Dynamic Performance of a Solar Hybrid Heating Network Integrated with a Micro-Cogeneration Unit Serving a Small-Scale Residential District including Electric Vehicles

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Abstract

A solar hybrid district heating network integrated with a seasonal borehole thermal energy storage is modelled, simulated and analyzed over a 5-year period. The system is devoted to satisfying the thermal demand of a small-scale district consisting of 6 typical Italian single-family houses in Naples (south of Italy); the charging of 6 plug-in electric vehicles is also considered. The performance of the proposed plant is investigated by considering two alternative natural gas-fueled back-up systems. The energy, environmental and economic performance of the proposed plant are analyzed and compared with those associated to a conventional heating system in order to assess the potential benefits.

Introduction

Solar energy is considered one of the most promising options for energy saving and reduction of harmful emissions. Seasonal thermal energy storage allows for thermal energy storage over weeks and months, with it being a challenging key technology for solving the time-discrepancy between solar energy supply and thermal energy demand; borehole thermal energy storage (BTES) has the most favorable condition for long-term energy storage (Rad and Fung, 2016; Ciampi et al., 2018). However, the utilization of intermittent energy sources characterized by a stochastic behavior requires other generation units to compensate the lack of energy. District heating (DH) networks based on solar energy are gaining more and more interest in the scientific community. Several technologies can be integrated into solar DH systems; in particular, micro-cogeneration (MCHP) systems, i.e. devices characterized by the combined production of electric and thermal energy from a single fuel source with an electric output lower than 50 kW_{el}, are considered by the European Community as one of the most effective measures to save primary energy and reduce greenhouse gas emissions in small-scale applications (Rosato et al., 2017; Sibilio and Rosato, 2015; Directive 2012/27/EU; Mura et al., 2015; Mura et al., 2015). The diffusion of electric vehicles (EVs) could help in (i) reducing the large energy consumption of the transport sector and related greenhouse gases emissions, (ii) improving the local air quality in urban areas thanks to the reduced emission of local pollutants, as well as (iii) lowering the costs per kilometer for the end-users when compared to internal combustion engine vehicles

(Angrisani et al., 2014). The micro-cogeneration devices applied in residential units generally operate under a heat-load following control strategy in response to variations in heat demand (Sibilio and Rosato, 2015); in this case, a large fraction of the cogenerated electricity is usually produced at times when the electric demand of the building is lower than MCHP electric output due to the usual mismatch between electric and thermal demands (Ribberink and Entchev, 2014), requiring substantial amounts of electricity to be exported to the grid with low revenues. EVs consume considerable amounts of electricity; they are mostly driven during the day and charged at home during the night, so that the recharging of EVs could be a way to increase the own use of cogenerated electricity, enhancing the profitability of MCHP devices. Few papers are available in literature focusing on small-scale solar hybrid DH systems. Buoro et al. (2014) investigated the integration between distributed energy supply system, solar thermal plant and heat storage for a district composed of 9 industrial facilities located in the north-east of Italy. The work of Kallert et al. (2017) focused on the analysis of a low temperature DH network serving a small group of 10 low energy residences. Marguerite et al. (2017) presented the results of a multi-criteria evaluation of different design scenarios for a micro-DH network in Vienna (Austria) serving two office buildings. To the knowledge of the authors, the potential of the joint use of solar DH networks and micro-cogeneration units under the climatic conditions of Italy has not been investigated with reference to small-scale applications. The literature review also revealed that possible synergy between micro-cogeneration and EV charging has been poorly analyzed (Ribberink and Entchev, 2014; Angrisani et al., 2015).

