fresnel reflectors (LFR), thanks to their potential to overcome techno-economic constraints associated with PTC, are considered a very promising solution as a solar concentrator for medium and high temperature thermal applications [9]. For this reason, under the H2020 EU funded project Innova MicroSolar [10], an innovative small scale LFR-ORC prototype plant was designed and is going to be tested in the near future. The conceptual plan of the plant was first proposed by researchers at Northumbria University and it was then developed and built by the partners of the whole consortium of the project led by Northumbria University. In particular, the plant consists of a 2kWe organic Rankine cycle system coupled with a LFR solar field and with a phase change material (PCM) thermal energy storage (TES) system equipped with reversible heat pipes. The plant was conceived to be coupled to residential or small business buildings to supply both thermal demand for space heating (SH) and domestic hot water (DHW) and electric demand. The aim of this work is to demonstrate the energy-saving potentials of such a system when installed in small residential buildings. As analyzed by other authors, the micro-ORC systems in residential applications have the ability to face highly variable thermal demand loads with a short response time [11]; however, the issue of the integration with the building dynamic has to be taken into account. Dentice d'Accadia et al. [12], in order to make this kind of evaluation, developed a test bench to test the optimum micro-CHP operation mode, which matches the users thermal and electrical loads in the case of residential and light commercial buildings. In Reference [13], a modelling framework to capture the impact of the adoption of micro-CHP systems on the total primary energy usage in both generation and distribution by using as case study four different sizes of U.K. houses was developed. Furthermore, another important aspect to be considered, in order to properly assess the performance of an ORC system for residential applications, is related with the climatic conditions of the installation site, as highlighted in Reference [14]. Thus, considering the relevance of the above-mentioned issues, i.e., building dynamic integration and geographical location, an in-depth analysis for the proposed micro-solar ORC plant was performed in this paper. In particular, the following aspects are analyzed and presented:

- The micro-CHP thermal and electric energy production is calculated for different European cities;

- The coupling between the micro-CHP system and different dwellings from the considered European cities is investigated by means of simulation models;
- The primary energy savings and cost savings compared to traditional production technologies allowed by the integration of the micro-CHP in such buildings are assessed together with the wasted thermal energy produced by the ORC and not usefully recovered.

The most important purpose of this study is to provide a correlation between the geographic location of this type of micro-CHP and the energetic and economic benefits due to their integration in buildings. Such results can help to evaluate the feasibility of similar systems in different conditions and are not available in literature.

The reminder of the paper is organized as follows: Section 2 presents the methodology of the analysis, in Section 3 the simulation model is described, while in Section 4 the simulation results are discussed. Finally, in Section 5, the main conclusions of the analysis are drawn.

2. Materials and Methods

In order to assess the energy performance of this innovative micro-solar ORC plant for residential applications, dynamic simulation models representing both the plant and the building were developed. The simulation model of the plant was run to obtain the thermal and the electric energy production in a specific location. First, the thermal energy was used to supply the space's heating and domestic hot water systems in the building model. Second, the electric energy demand of the building was compared with the plant electricity production. Different geographical locations and building specifications were chosen to perform a meaningful analysis in specific contexts, thus representing the variable behavior of the Innova MicroSolar system across Europe. In particular, for every configuration the share of the total building energy demand supplied with the micro-solar ORC plant was assessed, together with the primary energy savings and operational cost savings compared to traditional solutions (i.e., a condensing boiler).

2.1. Climatic Conditions

In this analysis, six EU countries were selected to represent different geographical locations in Europe, namely Spain, Italy, France, Germany, the U.K., and Sweden. Specifically, a city for each country, in its mild climate region, was designated, as specified in Table 1 and shown in Figure 1. According to the Köppen–Geiger climatic classification [15]), these cities belong to the climatic class Cfb, while Ancona belongs to the class Cfa (i.e., has the temperature of the hottest month in summer higher than 22 °C). In this way the general climatic conditions (i.e., average temperatures and precipitations) among the cities do not differ too much and the influence of the latitude can mainly be investigated. The direct normal irradiance (DNI), the global horizontal irradiance (GHI), and their ratio are also reported in Table 1 to characterize the solar energy availability in the different locations. Furthermore, the average value of the normal irradiance multiplied by the zenith angle is calculated in order to take into account the position of the sun, which differs with the latitude, which has an influence on the LFR solar field performance.

Table 1. Selected cities and their different climatic conditions.

