DYNAMIC SIMULATION OF A SOLAR HEATING AND COOLING SYSTEM INCLUDING A SEASONAL STORAGE SERVING A SMALL ITALIAN RESIDENTIAL DISTRICT

by

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A centralized solar hybrid heating and cooling system satisfying the thermal, cooling and sanitary water demands of a typical Italian small district composed of six residential buildings situated in Naples (southern Italy) is modelled, simulated and analysed through the software TRNSYS over a period of 5 years. The plant is based on the operation of solar thermal collectors coupled with seasonal borehole storage; the solar field is also composed of photovoltaic solar panels connected with electric energy storage. An adsorption chiller powered by solar energy is adopted for cooling purposes, while a condensing boiler is used as an auxiliary unit. The performance of the proposed system has been assessed from energy, environmental and economic points of view and contrasted with the operation of a typical Italian heating and cooling plant, highlighting the following main results: saving of primary energy consumption up to 40.2%; (decrease of equivalent CO_2 emissions up to 38.4%; reduction of operating costs up to 40.1%; and simple pay-back period of about 20 years.

Keywords: *borehole thermal energy storage, electric energy storage, solar energy, district heating and cooling, adsorption chiller*

Introduction

The building sector consumes around 40% of the total energy consumption, and it is in charge of the major portion of the greenhouse gas emissions [1]. Solar district heating (SDH) and cooling systems have attained relevant attention, playing a worldwide leading role with more than a thousand of applications installed [1]. Even if solar energy is easily and economically accessible in most part of the planet, one of the longstanding barriers to solar energy technology lies in the remarkable misalignment of solar energy availability with respect to heating requirements. Seasonal storages permit to store thermal energy for periods of up to several months, so that they could represent a challenging key technology for addressing this time-discrepancy. According to an extensive literature review, Rad and Fung [2] came to the conclusion that seasonal borehole thermal energy storages (BTES) are characterized by the most advantageous conditions for long-term energy storage thanks to the large amounts of energy involvement and relatively low cost of storage material. The BTES consist of

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closed-loops where heat is charged or discharged by vertical or horizontal borehole heat exchangers (BHE) which are installed into boreholes below the ground surface. After drilling, a U-pipe is inserted into the borehole; the borehole is then filled with a high thermal conductivity grouting material. The BHE can be single or double U-pipes and they can be hydraulically connected in series or in parallel. The underground is used as storage material in a BTES.

The SDH systems with seasonal storage are becoming a very promising alternative to fossil fuel heating and have been researched by several entities, such as IEA's Task 32 and Task 45 [3, 4], and the German programme Solarthermie [5]; the EINSTEIN European project was launched [6] with the aim of integrating long-term storages and solar plants. Various projects and installations integrating seasonal BTES into SDH systems have seen the light of day in Europe and North America, and related performances indicate that such plants can play a vital role in the implementation of future smart energy systems, even if the initial investment is high and, therefore, their development requires additional, comprehensive analysis in order to optimize and assess the potential benefits [2, 7]. In Alberta (Canada) [8], a BTES is integrated into a SDH system; the BTES is characterized by 144 boreholes drilled to a depth of 35 m. After four years of operation, it allowed satisfying 80% of the heating district demand (52 residential units). Another BTES installation connected to a SDH plant can be found in Anneberg (Sweden) [9]; it includes 100 boreholes to cover the heat load of 50 houses (depth of 65 m). After four years operation, 70% of the heating demand was satisfied. Attenkirchen BTES in Germany is characterized by 90 boreholes with a depth of 30 m and a volume of 500 m^3; the system, commissioned in 2002, is considered as one of the smallest systems in Germany; the solar fraction for the system was reported to be 73% based on two-year monitoring data [2]. To the knowledge of the authors, only a few and dated works [10-13] assessed the operation of such plants under the Italian boundary conditions, with only two of these studies [10, 11] by considering southern Italy as location. This point represents a significant gap taking into account that climatic conditions affect the energy load profiles, the exploitation of solar source as well as the selection of capacity/technology/control logic of components. In addition, most of these works focused on districts with a size much bigger than that one object of study in this paper. Moreover, typically the performances have been analysed only from an energy point of view, while the impacts in terms of emissions and costs have been neglected.

Finally, it could be underlined that in Italy there has been an increasing demand for cooling energy in the course of the summer, usually satisfied by electrically-driven units. Alternative eco-friendly chillers that could be driven by renewable energy have been proposed [1]. One of the most promising alternatives is the utilization of adsorption chillers. These devices have some unique advances over other systems in their ability to be driven by very low temperature heat sources; in fact, they may operate even for supply temperatures of 45-65 °C [1]. In comparison with the existing vapour compression and absorption refrigeration systems, notable advantages of the adsorption devices are the absence of rotating parts leading to less vibration, less noise and very low maintenance requirements with simple operation and control [1, 14], however, they are characterized by lower coefficients of performance (between 0.4 and 0.7), higher unit cost and the larger size for the same cooling capacity [1, 14]. Small adsorption refrigeration systems have been developed during the last years by a number of companies and are recently being transferred into the market [1, 14, 15]. Half effect absorption chillers could also work with the heat at a temperature below 80 °C, however, it was observed that they are characterized by coefficients of performance almost half of those obtained with single-effect absorption systems and, in addition, they are not in the commercial phase (but still in the stage of demonstration and prototyping) [16]. To the knowledge of the authors, there have been no scientific papers focusing on the performance of SDH and cooling networks integrating both seasonal thermal energy storages and adsorption chillers operating in Italy or other regions while serving small-scale districts [17].