In this paper a small-scale DH network based on a field of solar collectors and integrated with a seasonal borehole thermal energy storage is modelled, simulated and analyzed over a 5-year period by means of the TRaNsient SYStems software platform (TRNSYS). The system is devoted to satisfying the heating demand of a district consisting of 6 typical Italian single-family houses under the climatic conditions of Naples (south of Italy). The district also includes a set of 6 plug-in EVs characterized by different charging profiles representing scenarios in which EVs would drive two different daily distances (30 and 53 km) and would be charged at three different power levels (2.2, 3.6 and 6.6 kW_{el}); the charging profiles have

been identified by means of the Plug-in Electric Vehicle and Charge Impact Model developed by the Natural Resources Canada. The performance of the proposed plant is investigated by considering two alternative back-up systems in order to compensate the intermittency of solar source: 1) a conventional 26.6 kW_{th} natural gas-fired boiler (VAILLANT), and 2) a 28.0 kW_{th} natural gas-fueled internal combustion engine-based micro-cogeneration unit (COGENGREEN). The primary energy consumption, the equivalent carbon dioxide emissions and the operating costs of the proposed district network are evaluated based on the simulation results and compared with those associated to a conventional decentralized heating system assumed as reference with the main aims of assessing (i) the feasibility of micro-cogeneration units integrated into DH systems, (ii) the impact of EVs charging on MCHP profitability, as well as (iii) the overall potential energy, environmental and economic benefits of small-scale solar DH applications integrating seasonal thermal energy storages.

Description of the district

The district served by the proposed plant is composed of 6 typical Italian single-family residences located in Naples (latitude=40° 51' 46" 80 N; longitude=14° 16' 36" 12 E; Heating Degree Days=1,034). 3 different typologies of residential buildings have been considered (A, B, C). In particular, the district is composed of 2 buildings for each typology; each building typology differs from the others in terms of floor area, windows' area, volume, maximum simultaneous occupants, heat (heating and domestic hot water) and electricity demands, as indicated in Table 1.

Table 1: Description of building's typologies.

	Typology A	Typology B	Typology C
Number of buildings (-)	2	2	2
Floor/windows area (m ²)	60/84	78/102	114/230
Volume (m ³)	230	370	448
Maximum simultaneous occupants (-)	3	4	5
Annual heat/electricity demand (kWh)	2808.6/ 2344.6	3308.8/ 2455.5	5174.4/ 2692.5
Maximum daily heat/electricity demand (kWh)	43.7/11.6	52.9/12.9	62.8/13.8

For each building typology, a specific annual stochastic profile (composed of 365 different daily stochastic profiles) with a one-minute time resolution has been considered for modeling both the occupancy profiles as well as the electric demand profiles (related to lighting and domestic appliances); these annual stochastic profiles have been obtained based on the models developed by Richardson et al. (2010). The annual internal gain profiles

for each building typology have been derived from the above-mentioned profiles by assuming a heat gain of 70 /occupant, a heat gain of lighting systems equal to 70% of nominal electric power as well as a heat gain for each domestic appliance based on manufacturer data. In order to be compliant with Italian legislation requirements (DM 26/06/2015), the thermal transmittance of the buildings envelopes has been equated to the given threshold values (2.40 W/m²K for windows, 0.36 W/m²K for roofs, 0.40 W/m²K for floors, 0.38 W/m²K for external vertical walls), whatever the building typology is. The European Standard EN 12831 has been used to calculate the air exchange rate (assumed equal to 0.24 volumes per hour for each building typology), i.e. the number of interior volume air changes that occur per hour, induced by the wind and stack effect on the building envelope. Several sets of yearly load profiles for the domestic hot water (DHW) demand have been specified within the IEA-SHC Task 26 (Jordan and Vajen, 2001); each profile consists of a value of water flow rate for every time step, with the values and the time of occurrence of every incidence have been selected by statistical means. In this study, a demand profile with an average basic load of 100 l/day in the time scale of 1 minute has been used for both building typologies A and B, while a demand profile with an average basic load of 200 l/day in the time scale of 1 minute has used for building typology C.