EU Region	Country	City	DNI (kWh/m^2)	GHI (kWh/m^2)	DNI/GHI (kWh/m^2)	DNI·cos(z)
South	Spain	Santander	1008	1706	0.59	592
South	Italy	Ancona	1174	1876	0.63	684
Central	France	Paris	793	1411	0.56	503
Central	Germany	Hamburg	758	1325	0.57	467
North	UK	Finningley	597	1219	0.49	409
North	Sweden	Stockholm	1027	1531	0.67	521

Figure 1. Geographic collocation of the selected cities.

2.2. Building Specification

In each selected city, a building coupled with the micro-solar CHP system was analyzed. Considering the average size of dwellings in the different countries [16], 100 m^2 apartments were assumed as a good representative floor area. Given the purpose of the analysis, which aimed to assess the system performance in specific local contexts, the buildings regulations in every country were considered [16–19] and the specifications for each building's thermal performance were supposed as in Table 2. A window area of at least 10% of the wall surface was used. Single dwellings and terraced houses built after 2010 were considered the most suitable final users, as assessed in a previous analysis about potential application of the Innova MicroSolar plant [20]. The best available technologies for space heating (SH) and domestic hot water (DHW) production were taken into account in the evaluations (see Section 3.1).

Table 2. Building thermal specifications (U-values in W/m^{2}K).

Country	External Walls	Roof	Floor	Windows
Spain	0.74	0.46	0.62	3.1
Italy	0.34	0.32	0.30	2.0
France	0.36	0.20	0.22	2.1
Germany	0.28	0.20	0.30	1.3
UK	0.28	0.16	0.22	2.0
Sweden	0.18	0.15	0.15	1.2

3. Simulation Models

In the following sections the simulation models for the micro-solar ORC plant and for the building coupled to it are described.

3.1. Micro-Solar Orc Plant

The plant consisted of: (i) a concentrated linear Fresnel reflector solar field producing heat at temperatures in the range 250–280 °C, (ii) a 2 kWe/18 kWt organic Rankine cycle plant, and (iii) an advanced PCM thermal storage tank equipped with reversible heat pipes. Figure 2 reports the conceptual schematic of the integrated system.

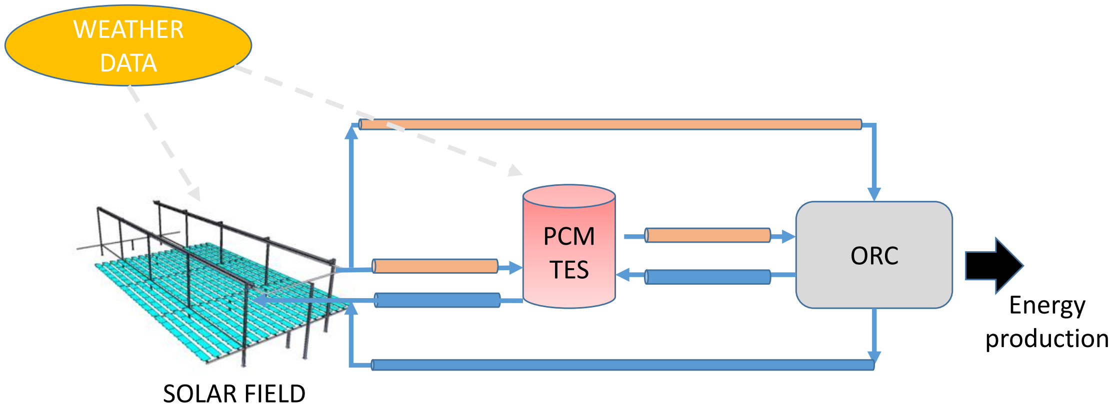

Figure 2. Conceptual schematics of the micro-solar organic Rankine cycle (ORC) plant.

The solar field was made up of LFR modules with a total length of about 20 m, a ground area of around 240 m^2, and a net mirror surface area of about 146 m^2. The receiver was placed at about 3.5 m from the ground and it consisted of evacuated tube collectors able to achieve a maximum operating temperature of 400 °C and a conversion efficiency of around 90%. The peak thermal power of the solar field was about 80 kW at nominal operating conditions (DNI equal to 900 W/m^2), as designed by the manufacturing company [21]. The LFR solar field collected the solar energy and diathermic oil was used as a heat carrier to transfer heat to the rest of the plant. Such thermal energy could be supplied directly to the ORC (when the power was over a given threshold), to the TES (when the power was too low to switch on the ORC), or to both in case a surplus of energy was available.

