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Simulation analysis of an innovative micro-solar 2kWe Organic Rankine Cycle plant coupled with a multi-apartments building for domestic hot water supply

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Abstract

Combined heat and power plants driven by renewable energy sources (RES) are becoming more and more popular, given the energy transition towards the integration of more renewable energy sources in the power generation mix. In this paper an innovative micro-solar 2kWe/18kWth Organic Rankine Cycle system, which is being developed by the consortium of several Universities and industrial organizations, with the funding from EU under the Innova MicroSolar project, is considered. In particular, its application to supply electricity and thermal energy for Domestic Hot Water (DHW) in a residential building is investigated by means of simulation analysis. Different Domestic Hot Water supply plant configurations are evaluated and the design parameters are varied in order to determine the best configuration to recover as much energy as possible from the ORC, while maintaining the final users' comfort. It was found out that with the considered plant around 67% of the Domestic Hot

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Water energy demand of 15 apartments can be satisfied with a water storage tank of 10’000 liters. However, in order to always guarantee the supply water temperature, a back-up boiler, which serves directly the final users when needed, is requested.

Keywords: renewable energy; micro-combined heat and power plant; distributed energy system; DHW; dynamic simulations.

1. Introduction

In order to reduce greenhouse gas emissions and pollutions, an increasing share of renewable energy sources (RES) is introduced in the power generation mix, supported by existing regulation and even subsidized [1]. In this context micro-solar CHP systems are considered effective means to provide clean, efficient and secure energy to dwellings, even if their adoption in buildings has been limited so far. At present, the most used technology for renewable thermal energy production at residential level is represented by evacuated tubes solar panels, because of their ease of installation and absence of tracking mechanisms [2]. However, the use of medium and high temperature solar technologies in buildings could be economically feasible given the high potential of cogeneration at residential scale [3], where both thermal and electric energy are requested. Several studies investigated the performance of solar CHP systems at different scales, including or not energy storages [4-6]. In a previous work [7], the authors analyzed the energy performance and the economic feasibility of a novel small-scale 2kWe Organic Rankine Cycle system coupled with a concentrated solar Linear Fresnel Reflector (LFR) plant and a phase change material (PCM) thermal storage system equipped with reversible heat pipes, as proposed in the Innova MicroSolar EU project [8] led by Northumbria University [9]. The analysis highlighted that the electric and thermal efficiencies of the plant are pretty good, even if its economic feasibility is still not attractive. Key points to improve its feasibility are capital cost reduction and operational cost savings increase. Capital costs can be reduced by means of optimal design of the components involved in the plant together with favorable economy of scale due to a wide diffusion of such micro-CHP systems. Operational cost savings, instead, are strictly related to the share of the energy demand that the micro-CHP can satisfy. In order to maximize the satisfied energy demand, in this work for the first time an in-depth analysis of the thermal energy demand for domestic hot water (DHW) in residential dwellings to be coupled with the ORC production is performed. Such theoretical study anticipates the testing phase of the micro-CHP prototype plant. The remainder of the paper is organized as follows: in section 2 the methodology used in the analysis is illustrated and the plant under consideration is described. Furthermore the simulation model is presented and the results are discussed in order to show the best configurations, in terms of design and operation, of the considered system in section 3. Finally, in section 4 main conclusions of the work are summarized.

2. Methods

The considered micro-CHP system was designed by the partners of the consortium in the framework of the European project Innova MicroSolar [8] for application in residential or small commercial buildings. In this work the plant is supposed to supply thermal energy for domestic hot water production, given its year-round need, in a multi-apartments building. A dynamic simulation model of the plant in such context is built by means of TRNSYS [10]. Two different design configurations and operational strategies of the system are considered and a sensitivity analysis by varying the most influencing parameters is carried out.

2.1. The micro-solar CHP plant

The innovative micro-CHP plant was designed to produce 18-kWth of thermal power and 2-kWel of electric power using solar thermal energy at temperatures in the range 250-280°C, according to the target technical specifications reported in Table 1.