Description of the proposed plant

The schematic of the proposed Central Solar Heating Plant with Seasonal Storage (CSHPSS) is reported in Figure 1. In this figure, the following main components can be identified: end-users (6 residential buildings), solar collectors field (SF), heat dissipator (HD), short-term thermal energy storage (STTES), borehole thermal energy storage (BTES) with vertical double U-pipes borehole heat exchangers, back-up system (BS), 2 heat exchangers (HE1 and HE2), 6 electric vehicles (EVs), local individual boilers (B) for DHW production, fan-coils (FC), pumps (P), 3-way valves and pipes. The solar energy captured by the solar thermal collectors is first transferred, through the heat exchanger HE1, into the short-term thermal energy storage; dissipation of solar thermal energy surplus is obtained by blowing air across a finned coil heat exchanger when the solar collectors outlet temperature is higher than 95 °C. From the STTES, if there is a heating demand, the solar energy is transferred through the heat exchanger HE2 into the distribution network, and then to the end-users for space heating (each building is equipped with a group of fan-coils). If the solar energy is not immediately required for heating purposes, it can be moved from the STTES to the BTES during the whole year ("BTES charging mode"). Only during the heating season, thermal energy stored in the BTES field can return into the STTES ("BTES discharging mode") to integrate the temperature level. During the charging phase, the flow direction is from the center to the boundaries of the BTES to obtain high temperatures in the center and lower ones at the boundaries of the storage; the flow direction is reversed during the discharging phase.

Figure 1: Schematic of the proposed central solar heating plant.

In order to supplement the space heating demand when the solar energy recovered and stored in the short- and long-term storages cannot meet the energy requirements, a back-up system is used. In particular, the following two alternative cases involving different technologies have been considered:

- case 1) 26.6 kW_{th} Main natural gas-fired Boiler (MB) (VAILLANT);
- case 2) 28.0 kW_{th} natural gas-fueled internal combustion engine-based micro-cogeneration unit (with a nominal electric output of 12.0 kW_{el}) (COGENGREEN).

Table 2 summarizes the main characteristics of the leading components. The total aperture area of solar collectors (55.44 m²), the volume of the STTES (6.0 m³), the volume of the BTES (435.8 m³) as well as the number (8) and depth (12.43 m) of the boreholes have been determined by the authors based on the simulation results of a huge sensitivity analysis performed in a previous study (Ciampi et al., 2018).

Natural Resources Canada has developed a Plug-in Electric Vehicle and Charge Impact Model (Natural Resources Canada); it is a versatile software tool that is used to determine the impact of EV charging on the future electricity grid, fuel costs and emissions. It is used in this paper to create a set of 6 EV weekly charging profiles (named EV1, EV2, EV3, EV4, EV5 and EV6) representing scenarios based up actually driving data in which EVs would drive two different daily distances (30 and 53 km) and would be charged at three different power levels (2.2, 3.6 and 6.6 kW_{el}). In this paper the proposed CSHPS has been analyzed with and without considering a set of 6 plug-in EVs (one EV per each single building)

characterized by the charging profiles indicated in Figures 2. Specifically, Figure 2a refers to profiles with a daily driving distance of 30 km and Figure 2b refers to profiles with 53 km as daily driving distance.

Table 2: Main characteristics of plant components.

Solar thermal collectors (Kloben)	
Collector technology / model	Flat plate / FSK 2.5
Apertura area of a single collector (m ²)	2.31
Number of collectors	24 (8 rows)
Tilted angle / Azimuth / Orientation	30° / 0° / South
Short-Term Thermal Energy Storage (PARADIGMA)	
Typology	Vertical cylindrical tank
Volume (m ³) / Height (m)	6.0 / 3.5
Boreholes Thermal Energy Storage	
Volume (m ³)	435.8
Borehole radius (m)	0.15
Number (-) / Depth of boreholes (m)	8 / 12.43
Thermal conductivity of soil (W/mK)	3.0
Thermal conductivity of grout (W/mK)	5.0
Center-to-center half distance (m)	0.05
U-pipe spacing / borehole spacing (m)	0.0254 / 2.25
Inner/outer radius of U-pipe (m)	0.01372 / 0.01669
Pipe / Gap thermal conductivity (W/mK)	0.42 / 1.40
Maximum storage temperature (°C)	90
Main Boiler (VAILLANT)	
Fuel / Rated capacity (kW)	Natural gas / 26.6
Minimum turn-down ratio (-)	0.4
MCHP unit (COGENGREEN)	
Fuel	Natural gas
Rated electric / thermal output (kW)	12.0 / 28.0
Rated electric / thermal efficiency (%)	27.9 / 65.1

The electric requirements (due to domestic appliances, lighting systems, pumps, fan-coils, EVs, etc.) are satisfied with the electric energy supplied by the central grid for the configuration with the Main Boiler as back-up system; in the case of the MCHP unit is adopted as back-up system, the cogenerated electricity is used directly in order to cover the electric demand; any unused excess electricity is sent to the power line, with the electric grid covering the peak demands.