The ORC unit, manufactured by ENOGIA (Marseille, France) [22], operated according to a regenerative cycle using NOVEC 649 as a working fluid [23]. On the basis of the operational conditions, the working fluid was heated up in the evaporator directly using the energy collected by the LFR solar field or the thermal energy stored by the storage tank ($P_{in,ORC}$). The fluid expanded in an axial turbine to theoretically achieve a gross electric power production of about 2 kWe and a conversion efficiency of about 10%. In particular, the electric power output from the ORC was assessed as in Equation (1):

$$P_{el,ORC} = \dot{m}_f \cdot \left[\eta_m \cdot \eta_{el} \cdot \Delta h_e - \Delta h_p / \left(\eta_m \cdot \eta_{el}\right)\right] \quad (1)$$

with $\dot{m}_f$ being the organic fluid flow rate, η_m being the mechanical efficiency, η_{el} being the electric efficiency, Δh_e and Δh_p being the actual specific enthalpy difference across the expander and the pump, respectively, based on the following assumptions:

- a minimum superheating at the evaporator of 5 °C;
- no subcooling at the outlet of the condenser;
- an organic working fluid flow rate of 0.21 kg/s at nominal operating conditions, which was adjusted, at every time step, in order to maintain the minimum superheating at the evaporator outlet;
- a generator electric efficiency equal to 0.9 and a mechanical efficiency of 0.95;
- a constant overall heat transfer efficiency of the heat exchangers.

The thermal power output from the ORC unit was evaluated as:

$$P_{th,ORC} = \dot{m}_c \cdot c_{p,c} \cdot (T_{out} - T_{in}) \quad (2)$$

where $\dot{m}_c$ was the cooling water flow rate, $c_{p,c}$ was the specific heat of the cooling water, and T_{out} and T_{in} were the outlet and inlet temperatures of the cooling water at the condenser. More precisely, the inlet cooling water was the return water from the final user heating system. In order to have a water supply temperature suitable for space heating and DHW in buildings, the design value of the outlet water was set at 70 °C with a typical temperature difference for the condenser heat exchanger of 10 °C.

The ORC thermal and electric efficiency were defined respectively as:

$$\varepsilon_{ORC,th} = \frac{P_{th,ORC}}{P_{in,ORC}} \tag{3}$$

$$\varepsilon_{ORC,el} = \frac{P_{el,ORC}}{P_{in,ORC}} \tag{4}$$

The PCM storage tank, investigated by Northumbria University [24] and the University of Lleida [25], was made of a nitrate solar salt kNO_3 (40 wt%)/$NaNO_3$ (54 wt%), which has a melting temperature in the range 216–223 °C [26], a high heat of fusion, but a low thermal conductivity. The TES was designed to store about 100 kWh of latent thermal energy from the solar field in order to guarantee 4 h of ORC unit operation during night time. More precisely, 3.8 tons of this material in a volume of 1.90 m^3 was required. Reversible heat pipes, charged with demineralized water and able to withstand a maximum pressure of 100 bar, were developed by Aavid Thermacore [27] to improve the heat transfer from/to the TES.

The PCM storage tank was modelled according to the guidelines of the IEA Task 32 report on advanced storage concepts [28]. In particular, the material was assumed to be isotropic and isothermal in each time-step whilst hysteresis and sub-cooling effects were neglected. The behavior of the heat pipes were taken into account by means of: (i) a limitation in the maximum power exchanged with the oil because of the limited heat pipes capacity (40 kW) and (ii) a minimum temperature difference between the oil and the PCM equal to 5 °C. Further details on the model of the TES can be found in Reference [29].

Depending on the solar radiation and the state of charge of the TES, the integrated system worked according to different operation modes, as extensively discussed in Reference [29], and the central control system for the plant was developed by S.TRA.TE.G.I.E. srl [30]. The collected thermal energy from the solar field was used to drive the ORC cycle and any excess could be stored in the PCM storage tank. The TES could also supply the ORC in case of low solar radiation. The diathermic oil from the solar field flowed to the TES and/or directly to the ORC depending on its temperature and on the amount of power collected at the receiver. On the contrary, when the power produced by the solar field was low or zero and the average TES temperature was within a given operating range (PCM melting temperature), the thermal energy of the TES could be used to run the ORC unit and assure its operation for a maximum of 4 h with no sun, as per the design specifications described above.

The main features of the plant are summarized in Table 3, where an operational life of 25,000 h was assessed considering about 2500 working hours per year for a period of 10 years (based on manufacturers' and literature knowledge [13]). A dynamic simulation model for the plant was set up in Trnsys (Madison, WI, USA) [31] and ad hoc subroutines were implemented to represent the main components of the plant (LFR solar field, TES with PCM and heat pipes and ORC) on the basis of manufacturer data. Further details about the simulation model of the micro-solar ORC plant can be found in the reference [29].