Characteristics of the district, proposed CSHCPSS plant and reference system

A district consisting of six typical Italian single-family houses situated in Naples (latitude = 40°51'46" 80 N and longitude = 14°16'36" 12 E) has been analysed; three types of houses (A, B, and C) have been considered, differing mainly in terms of floor area (60, 78, and 114 m^2, respectively) and number of occupants (3, 4, and 5, respectively), with two houses for each type. The thermal transmittance of windows and walls has been assumed equal to the maximum values (2.40 $Wm^{-2}K^{-1}$ for windows, 0.36 $Wm^{-2}K^{-1}$ for roofs, 0.40 $Wm^{-2}K^{-1}$ for floors, and 0.38 $Wm^{-2}K^{-1}$ for external walls) imposed by the Italian Law [18]. The air change of infiltration has been hypothesized equal to 0.24 h^{-1} in the course of the heating period, whatever the outside temperature is; in the course of the summer it has been assumed equal to 0.24 h^{-1} when the ambient temperature is lower than 26 °C and equal to 0.6 h^{-1} when the outdoor temperature is greater than 26 °C in order to take into account the more frequent openings of windows (according to Zarrella *et al.* [19]). The stochastic models suggested by Richardson *et al.* [20], with a one-minute time resolution, have been adopted in this paper to characterize the active occupancy and the electricity requirements (due to lighting and appliances) of the houses, resulting in an overall consumption of electricity for the six residential buildings equal 16.96 MWh per year. The IEA SHC Task 26 [21] developed a number of annual stochastic profiles representing the domestic hot water (DHW) requirements of domestic dwellings; in this work, one-minute time resolution profiles have been considered, with an average demand equal to 100 litres per day for the house types A and B and equal to 200 litres per day for the house type C.

Figure 1 reports the schematic of the central solar heating and cooling plant, including a seasonal storage (CSHCPSS) aiming at satisfying thermal, cooling and DHW demands of the district. The proposed plant is integrated with a seasonal BTES characterized by eight series-connected vertical single U-pipes. A water-ethylene glycol mixture (60%/40% by volume) is used as heat carrier fluid. The distribution network has a total length (supply and return pipes) of about 400 m with an inner diameter equal to 0.110 m. The solar energy recovered by the solar thermal panels is firstly moved, by means of the heat exchanger – HE1, into the short-term thermal energy storage (STTES), a heat dissipator (HD) is adopted in order to maintain the temperature at the outlet of the solar thermal collectors lower than 95 °C and, therefore, prevent the boiling of the heat carrier fluid. During the cooling season (from April 1st up to November 14th) the solar energy is moved from the STTES, by means of the heat exchanger – HE2, to the adsorption chiller (ADHP); this allows to obtain the desired cooling energy to be stored into the short-term cooling energy storage (STCES) and then provided to the houses for cooling purposes. During the heating season (from November 15th up to March 31st), solar energy stored into the STTES can be moved into the distribution network and, then, into the fan coils of the buildings to cover the heating load. Solar energy can always be transferred from the STTES into the BTES ("BTES charging mode") in the case of it is not instantaneously desired for heating/cooling purposes. Thermal energy in the BTES field can return into the STTES ("BTES discharging mode") only for the duration of the heating period in order to supplement the level of temperature inside the STTES. A main condensing boiler, fuelled with natural gas, is eventually used as an auxiliary unit with the aim of integrating the solar contribution and maintaining the desired level of supply temperature. A domestic hot water tank (DHWT), including an internal heat exchanger (HE), is installed inside each house with the aim of pre-heating the mains water for DHW production. In particular, the mains water enters the HE of the DHWT, and the water-ethylene glycol mixture exiting the heat exchanger – HE2 flows into the DHWT before going into the STTES. An individual natural gas-fired boiler (IB) is also installed inside every single building specifically devoted to eventually supplement the DHW level of temperature. The electricity delivered by the PV panels is primarily utilized to satisfy the electric load of end-users and plant components, while the excess is transferred into the batteries only when their charging status is lower 100%; the batteries are discharged only when their charging status is larger than 10%. In the case of the electric energy generated by the PV panels is greater than the overall electric load and the batteries charging level is equal to 100%, the electric production that cannot be charged into the batteries is then sold to the central grid. The central grid, as well as the batteries, are utilized to satisfy the peaks of electric load. Table 1 details the most important characteristics of CSHCPSS components.