Figure 2: EVs charging profiles with (a) 30 km as daily driving distance, and (b) 50 km as daily driving distance.

Simulation models

The TRaNsient SYStems (TRNSYS) software platform has been used to model and simulate the proposed plant over a 5-year period with a simulation time step of 2 minutes. In this paper the TRNSYS Types have been selected from the TRNSYS libraries and enhanced by manufactures performance data or information available in current scientific literature according to the common characteristics of the components used in practice. The duration of simulation period (5 years) has been defined in order to consider that it takes time to fully charge the seasonal storage. January 1st has been assumed as starting date of the simulations.

The Type 56 has been used to model the buildings composing the district. The Type 557a (Hellström, 1989), adopted to model the BTES, is considered to be the state-of-the-art in dynamic simulation of ground heat exchanger that interacts thermally with the ground and has been used by several researchers for simulating energy systems with BTES (Entchev et al., 2018). The storage volume has the shape of cylinder with vertical symmetry axis; within this cylindrical storage volume, the

ground is considered to be uniform. There is convective heat transfer in the ducts and conductive heat transfer in the ground. The layout of the borehole field is fixed hexagonally and uniformly within the storage volume in the simulation. The Type 534, used to model the STTES, is based on the assumption that the tank can be divided into fully-mixed equal sub-volumes; in this paper, the STTES has been modelled with 10 isothermal temperature layers to better represent the stratification in the tank, where the top layer is 1 and the bottom layer is 10. The tank model has been calibrated based on manufacturer data (PARADIGMA). Flat-plate solar collectors have been modelled by using the Type 1b; in this model, the collector efficiency has been defined by a second-order equation and correction for off-normal solar incidence is applied by a second-order incidence angle modifier equation. The coefficients adopted in the equations have been based on manufacturer specifications (KLOBEN). The main boiler has been modelled by the Type 700 by assuming its efficiency depending on the thermal output according to the manufacturer performance data (VAILLANT). Individual boilers installed within the houses for DHW production have been modelled by means of the Type 700 by assuming a constant efficiency of 90%. The performance of the MCHP unit has been defined by means of the Type 907 by assuming a simplified steady-state operation at nominal conditions (thermal output=28.0 kW_{th}, electric output=12.0 kW_{el}, thermal efficiency=65.1%, electric efficiency=27.9%). Fan-coils have been modelled by the Type 753d and calibrated based on manufacturer data (AERMEC).

In this study, a single pair of supply and return pipes has been used for both the distribution network as well as the solar field collector circuit. The Type 31 has been used to model the pipes and calculate the related heat losses by assuming a loss coefficient equal to 0.05 kJ/(hm²K). The DH network pump has been modelled by the Type 742, while the other pumps in the system have been modelled by means of the Type 656. A specific weather data file (EnergyPlus) has been considered for modelling the climatic conditions of Naples; the weather data are one year long and, therefore, have to be the same each year.

Control logics

The duration of the heating period has been assumed from 15th November up to 31st March. The DH network pump operates continuously with a flow rate varying between 497.7 kg/h and 18,015.7 kg/h (depending on the number of buildings requiring thermal energy for space heating) during the heating season. The operation of the HE2 pump depends on the inlet temperature of hot and cold sides ($T_{in,HE2,hot}$, $T_{in,HE2,cold}$). The heat carrier fluid is a mixture of water and ethylene glycol (60%/40% by volume) flowing through the fan-coils only in cases when there is a call for heat triggered by a thermostat installed in each building. The target room temperature $T_{room,set-point}$ is 20.0 °C only in the case of at least one occupant being inside the building; when the room temperature T_{room} is lower than 19.5 °C during the heating period, a mass flow rate