Table 3. Target specifications for the Innova MicroSolar system.

Technical SPECIFICATION	Innova MicroSolar
Electrical Power Production	2 kWel
Heating Capacity	18–20 kWth
Electrical Efficiency	10–12%
Thermal Efficiency	80%
Operational life	≈25,000 h
Specific Power	0.05 kWel/kg; 21 kWel/m^3

3.2. Building Model

The building model was designed accordingly to the thermal specifications reported in Table 2. A single dwelling of 100 m^2 and a terraced house with four dwellings (100 m^2 each) with north–south orientation were considered (more details about the building geometry and orientation are provided in Table 4). It was assumed there was about 30 m^2 per person, which provided an internal gain of 120 W each. A 0.5 ACH (air changes per hour) was modelled. The dynamic simulation tool used was TRNSYS [31] with a simulation time step of 10 min. The weather files were derived from the Meteonorm database [32].

Table 4. Building geometry and orientation specifications.

Orientation	Height (m)	External Surface (m^2)		Windows (m^2)	
		Single Dwelling	Terraced House	Single Dwelling	Terraced House
North	2.7	27	108	3.10	12.4
South	2.7	27	108	3.10	12.4
East	2.7	27	27	3.10	-
West	2.7	27	27	3.10	-

Radiant floor was assumed as a distribution system in the building, being the most efficient because of low working temperatures. The inside temperature set-point was set at 20 °C (±0.5 °C) to be maintained 24 h per day in winter, with continuous operation being a typical strategy for such systems. In Figure 3, the SH and DHW plant configuration is illustrated. A thermally stratified water storage tank was used to collect the thermal energy produced by the ORC unit. The ORC maximum supply temperature was 70 °C, but it could slightly vary with the working conditions and the TES temperature; however, the temperature difference with the return temperature was maintained at 10 °C. The stored thermal energy supplied both the SH distribution system and the DHW tank. The volume of the storage had a direct impact on the recovery efficiency of the ORC thermal energy, but it was also subject to space constraints in the installation. On the basis of results from a previous study (where a sensitivity analysis of the storage volume in case of only DHW demand was conducted [33]), a size of 1 m^3 per dwelling was considered as a good trade-off. A back-up boiler was included to cover the thermal energy demand not provided by the ORC, with a design power able to produce the peak DHW thermal demand (25 kW per dwelling). The water temperature supplied to the underfloor heating system was regulated on the basis of a linear compensation curve dependent on the ambient temperature (e.g., water supply temperature was 35 °C when the ambient temperature was 0 °C). The water flow rate was designed in accordance with a maintained 7 °C as a temperature difference between the inlet and outlet temperature to the floor. The daily DHW tap profile (see Figure 4) was obtained from the European standard UNI EN 15316-3, from which the tap profile number 2 was taken, because it is the most representative of the average DHW use in Europe [34]. A typical size of 300 L was assumed for the DHW tank in each dwelling and a tank with an internal coil was considered in order not to mix the technical water from the plant and the domestic water for the final user.

Regarding the electricity demand, the average value per dwelling for every country was assumed, derived from available statistical data in Reference [35]. The average electricity demand per dwelling in Europe was 3600 kWh. Among the selected countries Italy had the lowest electricity demand, while France and Sweden had a demand much higher than the average and this aspect was taken into account in the analysis.

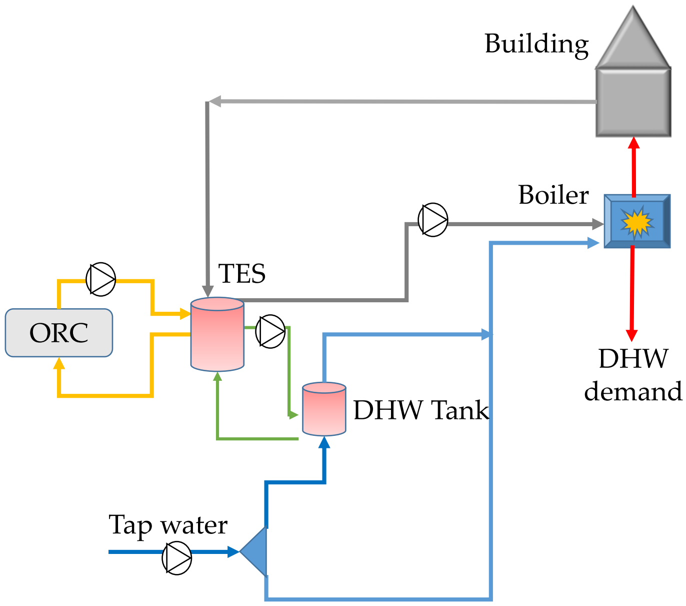

Figure 3. Space heating (SH) and domestic hot water (DHW) plant configuration.