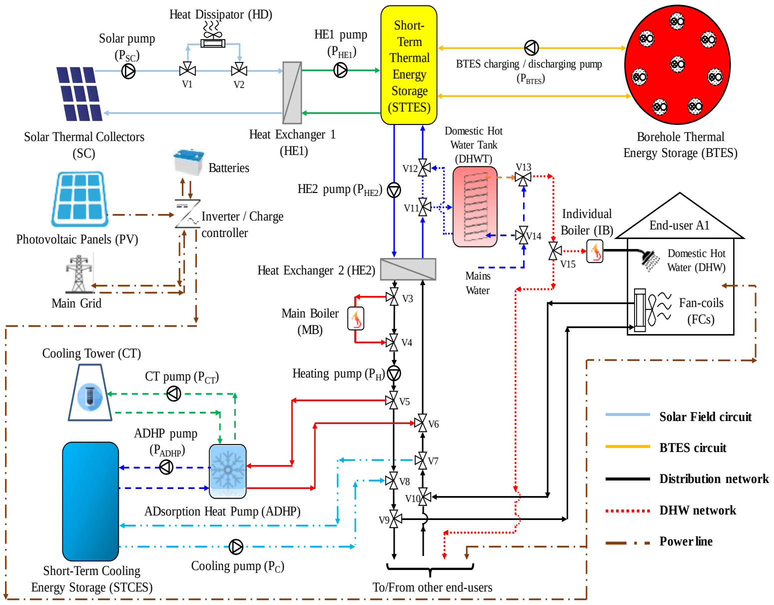


Figure 1. Schematic of the proposed CSHCPSS

The target room temperature is set at 20 °C and 26 °C, respectively, during the heating and cooling season (deadband of 1 °C). The temperature inside the buildings T_{room} [°C] is controlled only when at least one person being in the house. The recovery of solar energy is activated depending on the temperature difference between the exit of the solar collectors $T_{SC,out}$ and the node 10 of the STTES $T_{10,STTES}$ with a variable mass flow rate of heat carrier fluid. The charging/discharging of the BTES is activated depending on the temperature at nodes 1 ($T_{1,STTES}$) and 10 of the STTES ($T_{10,STTES}$), the temperature in the centre of the BTES field $T_{BTES,center}$ as well as the target temperature of heating period. The activation of the adsorption chiller is based on the temperature $T_{6,STCES}$ [°C] at the node six of the STCES, with the temperature driving the ADHP in the course of the cooling period targeted at 75 °C.

Table 1. Most important characteristics of CSHCPSS components

Solar thermal collectors [24]	
Collector typology / model	Flat plate / model FSK 2.5
Number of collectors / aperture area of a single collector [m^2]	105 (35 parallel-connected rows) / 2.31
Orientation / tilted angle / azimuth	South / 30° / 0°
Monocrystalline PV panels [25, 26]	
Module area [m^2] / number of collectors [-]	5.04 / 16 (4 parallel-connected rows)
Orientation / tilted angle / azimuth	South / 30° / 0°
Module open-circuit voltage [V] / current [A] at reference conditions [V]	43.15 / 18.3
STTES [27]	
Typology / volume [m^3] / height [m]	Vertical cylindrical tank / 23.9 / 3.5
STCES [27]	
Typology / volume [m^3] / Height [m]	Vertical cylindrical tank / 6.0 / 3.5
DHWT [28]	
Typology / volume [m^3] / Height [m]	Vertical cylindrical tank / 1.0 / 2
Battery [29]	
Number of batteries (series-connected)	2
Efficiency round-trip [%] / depth of discharge [%]	90 / 100
Single battery usable capacity [kWh] / single battery power [kW]	13.5 / 7 (peak), 5 (continuous)
Inverter and charge controller [25]	
Inverter efficiency [%] / regulator efficiency [%]	96.0 / 78.0
Fractional state of charge: High limit / low limit [%]	100 / 10
BTES system	
Volume of BTES [m^3] / radius of a single borehole [m]	435.8 / 0.15
Number of series-connected single U-pipe boreholes [–] / boreholes depth [m]	8 / 12.43
Thermal conductivity of soil / grout [Wm^{-1}K^{-1}]	3.0 / 5.0
U-pipe / borehole spacing [m]	0.0254 / 2.25
Outer / inner radius of U-pipe [m]	0.01669 / 0.01372
Main back-up condensing boiler (MB) [23]	
Rated capacity [kW] / fuel	74.7 / Natural gas
Rated efficiency η_{MB} during heating / cooling period [%]	108 / 98
IB [23]	
Rated capacity [kW] / fuel / rated efficiency η_{IB} [%]	26.6 / Natural gas / 90
Adsorption chiller [15]	
Model / rated cooling capacity [kW] / rated maximum COP [-]	eCoo 30 ST / 9.0-50.0 / 0.40-0.65
Rated maximum electrical consumption [kW]	2.140
Temperature of the driving / ee-cooling / cold water circuits [°C]	50-95 / 22-40 / 8-21
Rated volumetric flow rate of driving / re-cooling / cold water circuits [m^{3}h^{-1}]	7.50 / 7.70 / 8.70

During the winter, the main boiler operates in order to maintain the outlet temperature $T_{out,MB}$ between 50 °C and 55 °C; the activation of the ADHP, cooling tower (CT) and heating pumps occur depending on $T_{6,STCES}$. The DHW is delivered at 45 °C by means of the IB and the DHWT. Table 2 summarizes the principal strategies controlling the operation of main system components.