of heat carrier fluid $\dot{m}_{FC}$ flows into the fan-coils; the call for heat signal will be disabled when the room temperature reaches 20.5 °C. The set-point for the DH supply temperature is 55.0 °C, so that the operation of the back-up system (main boiler of MCHP unit) depends on the inlet and outlet temperatures ($T_{in,MB}/T_{in,MCHP}$ and $T_{out,MB}/T_{out,MCHP}$). The target temperature of the DHW mass flow rate $\dot{m}_{DHW}$ is assumed equal to 45°C; the operation of the individual boilers for DHW production depends on their inlet/outlet temperatures ($T_{in,B}/T_{out,B}$). The solar energy recover is based on the comparison between the current values of temperature at node 10 (lower part) of STTES $T_{10,STTES}$ and the temperature of the fluid exiting the solar collector field $T_{SF,out}$. The BTES charging/discharging is controlled based on the current values of the temperature at nodes 1 (upper part) and 10 (lower part) of STTES ($T_{1,STTES}$ and $T_{10,STTES}$), the temperature in the center of BTES field $T_{BTES,center}$ as well as the room target temperature $T_{room,set-point}$. In more detail, during the BTES charging mode, the flow rate, which is constant, is set to half of the nominal flow rate in the collector array; in the BTES discharging mode, the flow rate is set to the current value used in the distribution network. Table 3 reports the control strategies for the activation/deactivation of the plant components.

Description of the reference system

A conventional decentralized heating system (CS) has been modeled and simulated to be compared with the proposed CSHPSS while serving the same district with and without the charging of 6 plug-in EVs. In the reference heating system, each building is equipped only with a natural gas-fired boiler (modelled with a constant thermal efficiency of 90.0 % as well as a rated capacity of 26.6 kW) for both space heating and DHW production. The heat carrier fluid flows through the radiators installed inside the buildings with the same control logic adopted in the proposed CSHPSS. The set-point of the individual boilers is 55.0 °C for heating purposes, with a dead band of 5.0 °C (as in the proposed CSHPSS). The DHW demand profiles used for the proposed CSHPSS have been also assumed for the reference heating system. As in the proposed CSHPSS, the DHW temperature is assumed to be produced at 45 °C.

Methods

In this paper the simulation results associated to the proposed plant have been compared with those associated to the conventional heating system assumed as reference. The comparison has been performed in terms of primary energy consumption, carbon dioxide equivalent emissions and operating costs as detailed in the next subsections. The energy comparison between the proposed and conventional systems has been performed in terms of primary energy consumption by means of the index named Primary Energy Saving (PES):

$$PES = \left(E_p^{CS} - E_p^{CSHPSS} \right) / E_p^{CS} \quad (1)$$

where E_p^{CSHPSS} is the primary energy consumed by the proposed system and E_p^{CS} is the primary energy consumed by the conventional system. These terms are calculated as follows:

$$E_p^{CSHPSS} = E_{th,MB} / \eta_{MB} + E_{p,MCHP} + E_{th,DHW} / \eta_B + E_{el,import} / \eta_{PP} \quad (2)$$

$$E_p^{CS} = E_{th,B} / \eta_B + \left(E_{el,individual pumps} + E_{el,lighting} + E_{el,domestic appliances} + E_{el,EV} \right) / \eta_{PP} \quad (3)$$

where $E_{th,MB}$ is the thermal energy produced by the main boiler, $E_{p,MCHP}$ is the primary energy consumption of the MCHP unit, $E_{th,DHW}$ is the thermal energy consumed for DHW production in the proposed system, $E_{el,import}$ is the electric energy imported/purchased from the grid in the proposed system, $E_{th,B}$ is the thermal energy supplied by the individual boilers for both heating and DHW in the conventional system, $E_{el,individual pumps}$ is the electricity consumed by the individual pumps ($P_{A1}, P_{A2}, P_{B1}, P_{B2}, P_{C1}, P_{C2}$), $E_{el,lighting}$ is the electric energy consumed by the lighting systems, $E_{el,domestic appliances}$ is the electric energy consumed by the domestic appliances and $E_{el,EV}$ is the electric energy consumed for the electric vehicles charging, η_{MB} is the efficiency of the main boiler, η_B is the efficiency of the individual boilers, η_{PP} is the power plant average efficiency in Italy, including transmission losses, assumed equal to 0.42 (Ciampi et al., 2018). The electric energy imported/purchased from the grid $E_{el,import}$ is calculated, time-step by time-step, as the difference between the overall electricity demand $E_{el,demand}$ (due to the pumps, heat dissipator, fan-coils, the lighting systems, domestic appliances as well as electric vehicles charging) and the electric energy congenerated by the MCHP unit $E_{el,MCHP}$ in the case of $E_{el,demand} > E_{el,MCHP}$.