Table 1. 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

The proposed system consists of: (i) a solar concentrating collector based on novel Linear Fresnel Reflectors; (ii) a micro ORC plant combined with (iii) advanced phase change material (PCM) thermal storage equipped with (iv) reversible heat pipes. The plant was designed for its application mainly in residential buildings where, integrated with a traditional domestic boiler, can supply domestic hot water, space heating and electricity.

In a previous work the authors analyzed the performance of the micro-solar CHP plant installed in the city of Cagliari (Italy). The results showed a yearly electric energy production of about 5100 kWh_{el} and a yearly thermal energy production of about 50'000 kWh_{th}. The maximum production was observed in July with respectively 716 kWh_{el} and 7600 kWh_{th}. It was evident the increase of the overall production during summer and spring months, especially for thermal energy, given the higher solar radiation available. More details about the plant performance can be found in [7]. Figure 1 reports a schematic of the simulation model.

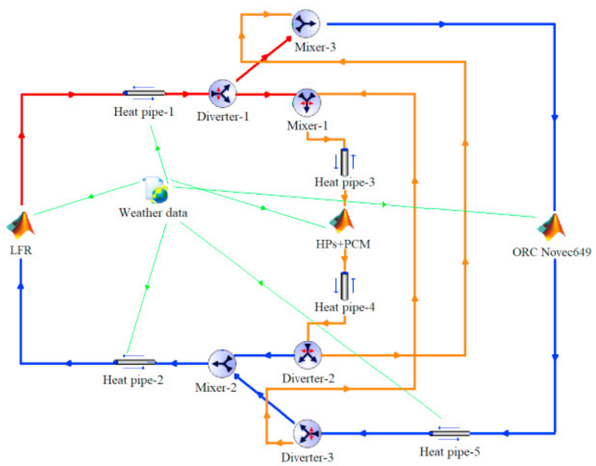

Fig.1. Schematic of the simulated micro solar CHP plant.

2.2. The simulation model

In this work a simulation model to analyze the coupling of the micro-solar CHP plant production with the final users' energy demand was developed. Given that the thermal energy production is available through the all year, but it is especially high in summer, its most favorable use is for DHW supply. Thus the integration of the CHP plant with a back-up boiler for a multi-apartments building in Cagliari was evaluated. Two different configurations were considered: (i) the boiler supplies energy into the same water tank as the ORC; (ii) the boiler supplies energy directly to the final users. In Figure 2 a schematic of the two configurations is shown.

Fig.2. Schematic of the DHW supply system: (a) boiler integrates energy into the DHW tank; (b) boiler supplies energy directly to final users.

The ORC supplies heat at a design value of 70°C with a temperature difference of 10°C. The heat supplied from the ORC is collected into a thermally stratified water tank by means of an internal coil in order to decouple the thermal energy production with the demand since a time shift between the two can exist. Final users draw hot water from the tank, mixed with tap water to get the final desired supply water temperature. The considered DHW tapping profile was taken from the European standard for domestic hot water systems [11]: every apartment needs daily 360 liters of DHW, corresponding to 11.5 kWh. The DHW tapping temperature profile and power demand are shown in Figure 3. The boiler steps in when the supply water temperature is lower than the design temperature and in the case of Fig. 2a it supplies heat into the DHW tank when the tank temperature is below 60°C, while in the case of Fig. 2b it supplies heat after the tank directly to the users when a surplus heat production is needed.

3. Results and discussion

Purpose of the analysis is to design the DHW supply plant in order to maximize the use of the thermal energy produced by the ORC. Therefore, the number of apartments to be served was assessed to use completely the maximum daily thermal energy production of the ORC plant, which occurs during a day in June and corresponds to about 345 kWh. Given the daily DHW energy consumption for an apartment (about 11.5 kWh), a building with 30 dwellings was considered. For the volume of the tank, instead, as initial value was assumed the sum of the daily water consumption for all the apartments, i.e. about 10’000 liters.