A conventional Italian heating and cooling system (CS) has been compared with the CSHCPSS while satisfying the energy requests of the same district. According to the current Italian scenario [22], an individual boiler (IBCS), fuelled with natural gas and characterized by an efficiency η_{IBCS} of 90% [23], coupled with radiators, is adopted for heating purposes as well as producing DHW at 45°C in the CS; a typical multi-split air-to-air vapour compression electric refrigeration unit, with a constant COP of 3.0 (according to the average performance of refrigeration machines available on the Italian market [22]) is used to cover the cooling load in the CS.

Table 2. Control strategies of principal CSHCPSS components

	OFF	ON
FC blower & individual pumps	Heating season: $T_{room} \geq 20.5$ °C Cooling season: $T_{room} \leq 25.5$ °C	Heating season: $T_{room} \leq 19.5$ °C Cooling season: $T_{room} \geq 26.5$ °C
Solar pump & HE1 pump	$(T_{SC,out} - T_{10,STTES}) \leq 2$ °C OR $T_{1,STTES} > 90$ °C	$(T_{SC,out} - T_{10,STTES}) \geq 10$ °C AND $T_{1,STTES} \leq 90$ °C
Charging / discharging pump of the BTES	CHARGING MODE Heating season: $(T_{10,STTES} - 20$ °C$) \leq 2$ °C OR $T_{1,STTES} \leq 55$ °C OR $(T_{1,STTES} - T_{BTES,center}) \leq 2$ °C Cooling season: $(T_{1,STTES} - T_{BTES,center}) \leq 2$ °C DISCHARGING MODE Heating season: $(T_{BTES,center} - T_{10,STTES}) \leq 2$ °C OR $T_{1,STTES} > 65$ °C OR Solar pump ON	CHARGING MODE Heating season: $(T_{10,STTES} - 20$ °C$) \geq 10$ °C AND $T_{1,STTES} \geq 60$ °C AND $(T_{1,STTES} - T_{BTES,center}) \geq 10$ °C Cooling season: $(T_{1,STTES} - T_{BTES,center}) \geq 10$ °C DISCHARGING MODE Heating season: $(T_{BTES,center} - T_{10,STTES}) \geq 5$ °C AND $T_{1,STTES} \leq 60$ °C AND Solar pump OFF
Heating pump	Heating season: $T_{room} \geq 20.5$ °C Cooling season: $T_{6,STCES} \leq 10$ °C	Heating season: $T_{room} \leq 19.5$ °C Cooling season: $T_{6,STCES} \geq 13$ °C
Cooling pump	Heating season OR (Cooling season AND $T_{room} \leq 25.5$ °C)	Cooling season AND $T_{room} \geq 26.5$ °C
HE2 pump	No DHW demand OR Heating pump OFF OR $(T_{in,HE2,hot} - T_{in,HE2,cold}) \leq 2$ °C	DHW demand OR (Heating pump ON AND $(T_{in,HE2,hot} - T_{in,HE2,cold}) \geq 5$ °C)
ADHP pump and CT pump	Heating season OR (Cooling season AND $T_{6,STCES} \leq 10$ °C)	Cooling season AND $T_{6,STCES} \geq 13$ °C
Main boiler	Heating season: $T_{out,MB} \geq 55$ °C Cooling season: ADHP pump OFF OR $T_{out,MB} \geq 75$ °C	Heating season: $T_{in,MB} < 50$ °C Cooling season: ADHP pump ON AND $T_{in,MB} < 70$ °C
IB	$T_{out,IB} \geq 45$ °C	$T_{in,IB} < 45$ °C

Simulation models and methods of analysis

The TRaNsient SYStems (TRNSYS) software platform [30] has been used to model and simulate the proposed CSHCPSS for 5 years, with a one-minute resolution time, starting from January 1st. Detailed models have been applied in order to consider the dynamic nature of occupancy and building loads as well as the part-load operation of energy systems. In TRNSYS environment each physical piece of the equipment is modelled with a mathematical component (named “Type” in TRNSYS terminology). In particular, the following main TRNSYS types have been adopted in this study: Type 56 for buildings, Type 1b for SC, Type 194 for PV panels, Type 47a for inverter/charge controller, Type 48b for batteries, Type 534 for STTES, STCES, and DHWT, Type 557a for BTES, Type 700 for MB, IB, and IBCS, Type 909 for ADHP, Type 51b for CT, Type 742 for pumps, Type 31 for pipes, Types 508c and 753e for fan coils, Type 941 for vapour compression chiller, Type 1231 for radiators and Type 2 for controllers. In more detail, the BTES field has been modelled by means of the duct ground heat storage model, representing the state-of-the-art in modelling BHE [6]. In this model the storage is characterized by a cylindrical shape with vertical symmetry axis. The layout of boreholes is fixed in a hexagonal shape and uniformly within the BTES field, and the ground is assumed to be homogeneous, the top of the storage is covered with insulating material. The short-term storages STTES, STCES and DHWTs have been modelled by considering 10 isothermal temperature nodes to take into account the stratification in the tanks. In particular, the node at the top of the tanks is indicated with the number 1, while the node at the bottom of the tanks is indicated with the number 10.