The assessment of the environmental impact has been performed in this study through an energy output-based emission factor approach (Chicco and Mancarella, 2008) in terms of global carbon dioxide equivalent emissions by means of the following indicator:

$$\Delta CO_2 = \left(m_{CO_2}^{CS} - m_{CO_2}^{CSHPSS} \right) / m_{CO_2}^{CS} \quad (4)$$

where $m_{CO_2}^{CSHPSS}$ is the mass of carbon dioxide equivalent emissions associated to the proposed system and $m_{CO_2}^{CS}$ is the mass of carbon dioxide equivalent emissions associated to the conventional system. The values of $m_{CO_2}^{CSHPSS}$ and $m_{CO_2}^{CS}$ used in Eq. 4 have been computed as reported below:

$$m_{CO_2}^{CSHPSS} = \beta \cdot E_{th,MB} / \eta_{MB} + \beta \cdot E_{p,MCHP} + \beta \cdot E_{th,DHW} / \eta_B + \alpha \cdot E_{el,import} \quad (5)$$

$$m_{CO_2}^{CS} = \beta \cdot E_{th,B} / \eta_B + \alpha \cdot \left(E_{el,individual pumps} + E_{el,lighting} + E_{el,domestic appliances} + E_{el,EV} \right) \quad (6)$$

where α is the CO_2 equivalent emission factor for electricity production and β represents the CO_2 equivalent emission factor associated to the natural gas consumption. According to the values suggested by Ciampi et al. (2018) for the Italian scenario, α has been assumed equal to 573 g_{CO_2}/kWh_{el} and β has been considered of 207 g_{CO_2}/kWh_p .

Table 3: Control strategies of proposed CSHPSS.

	ON	OFF
Individual pumps & FC blower	Heating period AND $T_{room} \leq 19.5^\circ C$	Cooling period OR $T_{room} \geq 20.5^\circ C$
Solar pump & HE1 pump	$(T_{SF,out} - T_{10,STTES}) \geq 10^\circ C$ AND $T_{1,STTES} \leq 90^\circ C$	$(T_{SF,out} - T_{10,STTES}) \leq 2^\circ C$ OR $T_{1,STTES} > 90^\circ C$
BTES pumps (charging and discharging)	<p>CHARGING MODE <u>Heating period:</u> $(T_{10,STTES} - T_{room,set-point}) \geq 10^\circ C$ AND $T_{1,STTES} \geq 60^\circ C$ AND $(T_{1,STTES} - T_{BTES,center}) \geq 10^\circ C$</p> <p><u>Cooling period:</u> $(T_{1,STTES} - T_{BTES,center}) \geq 10^\circ C$</p> <p>DISCHARGING MODE <u>Heating period:</u> $(T_{BTES,center} - T_{10,STTES}) \geq 5^\circ C$ AND $T_{1,STTES} \leq 60^\circ C$</p>	<p>CHARGING MODE <u>Heating period:</u> $(T_{10,STTES} - T_{room,set-point}) \leq 2^\circ C$ OR $T_{1,STTES} \leq 55^\circ C$ OR $(T_{1,STTES} - T_{BTES,center}) \leq 2^\circ C$</p> <p><u>Cooling period:</u> $(T_{1,STTES} - T_{BTES,center}) \leq 2^\circ C$</p> <p>DISCHARGING MODE <u>Heating period:</u> $(T_{BTES,center} - T_{10,STTES}) \leq 2^\circ C$ OR $T_{1,STTES} > 65^\circ C$</p>
DH network pump	Heating period AND $T_{room} \leq 19.5^\circ C$	Cooling period OR (Heating period AND $T_{room} \geq 20.5^\circ C$)
HE2 pump	DH network pump ON AND $(T_{in,HE2,hot} - T_{in,HE2,cold}) \geq 5^\circ C$	DH network pump OFF OR $(T_{in,HE2,hot} - T_{in,HE2,cold}) \leq 2^\circ C$
Main boiler/MCHP unit	Heating period AND $\dot{m}_{FC} \neq 0$ AND $T_{in,MB}/T_{in,MCHP} < 50^\circ C$	Coiling period OR $\dot{m}_{FC} = 0$ OR $T_{out,MB}/T_{out,MCHP} \geq 55^\circ C$
Individual boilers for DHW production	$\dot{m}_{DHW} \neq 0$ AND $T_{in,B} < 45^\circ C$	$\dot{m}_{DHW} = 0$ AND $T_{in,B} \geq 45^\circ C$