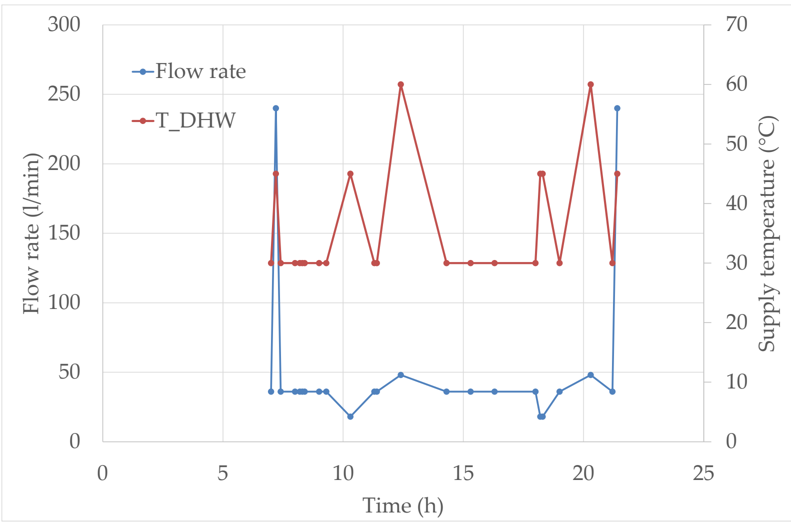

Figure 4. DHW daily tap profile.

4. Results and Discussion

The model of the Innova MicroSolar plant was run considering the different climatic conditions reported in Table 1. Hence, the thermal and electric energy production obtained are summarized in Table 5.

Table 5. Thermal and electric energy production of the Innova MicroSolar plant in different locations.

Location	Thermal Energy (kWh/year)	Electric Energy (kWh/year)
Santander (ES)	27,565	2708
Ancona (IT)	34,098	3357
Paris (FR)	18,992	1869
Hamburg (DE)	17,550	1746
Finningley (UK)	14,041	1367
Stockholm (SE)	23,206	2294

Looking at the energy production, it was evident that the cities located in the south of Europe guaranteed higher thermal and electric energy outputs, thanks to the higher solar radiation, as expected. As far as the production in Sweden is concerned, Stockholm had a higher performance than Paris and Hamburg, even if located in northern Europe, because it had a higher DNI and DNI/GHI ratio (see Table 1). Finnigley had the lowest DNI/GHI ratio; the performance of the Innova MicroSolar plant was highly affected by the climatic conditions and especially by the DNI available, as studied in Reference [36].

Regarding the electric energy, its production was much lower than the thermal energy output. Comparing it with the average electricity demand per dwelling (see Section 3.2), it was generally not sufficient to cover the final users' needs (with the exception of Ancona); while in the locations in the south of Europe the electricity demand coverage factor for a dwelling was close to 1, at the other latitudes, it was 0.4 on average.

In Tables 6 and 7, the simulation results for the thermal coupling between the plant and the building (single dwelling or terraced house respectively) are reported. In particular, the following quantities were obtained from simulations: the energy demand for space heating (D_SH), the energy demand for domestic hot water (D_DHW), the energy integrated by the boiler (E_boiler), the fraction of ORC thermal energy not usefully recovered through the thermal storage tank and wasted (Waste). As previously explained, the electricity demand (D_el) was derived from the average values per dwelling per country [35]. On the basis of these values, the electric energy demand coverage (Cov_el), the thermal energy demand coverage (Cov_th), and the total energy demand coverage (Cov_tot) by the micro-solar CHP plant were calculated. These parameters were defined as the percentage of the corresponding energy demand, which could be satisfied by the energy produced by the microsolar ORC without using the boiler or the electricity from the grid.

Table 6. Thermal performance of the Innova MicroSolar plant coupled with one single dwelling.

City	D_SH (kWh)	D_DHW (kWh)	D_el (kWh)	E_boiler (kWh)	Waste	Cov_el	Cov_th	Cov_tot
Santander	4765	2013	3944	1899	82%	69%	72%	71%
Ancona	3997	2013	2432	1848	87%	138%	69%	78%
Paris	5645	2013	5036	3749	82%	37%	51%	46%
Hamburg	6458	2013	3079	5040	82%	57%	40%	45%
Finningley	5541	2013	3941	4034	79%	35%	47%	43%
Stockholm	6478	2013	7752	5314	86%	30%	37%	34%

Table 7. Thermal performance of the Innova MicroSolar plant coupled with a terraced house (4 dwellings).