An EnergyPlus file [31] has been used for characterizing the climatic data of the city of Naples, Italy, consisting of one-year long weather information (as a consequence, each year is characterized by the same climatic conditions). According to the weather data, an average annual solar irradiation on horizontal surfaces of about 314.9 W/m corresponds to Naples.

The characteristic equations and details of each TRNSYS type are fully described in the TRNSYS manual [25, 32]. Validation studies performed using data from the Colorado State University experimental houses demonstrated that the TRNSYS program may be safely used in the analysis of solar heating/cooling systems [33].

The operation of the BTES has been characterized by means of its efficiency η_{BTES}:

$$\eta_{\mathrm{BTES}} = \frac{E_{\mathrm{th,BTES\ discharging}}^{\mathrm{CSHCPSS}}}{E_{\mathrm{th,BTES\ charging}}^{\mathrm{CSHCPSS}}} \tag{1}$$

The energy analysis of the CSHCPSS has been performed by means of the so-called thermal Solar Fraction SF_{th} [%], defined as the ratio between the thermal energy obtained through the solar thermal panels and the overall thermal energy required for space heating/cooling as well as DHW production:

$$SF_{\mathrm{th}} = \frac{E_{\mathrm{th,HE2}}^{\mathrm{CSHCPSS}} + E_{\mathrm{th,HE\text{-}DHWT}}^{\mathrm{CSHCPSS}}}{E_{\mathrm{th,HE2}}^{\mathrm{CSHCPSS}} + E_{\mathrm{th,HE\text{-}DHWT}}^{\mathrm{CSHCPSS}} + E_{\mathrm{th,MB}}^{\mathrm{CSHCPSS}} + E_{\mathrm{th,IB}}^{\mathrm{CSHCPSS}}} \tag{2}$$

The electric solar fraction, SF_{el} [%] has also been used for characterizing the energy performance of the CSHCPSS; it is calculated as the electricity requirement covered by PV panels divided by the total electricity requests by means of the following formula:

$$SF_{\mathrm{el}} = \frac{E_{\mathrm{el,PV}}^{\mathrm{CSHCPSS}}}{E_{\mathrm{el,demand}}^{\mathrm{CSHCPSS}}} \tag{3}$$

According to [22], the comparison between the CS and the CSHCPSS in terms of primary energy has been assessed via the following index called primary energy saving (PES) [%]:

$$PES = \frac{E_{\mathrm{p}}^{\mathrm{CS}} - E_{\mathrm{p}}^{\mathrm{CSHCPSS}}}{E_{\mathrm{p}}^{\mathrm{CS}}} \tag{4}$$

The energy output-based emission factor method suggested by Chicco and Mancarella [34] has been adopted to evaluate the impact from an environmental point of view in terms of global equivalent emissions of carbon dioxide. The parameter $\Delta\mathrm{CO_2}$ [%] described in the next equation has been used:

$$\Delta\mathrm{CO_2} = \frac{m_{\mathrm{CO_2}}^{\mathrm{CS}} - m_{\mathrm{CO_2}}^{\mathrm{CSHCPSS}}}{m_{\mathrm{CO_2}}^{\mathrm{CS}}} \tag{5}$$

According to the values suggested in [22] for the Italian scenario, the $\mathrm{CO_2}$ emission factors for electricity production and for natural gas consumption have been assumed equal to 0.573 $\mathrm{kgCO_2}$ per $\mathrm{kWh_{el}}$ and 0.207 $\mathrm{kgCO_2}$ per $\mathrm{kWh_{p,}}$ respectively. The economic assessment has been performed by contrasting the operation costs of the CSHCPSS and those of the CS through the index ΔOC [%] defined in the next equations according to [22]:

$$\Delta OC = \frac{OC^{\mathrm{CS}} - OC^{\mathrm{CSHCPSS}}}{OC^{\mathrm{CS}}} \tag{6}$$

$$OC^{\mathrm{CSHCPSS}} = \frac{UC_{\mathrm{ng}} E_{\mathrm{th,MB}}^{\mathrm{CSHCPSS}}}{LHV_{\mathrm{ng}} \rho_{\mathrm{ng}} \eta_{\mathrm{MB}}} + \frac{UC_{\mathrm{ng}} E_{\mathrm{th,IB}}^{\mathrm{CSHCPSS}}}{LHV_{\mathrm{ng}} \rho_{\mathrm{ng}} \eta_{\mathrm{IB}}} + UC_{\mathrm{el,imported}} E_{\mathrm{el,imported}}^{\mathrm{CSHCPSS}} - UC_{\mathrm{el,exported}} E_{\mathrm{el,exported}}^{\mathrm{CSHCPSS}} \tag{7}$$

$$OC^{\mathrm{CS}} = \frac{UC_{\mathrm{ng}} E_{\mathrm{th,IBCS}}^{\mathrm{CS}}}{LHV_{\mathrm{ng}} \rho_{\mathrm{ng}} \eta_{\mathrm{IBCS}}} + UC_{\mathrm{el,imported}} E_{\mathrm{el,demand}}^{\mathrm{CS}} \tag{8}$$

The unit costs of electricity and natural gas have been accurately defined according to the current scenario in the city of Naples [35, 36].