The economic analysis has been performed by comparing the operating costs of the proposed system with those of the reference heating system by means of the following parameter:

$$\Delta OC = (OC^{CS} - OC^{CSHPSS}) / OC^{CS} \quad (7)$$

where OC^{CSHPSS} represents the operating costs associated to the proposed system and OC^{CS} represents the operating costs associated to the conventional system.

The values of OC^{CS} and OC^{CSHPSS} used in Eq. 7 have been computed as reported below:

$$OC^{CSHPSS} = UC_{ng} \cdot E_{th,MB} / (LHV_{ng} \cdot \rho_{ng} \cdot \eta_{MB}) + UC_{ng,MCHP} \cdot E_{p,MCHP} / (LHV_{ng} \cdot \rho_{ng}) + UC_{ng} \cdot E_{th,DHW} / (LHV_{ng} \cdot \rho_{ng} \cdot \eta_B) + UC_{el} \cdot E_{el,import} - UC_{el,sold} \cdot E_{el,MCHP,exp} \quad (8)$$

$$OC^{CS} = UC_{ng} \cdot E_{th,B} / (LHV_{ng} \cdot \rho_{ng} \cdot \eta_B) + UC_{el} \cdot \left(E_{el,individual pumps} + E_{el,lighting} + E_{el,domestic appliances} + E_{el,EV} \right) \quad (9)$$

where UC_{ng} is the unit cost of natural gas consumed by the boilers (ARERA), $UC_{ng,MCHP}$ is the unit cost of natural gas consumed by the MCHP unit (ARERA), LHV_{ng} is the lower heating value of natural gas (assumed equal to 49,599 kJ/kg) and ρ_{ng} is the density of natural gas (assumed equal to 0.72 kg/m³) (Ciampi et al., 2018), UC_{el} is the unit cost of electric energy purchased from the central grid (ARERA), $UC_{el,sold}$ is the unit cost of the cogenerated electricity exported to the grid ($E_{el,MCHP,exp}$) (GSE). The tariffs of both the electric energy as well as the natural gas have been kept up-to-date according to the Italian scenario (ARERA, GSE).

Results

The following 4 plant configurations have been simulated and analyzed over a period of 5 years:

- 1) Boiler w/o EVs: CSHPSS equipped with the main boiler as back-up system, without considering the charging of 6 EVs;
- 2) Boiler with EVs: CSHPSS equipped with the main boiler as back-up system, in the case of the 6 EVs have to be charged;
- 3) MCHP w/o EVs: CSHPSS equipped with the MCHP unit as back-up system, without considering the charging of 6 EVs;
- 4) Boiler with EVs: CSHPSS equipped with the MCHP unit as back-up system, in the case of the 6 EVs have to be charged.

Figure 3 reports the values of PES as a function of the simulation year for the above-mentioned 4 configurations. This figure highlights that the values of PES significantly increase from the 1st to the 2nd year of operation and then become substantially constant; this is thanks to the fact that the average temperature of the long-term thermal energy storage mainly increases from the 1st to the 2nd year of simulation, allowing for a more effective exploitation of solar energy. Similar trends have been obtained for the values of ΔCO_2 and ΔOC , so that the performance during

the 5th year of operation can be assumed as the steady-state value (whatever the plant configuration is).