City	D_SH (kWh)	D_DHW (kWh)	D_el (kWh)	E_boiler (kWh)	Waste	Cov_el	Cov_th	Cov_tot
Santander	11,727	8050	15,776	8719	51%	17%	56%	39%
Ancona	9678	8050	9728	7742	63%	35%	56%	49%
Paris	14,749	8050	20,144	15,003	50%	9%	34%	23%
Hamburg	17,782	8050	12,316	18,795	51%	14%	27%	23%
Finningley	13,861	8050	10,910	15,168	44%	9%	31%	22%
Stockholm	19,754	8050	31,008	20,302	57%	7%	27%	17%

Analyzing the results for a single dwelling (Table 6), it was possible to notice that the total energy demand coverage varied from a minimum of 34% up to a maximum of 78% with the location. The city where the ORC energy output was maximum (Table 5), Ancona, had a total energy demand coverage of about 80%. Indeed, the electricity produced was even higher than the demand, while about 69% of the thermal demand for space heating and domestic hot water came directly from the solar micro-CHP plant. However, around 87% of the CHP thermal energy production was wasted in this configuration. On the other hand, considering a terraced house with four dwellings in Ancona, the total energy demand coverage decreased to 49%, meaning that the plant could still cover about half of the overall energy demand. However, this situation occurs only in Ancona, where the ORC plant energy production was the biggest, while in the other cities the energy demand coverage for a terraced house with four dwellings was much lower (20–30%). Looking at the thermal energy dissipated, it also remained quite high for the case of four dwellings (63% in Ancona). Such waste heat was mainly related with the thermal energy storage (size and thermal losses) and with the dwelling thermal demand (amount and occurrence in time). Indeed, if there was not simultaneity between heat production and demand, the excess heat was stored in the TES, but when the TES was fully charged, it was no longer possible to recover the ORC plant thermal energy. Figure 5 shows the trend of waste heat (Waste) and thermal energy demand coverage throughout the year for the city of Ancona in a terraced house (with a tank of 4000 L, standard configuration, and with a tank of 8000 L). Mostly heat was wasted in summer, when the thermal energy demand was low (only DHW), while the thermal energy produced was high for the higher solar radiation. However, even in winter when the thermal energy demand coverage was limited, there were no negligible thermal dissipations and they were mainly due to storage thermal losses and shifting in time between demand and production. The latter issue could be partially solved by means of a bigger storage tank. Hence the performance of the integrated system was also evaluated for a double volume storage tank of 8000 L. Figure 5 reports the results of this configuration: the waste heat was a bit reduced and the thermal energy demand coverage slightly increased, but not so much to justify such a bigger storage volume. In any case, a considerable amount of thermal energy was always expected to be lost in similar systems because the thermal energy demand was always lower when the production was higher (i.e., summer). In order to exploit the thermal energy produced at maximum, it would be necessary to have a final user with high thermal energy demand in summer (e.g., small business buildings, such as laundries), or to use the thermal energy to supply absorption chillers to satisfy the summer cooling load. In a previous study, it was also considered that the application of the micro-solar CHP plant could supply only DHW to multi-apartments buildings. In this way, a more constant thermal energy demand throughout the year is present and up to 15 apartments could be satisfied; however, the overall economic feasibility of the coupling was not attractive because neither space heating can be provided, nor enough electricity demand can be covered for such big buildings [33].

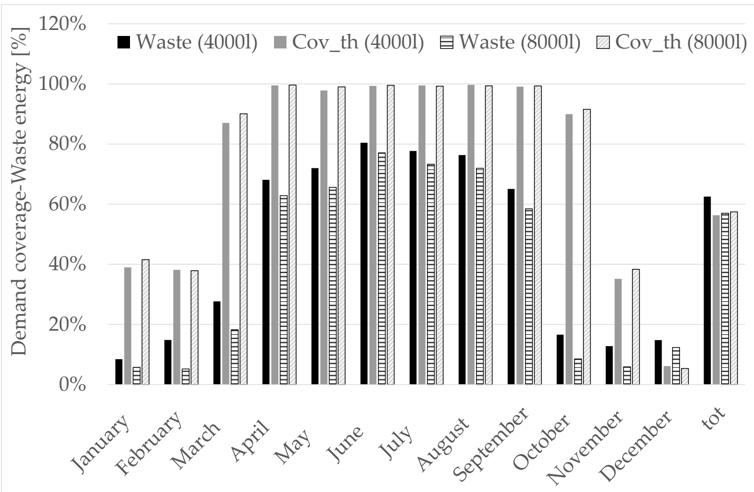

Figure 5. Monthly thermal energy wasted and total energy demand coverage for the case of a terraced house in Ancona with a thermal energy storage (TES) volume of 4000 L (standard configuration) and with a TES volume of 8000 L (double size compared to the standard configuration).