The economic analysis has been carried out also in terms of capital costs by calculating the so-called simple pay-back (SPB) period [years], representing the time required to

$$SPB = \frac{CC^{\mathrm{CSHCPSS}} - CC^{\mathrm{CS}}}{OC^{\mathrm{CS}} - OC^{\mathrm{CSHCPSS}} + EI^{\mathrm{CSHCPSS}}} \tag{9}$$

recover the extra investment cost. The following formula has been used:

The calculation of the difference ($CC^{\mathrm{CSHCPSS}} - CC^{\mathrm{CS}}$) has been computed by considering the costs of:
- the solar thermal collectors (169 €/m [37]),
- the solar and HE1 pumps (1488 € per each [38]),
- the STTES (16884 € according to Pahud [39]),
- the BTES field (22917 € according to Pahud [39]),
- the BTES charging/discharging pump (2826 € [38]),
- the main condensing boiler (4109 € [40]),
- the pipes and pumps of the distribution network 14500 € [41]),
- the electric batteries (12994 € [29]),
- the DHWT (1420 € per each [39]),
- the PV panels (1351 €/kW_{peak} [40]),
- the ADHP system including the CT (1992 €/kW [42]), and
- the STCES (5652 € according to Pahud [39]).

With respect to the economic incentives, an annual tax deduction EI^{CSHPSS} equal to [1.10 × ($CC^{\mathrm{CSHCPSS}} - CC^{\mathrm{CS}}$)/5] per year (up to a maximum of 30000 € for each residential end-user [43]) over a period of maximum five years has been assumed according to the so-called *eco-bonus* [43] put in place by the Italian Government since July 1st, 2020. The maintenance costs have been neglected.

Results and discussion

The simulation data highlighted that the reference plant assumed as baseline is characterized by a primary energy consumption $E_{\mathrm{p}}^{\mathrm{CS}}$ of 83.4 MWh/year, a mass of equivalent CO_2 emissions $m_{CO_2}^{\mathrm{CS}}$ equal to 19.2 tCO_2/year as well as an operational cost OC^{CS} of 7.27 k€/year.

Figure 2(a) outlines the average temperature of the ground in the storage volume T_{BTES} together with the values of thermal power charged/discharged into/from the BTES field per unit of BHE length as a function of the time during the first 5 years of operation. Figure 2(b) reports the results of simulations in terms of *PES*, eq. (4), ΔCO_2, eq. (5), ΔOC, eq. (6), η_{BTES}, eq. (1), SF_{th}, eq. (2), and SF_{el}, eq. (3) upon varying the year, showing that they greatly rise from the 1st to the 2nd year of simulation and later evolve into almost completely constant values. This is mostly thanks to the fact that, fig. 2(a) T_{BTES} is initially equal to 10 °C on Janu-

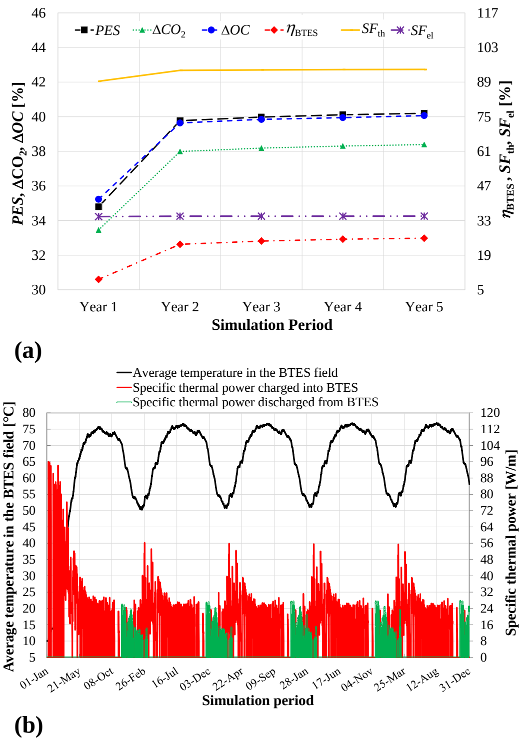


Figure 2. Average temperature of the BTES and specific thermal power charged/discharged into/from the BTES as a function of time; (a) *PES*, ΔCO_2, ΔOC, η_{BTES}, SF_{th}, and SF_{el} and (b) upon varying the year.