Figure 3: Values of PES as a function of the time.

Figure 4a reports the values of PES, ΔCO_2 and ΔOC , while figure 4b highlights the main energy flows during the 5th year of simulation upon varying the configuration plant; in particular, the electric energy generated by the MCHP unit, the electric energy imported from the grid, the electric energy exported to the grid, the net solar energy recovered from solar collectors, the thermal energy injected into the BTES, the thermal energy extracted from the BTES, the thermal energy supplied by the main boiler or the MCHP unit are indicated in Figure 4b.

Figure 4: (a) PES, ΔCO_2 , ΔOC , and (b) energy flows during the 5th year of simulation.

Figures 4a and 4b show that:

- the values of PES^{5th year}, $\Delta\text{CO}_2^{\text{5th year}}$ and $\Delta\text{OC}^{\text{5th year}}$ are always positive, whatever the configuration plant is; this means that the proposed configurations of the CSHPSS allow to reduce the primary energy consumption, the equivalent CO_2 emissions and the

operating costs in comparison to the reference heating system at any case;

- the maximum values of PES^{5th year} (8.1%), $\Delta\text{CO}_2^{\text{5th year}}$ (5.4%) and $\Delta\text{OC}^{\text{5th year}}$ (8.2%) are obtained in the case of the main boiler is used as back-up system, without considering the EVs charging;
- the worst energy, environmental and economic performance (PES^{5th year}=2.7%, $\Delta\text{CO}_2^{\text{5th year}}$ =2.3% and $\Delta\text{OC}^{\text{5th year}}$ =4.0%) corresponds to the configuration including the MCHP unit as back-up system together with the EVs charging;
- whatever the back-up system (main boiler or MCHP unit) is, the EVs charging significantly reduces the values of PES^{5th year}, $\Delta\text{CO}_2^{\text{5th year}}$ and $\Delta\text{OC}^{\text{5th year}}$ in comparison to the case when the EVs charging is not taken into account; this is due to the fact that the amount of electric energy imported from the grid increases with the utilization of the EVs. The reduction is more relevant when the boiler is adopted as back-up system (with the values of PES^{5th year}, $\Delta\text{CO}_2^{\text{5th year}}$ and $\Delta\text{OC}^{\text{5th year}}$ lowered by about 3.4%, 2.3% and 4.8%, respectively) due to the fact that in this case the total electric demand is fully covered by the central grid (without the contribution of cogenerated electricity);
- in the case of the EVs have to be charged, the best energy and environmental performance (PES^{5th year}=4.7%, $\Delta\text{CO}_2^{\text{5th year}}$ =3.1%) are obtained when the boiler is used as back-up system thanks to the fact that the solar energy recovered from solar collectors is more significant, allowing for a lower thermal contribution from the back-up system (even if the electricity imported from the grid is larger), while the adoption of the MCHP unit allows to achieve a larger saving in terms of operating costs ($\Delta\text{OC}^{\text{5th year}}$ = 4.0%) thanks to (i) the lower unit cost of natural gas for cogenerative use with respect to other applications, (ii) the revenues associated to the electric energy (about 1.9 MWh) sold to the grid, and (iii) the reduced electricity imported from the grid.

Conclusions

The energy, environmental and economic performance of a solar hybrid district heating network integrated with a seasonal borehole thermal energy storage are analyzed and compared with those of a conventional heating system upon varying the back-up system as well as the electric demand profiles (with or without 6 electric vehicles). The results highlighted that: (i) the proposed configurations of the CSHPSS allow to reduce the primary energy consumption, the equivalent CO_2 emissions and the operating costs in comparison to the reference heating system at any case; (ii) whatever the back-up system (boiler or MCHP unit) is, the EVs charging significantly reduces the overall performance; (iii) if the EVs charging is not performed, the configuration with the boiler as back-up system allows to obtain better results with respect to the case with the MCHP unit.

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