Considering the first configuration as reported in Fig. 2a, the trend of temperatures and power of the streams entering and exiting the storage tank are shown for a typical summer day in Fig. 3. It is worth noticing that the ORC supply temperature is not fixed at 70°C, but it varies with the working conditions, however the temperature difference with the return temperature is maintained at 10°C. The boiler has a maximum rated power of 650 kW, but it works mainly at partial load. It can also provide higher temperature than the set-point (60°C) if the DHW energy demand is higher. Moreover, the presence of the tank is justified by the trends of the power produced by the ORC and of the power demand for the DHW. The latter presents a high power demand during short periods of time, while the ORC produces for long periods at lower power rate, including when there is no sun such as at night (thanks to the PCM storage tank included in the micro-solar ORC plant able to store the surplus of solar energy during daytime to provide energy in the night period [7]).

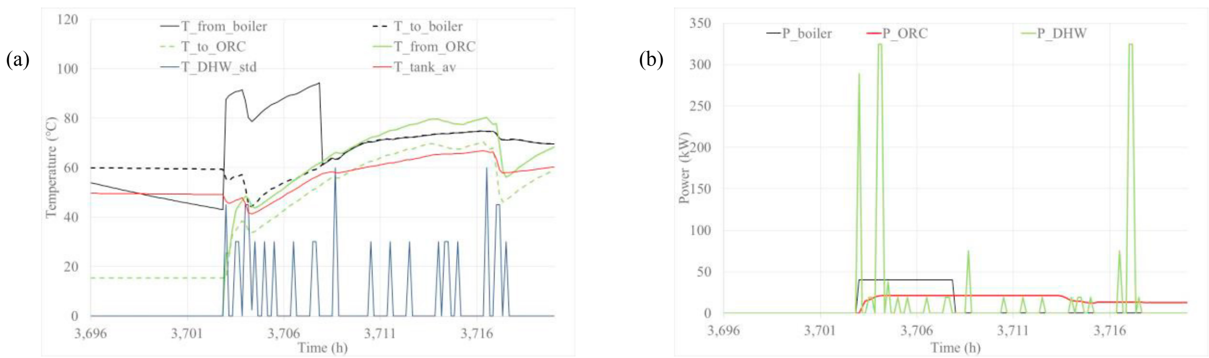

Fig.3. Temperature (a) and power (b) trends for the inlet and outlet streams to the water tank.

In Table 2 the overall energy balance and the comfort performance are reported. For the abovementioned configuration (Case 1a) the ORC can deliver to the storage tank about 39% of the DHW energy demand (in total about 120'000 kWh) with a discomfort of about 17% (i.e. time with water supply temperature lower than the design value). In order to decrease the discomfort hours, the effect of varying the tank volume or the number of apartments in the building was also evaluated. With a tank volume of 5000 l, the ORC dissipated energy increases as well as the discomfort (up to 21%). Furthermore, in case of a 3000 l tank the ORC energy lost rises up to 26%.

With the aim of increasing the share of DHW energy covered by the ORC unit, the number of apartments was reduced to 15. Therefore, the new energy share ($E_{ORC\_to\_tank}/E_{DHW\_std}$) rises to 69% (of a total energy demand of about 67'000 kWh) with a tank of 10'000 l (Case 4a), while the ORC thermal energy lost is 16%. Moreover, the discomfort is strongly reduced and it remains lower than 11% even with a tank of 3000 l.

Table 2. Energy balance and comfort performance of the first DHW supply plant configuration.

Case	N. app	Tank	E_{boiler}	$E_{ORC\_to\_tank}$	$E_{ORC\_to\_tank}/E_{DHW\_std}$	E_{ORC_diss}		$E_{DHW\_delivered}$	discomfort		E_saving
		[l]	[kWh]	[kWh]	[%]	[kWh]	[%]	[kWh]	[h]	[%]	[%]
1a	30	10000	58844	48674	39%	1980	4%	103543	235	17%	43%
2a	30	5000	51639	45109	37%	5544	11%	94599	292	21%	45%
3a	30	3000	46681	37315	30%	13338	26%	84763	358	26%	45%
4a	15	10000	22062	42555	69%	8099	16%	58898	85	6%	63%
5a	15	5000	22886	37650	61%	13003	26%	56867	119	9%	60%
6a	15	3000	25570	31798	52%	18856	37%	54849	152	11%	53%