ary 1st and, after that, it rises up to about 75 °C during the summer of the 1st simulation year thanks to the solar energy injection from the STTES; then, it decreases (due to both heat losses and BTES discharging) during the heating season between the 1st and the 2nd operation years, achieving a value of about 50 °C; finally, it in again up to a maximum of about 77 °C during the summer of the 2nd simulation year; both the largest and lowest temperatures during the 3rd, 4th and 5th years are substantially similar to those achieved during the 2nd year; this means that the thermal behavior of the storage emerges as stable (not transient) after about 2 simulation years. Figure 2(a) also highlights that heat is discharged from the BTES field only during the winter, reaching a maximum of about 28 W/m; the injection rate into the BTES of thermal power is more relevant during the 1st year thanks to the lower average temperature of the BTES field; its largest value is about 96 W/m. Figure 2(b) indicates that the values of *PES*, eq. (4), ΔCO_2, eq. (5), and ΔOC, eq. (6) are always positive, achieving maximum values of 40.2% (coherent with the value found in [10]), 38.4% and 40.1%, respectively, during the 5th year; positive values of *PES*, ΔCO_2, and ΔOC mean that the proposed scheme decreases the consumption of primary energy, the equivalent emissions of CO_2 and the operating costs, respectively, in comparison to the conventional plant. The *SPB* period, eq. (9) is equal to about 20 years and comparable with the expected lifespan of the CSHCPSS. Figure 2(b) also highlights that the BTES is characterized by a suitable efficiency, eq. (1), in the range between 9.3% (1st year) and 25.9% (in the course of the last year). The values of η_{BTES} are consistent with those found in the simulation study of Zhu and Chen [44] performed under the climatic conditions of the city of Tianjin (East Coast of China), characterized by a latitude similar to Naples; they found values of η_{BTES}: between 20% and 30% in about 17% of simulation cases, and lower than 50% in about 54% of investigated plant configurations. The solar thermal fraction, eq. (2) is really significant, ranging from 89.3% (1st year) up to 94.1% (in the course of the last year), denoting that the total thermal energy requirement is almost entirely covered by solar energy; the values of SF_{th} are coherent with those reported in [2, 8, 10]. The solar electric fraction, eq. (3) is largely constant in the course of the 5 years and equal to 34.8%; this highlights that the PV panels are basically able to satisfy more than a third of the total electricity need.

Figures 3(a) and 3(b) report the values of thermal energy flows and electric energy flows, respectively, corresponding to the 5th year of functioning of the CSHCPSS as a function of the season. Figure 3(a) shows that:

- the solar energy obtained by means of the SC in the course of the cooling period is about 5.4 times bigger than that one corresponding to the heating season; with reference to the monthly values, the solar energy recovery is more relevant during July (16.1 MWh) and less significant during December (3.0 MWh),
- thermal energy charged into the BTES during the summer is about 5.0 times larger than that one charged into the BTES during the winter; with reference to the monthly values, the injection is more consistent during April (2.6 MWh) and less notable during December (0.1 MWh),
- thermal energy generated by the MB during the summer is more than 3.0 times bigger than that one of the winter,
- the seasonal coefficient of performance of the ADHP, *i.e.* the ratio between the cooling energy fulfilled by the ADHP and the heat input to the ADHP, is around 0.48; this result is coherent with the values of COP indicated by the manufacturer [15],
- thermal energy needed by the ADHP is covered only for a small portion (equal to about 3.7%) by the MB in the course of the cooling period, and
- thermal energy required for producing DHW in the course of the heating season is about 26% of the space heating load; thermal energy generated by the IB is about 25% of the total DHW demand (the remaining portion is satisfied by the energy recovered through the DHWT).

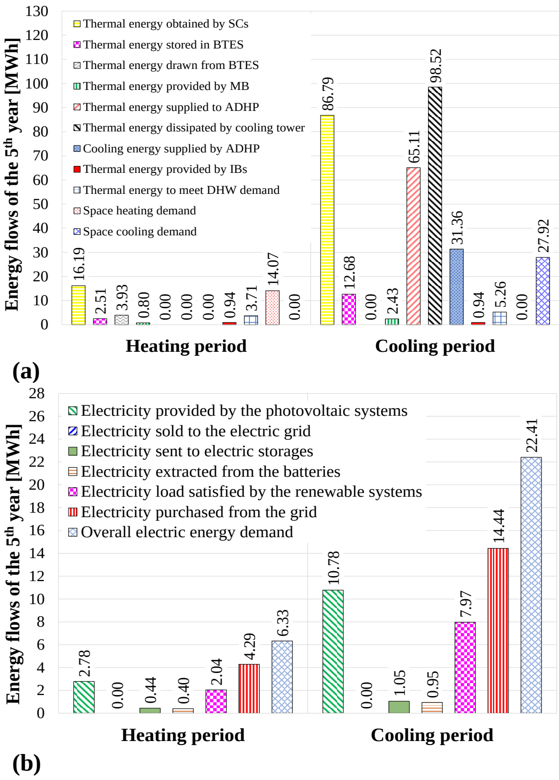
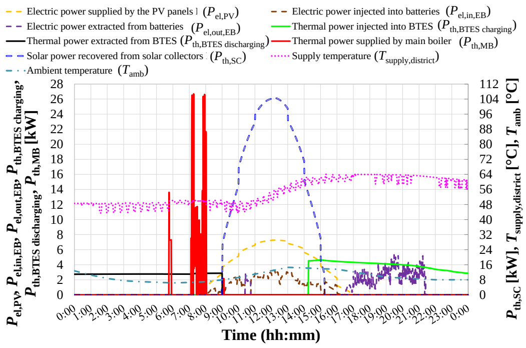


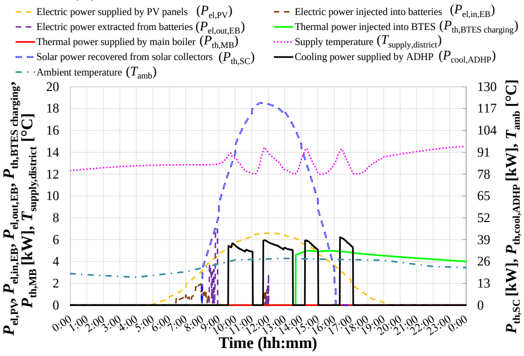
Figure 3. (a) Seasonal thermal energy flows and (b) seasonal electric energy flows of the CSHCPSS during the 5th year