The city with a lower energy demand coverage was Stockholm: 34% for a single dwelling and 17% for a terraced house. Here, even if the micro-CHP energy production was higher than other cities in Central Europe, both the thermal energy demand and electricity demand per dwelling were significantly bigger than in the other locations. In Figure 6, the monthly trend of the thermal energy demand (including both SH and DHW) is illustrated. Stockholm had the highest values, followed by Hamburg, while Ancona showed the lowest thermal demand, especially in the mead season. In summer, mainly the thermal energy demand was due to DHW requirements.

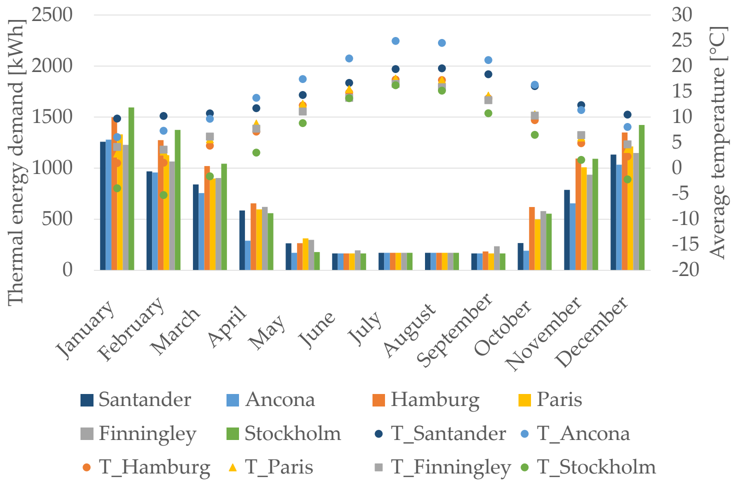

Figure 6. Monthly thermal energy demand (left axis) for a single dwelling in the different cities, whose average monthly temperature is reported on the right axis.

In Tables 8 and 9, the comparison of the proposed microsolar CHP system with separate generation by means of traditional technologies is shown. The primary energy use by taking the electricity from the grid and by producing thermal energy with a condensing boiler (110% efficiency) was assessed and compared with the primary energy (PE) use when the microsolar CHP system was introduced (2.5 and 1 were assumed as conversion factors for PE related with electricity and natural gas respectively). Furthermore, the operational costs reduction was also evaluated, by considering national prices for electricity and natural gas [37,38]. It was evident that there was a strict relation between primary energy and energy cost savings. For a dwelling, the operational cost savings could be reduced from 33% (in Stockholm) up to 87% (in Ancona). While considering a terraced house, cost savings go from a reduction of 14% to 42%, demonstrating that they were not reduced proportionally with the increase of the energy demand.

Table 8. Primary energy (PE) savings and operational cost savings of the Innova MicroSolar (IMS) plant coupled with one single dwelling compared to traditional technologies (trad).

City	PE_trad (kWh)	PE_IMS (kWh)	Variation_PE %	Cost_trad €	Cost_IMS €	Variation_cost
Santander	16,022	1680	70%	1279	387	70%
Ancona	11,544	1680	85%	895	118	87%
Paris	19,552	11,325	42%	1351	788	42%
Hamburg	15,398	7915	49%	1394	680	51%
Finningley	16,720	10,102	40%	1071	661	38%
Stockholm	27,099	18,475	32%	2486	1677	33%

Table 9. Primary energy (PE) savings and operational cost savings of the Innova MicroSolar (IMS) plant coupled with a terraced house (4 dwellings) compared to traditional technologies (trad).

City	PE_trad (kWh)	PE_IMS (kWh)	Variation_PE	Cost_trad €	Cost_IMS €	Variation_cost
Santander	57,421	40,596	29%	4670	3403	27%
Ancona	40,438	22,965	43%	3178	1833	42%
Paris	71,087	59,326	17%	4950	4161	16%
Hamburg	54,274	43,512	20%	5130	4216	18%
Finningley	59,330	49,782	16%	3930	3383	14%
Stockholm	102,798	90,240	12%	9266	7981	14%

In order to generalize the obtained results, the primary energy and cost savings due to the Innova MicroSolar plant were related to the building energy demand (D_{tot}) and to the useful direct normal irradiance through the factor *F*:

$$F = DNI \cdot \cos(z)/D_{tot} x100 \quad (5)$$

where the term *DNI·cos(z)* takes into account the position of the sun and thus the energy that the LFR solar field can really capture. In Figure 7, it is possible to see an almost linear trend among the above-mentioned variables. When the factor *F* was greater than about 4, the savings could be higher than 50%.