The second configuration (Fig. 2b) shows the advantage that the boiler supplies energy directly to the final users when it is needed, allowing a better performance in terms of water supply temperatures. The boiler was sized to cover the maximum energy demand for the considered DHW profile (650 kW for 30 apartments and 325 kW for 15 apartments). The obtained results are summarized in Table 3. It is evident that with this set-up the ORC energy recovery slightly increases and the discomfort hours are cancelled. As expected the energy delivered by the boiler generally is higher than in the previous configuration: 27% more comparing Case 1a with Case 1b, while it is pretty much the same comparing Case 4a with Case 4b.

Table 3. Energy balance and comfort performance of the second DHW supply plant configuration.

Case	N. app	Tank	E_{boiler}	$E_{ORC\_to\_tank}$	$E_{ORC\_to\_tank}/E_{DHW\_std}$	E_{ORC_diss}		$E_{DHW\_delivered}$	discomfort		E_saving
		[l]	[kWh]	[kWh]	[%]	[kWh]	[%]	[kWh]	[h]	[%]	[%]
1b	30	10000	74652	49518	40%	1135	2%	123458	0.00	0.00%	40%
2b	30	5000	74301	48792	40%	1862	4%	123461	0.00	0.00%	40%
3b	30	3000	74903	46841	38%	3812	8%	123442	0.00	0.00%	39%
4b	15	10000	20487	44588	72%	6066	12%	61730	0.00	0.00%	67%
5b	15	5000	22024	41736	68%	8918	18%	61727	0.00	0.00%	64%
6b	15	3000	24535	38573	62%	12081	24%	61724	0.00	0.00%	60%

Concluding, the best system configuration to recover as much thermal energy as possible from the ORC is represented by the second set-up proposed with the boiler supplying directly the final users. A storage tank of 10'000 liter is enough to store the ORC surplus of energy (only 12% of ORC energy lost), while the number of apartments which fits the best with the production of the considered plant is 15. The DHW energy demand actually saved (E_saving), because produced with the ORC by avoiding to use the boiler, is about 67% (taking also into account energy losses in the heat transfer and energy storage process and the temperature of the heat available vs. the requested DHW supply temperature).

Eventually the exploitation of the electric energy produced by the ORC was also considered. The electricity profile for the consumption of each apartment was obtained by means of [12]. 15 apartments use in a year about 46’500 kWh_{el}, the considered micro solar CHP plant produces about 5100 kWh_{el} in a year, thus the ORC electricity can cover about 10% of the final users’ demand of electricity (i.e. barely two apartments), confirming the bigger relevance of such systems to satisfy the thermal energy demand.

4. Conclusions

In this paper the application of an innovative micro-solar 2kWe/18kWth Organic Rankine Cycle system in a residential multi-apartments building is considered. In particular, the use of thermal energy to supply domestic hot water (DHW) is analyzed. Two different DHW supply plant configurations are evaluated: (i) with a boiler integrated into the DHW storage tank; and (ii) with a boiler supplying energy directly to the final users. Moreover, influence of operational strategies of the system are also considered and a sensitivity analysis by varying the most influencing parameters carried out.

With reference to the first configuration the system was firstly designed to recover all the maximum daily thermal energy produced by the ORC and then different storage tank sizes were considered. Secondly, the number of apartments was reduced with the aim of increasing the share of DHW energy covered by the ORC unit and the performance of the configuration evaluated.

Later, performance of the second configuration was assessed for different storage tank sizes and number of apartments. It was found out that this configuration, with the boiler which serves directly the final users, is the best one to maintain the comfort, while the considered ORC plant can deliver to the storage tank around 72% of the DHW energy demand of 15 apartments with a tank volume of 10’000 liters, achieving a final energy demand saving of 67%. As regards the electricity produced by the ORC, it is about 10% of the electric energy demand of the same multi-apartments building.

The analysis has shown the effectiveness of this innovative micro-CHP to efficiently satisfy the thermal energy demand for domestic hot water supply in multi-apartments buildings when the system is properly designed and sized with respect to the user demand.

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