Figure 3(b) highlights that:

- the electric energy generated by the PV panels during the cooling period is about 3.9 times bigger than that one corresponding to the heating season; with reference to the monthly values, the electric generation is more relevant during July (1.6 MWh) and less consistent during December (0.6 MWh),
- the percentage of the total electricity requirement satisfied by the solar energy (PV panels + batteries) is about 35.0%,
- the electric energy imported from the national grid during the cooling season is about 3.4 times bigger than that one corresponding to the heating period, and
- the percentage of electricity delivered by the PV panels and then moved into the batteries is around 16% in the course of the heating period, while it is about 10% during the cooling season.



(a)



(b)

Figure 4. Daily profiles of the most relevant energy flows for 2 selected days: (a) typical day of the heating period (February 1st), (b) typical day of the cooling period (July 1st)

The simulations indicated that, with reference to the 5th simulation year, the district is characterized by an annual cooling load density of 52.1 kWh/m^2, an annual heating load density equal to 29.0 kWh/m^2, an annual DHW load density of 17.8 kWh/m^2 as well as an electric load density corresponding to 31.4 kWh/m^2; these values denote the feasibility of the district heating and cooling infrastructure over individual plant according to the threshold values of [45].

Figures 4(a) and 4(b) report the daily profiles of the most relevant energy flows during two selected typical days (February 1st for the heating period, in fig. 4a, and July 1st for the cooling period, in fig. 4(b) of the 5th year of simulation in order to illustrate the system dynamic operation. These figures highlight that during the winter day:

– the main boiler operates in order to compensate the lack of solar energy and maintain the desired supply temperature and
– the BTES discharging occurs during the first part of the day to compensate the temperature levels in the STTES.

During the summer day the ADHP is activated in order to reach the target temperature inside the STCES supplying the fan coils of the houses. During both the selected winter and summer days:

– the BTES charging occurs during afternoon and evening thanks to the solar energy previously stored into the STTES and
– the solar energy recovered by the SC as well as the electricity produced by the PV panels increase with the time up to reaching a maximum at 12 a. m. and then reduce.

Conclusion

The comparison between a small-scale SDH and cooling system with seasonal storage operating in Naples (Italy) and a reference plant allowed to assess the following results:

- saving of primary energy up to 40.2%.
- decrease of equivalent emissions of CO_2 up to 38.4%.
- reduction of operating costs up to 40.1%.
- *SPB* period of about 20 years.
- SF_{th} up to 94.1%; (vi) SF_{el} up to 34.8%.
- η_{BTES} up to 25.9%.

The methods of analysis, design criteria, as well as potential benefits of this study could also be applied to small-scale district energy systems operating in regions other than Italy characterized by an average annual solar irradiation on horizontal surfaces similar to that one corresponding to Naples (about 314.9 W/m^2) in the case of annual heating/cooling/electric load densities comparable to those of the district analysed in this study (about 29.0/52.1/21.4 kWh/m^2, respectively).

Nomenclature

CC – capital cost [€]
E – energy [kWh]
EI – economic incentives [€]
LHV – lower heating value [kWhkg^{-1}]
m_{CO_2} – carbon dioxide emissions [kgCO$_2$]
OC – operation costs [€]
P – power [kW]
PES – primary energy saving [%]
SF – solar fraction [%]
SPB – simple pay-back period [years]
T – temperature [°C]
UC_{el} – unit cost of electricity [€kWh^{-1}]
UC_{ng} – unit cost of natural gas [€m^{-3}]

Greek symbols

Δ – percentage difference [%]
η – efficiency [%]
ρ – density [kgm^{-3}]

Subscripts

amb – outside air
BTES – borehole thermal energy storage
C – cooling circuit
cold – cold side
cool – cooling purposes
EB – electric batteries
el – electric
H – heating circuit
HE – heat exchanger
HE-DHWT – internal heat exchanger of the DHWT
hot – hot side
IB – individual boiler of the proposed system
IBCS – Individual boiler of the Conventional System
in – inlet, injected
MB – main boiler
ng – natural gas
out – outlet, exiting
p – primary
PV – photovoltaic
SC – solar collector
STCES – short-term cooling energy storage
STTES – short-term thermal energy storage
th – thermal

Superscripts

CS – conventional system
CSHCPSS – central solar heating and cooling plant including a seasonal storage

Acronyms

ADHP – adsorption heat pump
BHE – borehole heat exchanger
BTES – borehole thermal energy storage
COP – coefficient of performance
CS – conventional heating and cooling system
CSHCPSS – central solar heating and cooling plant including a seasonal storage
CT – cooling tower
DHW – domestic hot water
DHWT – domestic hot water tank
FC – fan-coil
HD – heat dissipator
HE – heat exchanger
IB – individual boiler
MB – main boiler
P – pump
PV – photovoltaic
SC – solar collector
SDH – solar district heating
STCES – short-term cooling energy storage
STTES – short-term thermal energy storage

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