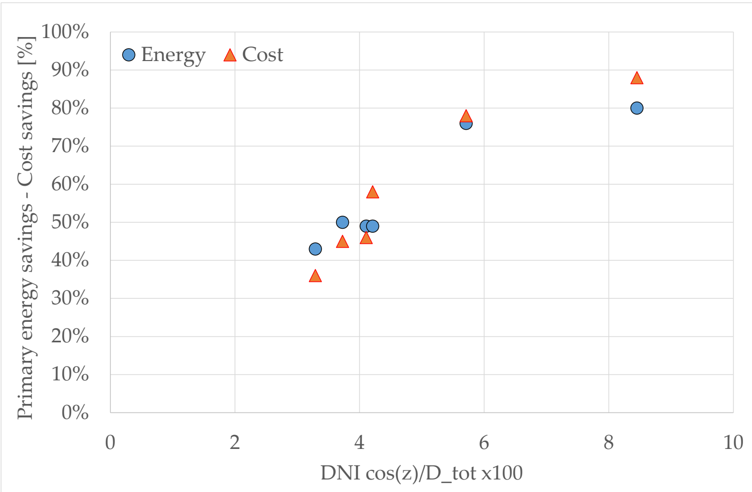

Figure 7. Energy and costs savings of the Innova MicroSolar plant in relation with the solar irradiance and with the building energy demand.

Eventually, it was possible to conclude that the proposed microsolar CHP plant performed better if located in southern Europe, because the plant energy production was higher and the dwellings energy demand was lower. Indeed, the thermal and electric demand and the local energy prices have a huge impact on the feasibility of similar systems. Furthermore, this analysis does not take into account the capital cost of the plant and the payback period because the focus was only on operational performance and achievable savings. However, it is undoubtable that the economic feasibility is strictly related with the initial investment, even if such systems are still in a development phase and their investment costs are too high yet to be compared with traditional off-the-shelf technologies [29].

5. Conclusions

This paper analyzed the performance of an innovative microsolar CHP plant used in residential applications. The operational performance of the coupling between the plant and the building was evaluated for different cities in Europe. Local specifications for building thermal properties, energy prices, and electricity demand per dwelling were taken into account in the evaluation in order to consider the influence of the installation context. Results show that:

- The plant had the best performance in southern Europe because the plant energy production was higher, while the energy demand is lower.
- The microsolar CHP system can satisfy almost 80% of the energy demand (thermal and electric) for a dwelling in locations of southern Europe, while about 50% in locations of central and northern Europe.
- By increasing the number of dwellings, the energy demand coverage decreased less than proportionally.
- A huge amount of the heat produced was always wasted because the building's thermal demand was too low in summer when the production was high. A bigger thermal energy storage could partially solve this issue or the excess heat available could be used for other purposes (e.g., to produce cooling by means of absorption chillers).
- Even in the worst scenario analyzed, almost 15% operational cost reduction can be achieved in comparison with traditional technologies.

Eventually, results provided a useful correlation between the achievable energy and cost savings produced by the Innova MicroSolar plant and solar irradiance and latitude. However, it is necessary to highlight that the results provided were mainly based on a theoretical analysis and a validation through experimental tests is necessary and will be the objective of an upcoming work.

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Nomenclature

Symbol	Definition
ACH	air change per hour
CHP	combined heat and power
Cov	coverage
CSP	concentrated solar power
D	demand
DHW	domestic hot water
DNI	direct normal irradiance
E	energy
ϵ	ORC efficiency
el	electric
F	geographical factor
GHI	global horizontal irradiance
IMS	Innova MicroSolar
LFR	linear Fresnel reflector
m	mechanical
$\dot{m}_c$	condenser flow rate
$\dot{m}_f$	organic fluid flow rate
η	Efficiency
ORC	organic Rankine cycle

P	power
PCM	phase change material
PE	primary energy
PTC	parabolic through collector
SH	space heating
TES	thermal energy storage
th	thermal
tot	total
trad	traditional
Δh_e	actual specific enthalpy variation across the expander
Δh_p	actual specific enthalpy variation across the pump
z	zenith angle

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