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Parametric simulation analysis of a centralized solar heating system with long-term thermal energy storage serving a district of residential and school buildings in Italy

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ABSTRACT

In this paper, a solar district heating system (basically composed of a solar collectors array, a short-term thermal energy storage (STTES), a long-term borehole thermal energy storage (BTES), an auxiliary natural gas-fired boiler and a heat distribution network) has been analysed by means of dynamic simulations over a 5-year period when serving a district composed of 6 typical single-family houses and 3 typical schools under the climatic conditions of Naples (Italy). A sensitivity analysis has been carried out by simulating 27 configurations obtained by varying the solar collectors area, the volume of STTES and the volume of BTES.
The simulations results have been compared with those associated to a conventional decentralized heating system in terms of solar fraction, primary energy consumption, operating costs and simple pay-back period in order to (i) evaluate the potential benefits, (ii) explore the influence of the components size on the system performance and (iii) establish some simple rules for the initial design of the main subsystems.

1. INTRODUCTION

One of the longstanding barriers to solar energy technology lies in the noticeable misalignment between energy supply and consumption. Long-term storage allows for thermal energy storage over weeks and months, with it being a challenging key technology for solving the time-discrepancy problem of solar energy utilization.

Long-term thermal storage technology has been under exploration and inspection [1-3] since 1970. Three main heat storage mechanisms can be identified: chemical heat, latent heat and sensible heat [1-2]. Most past and present systems have stored heat in a sensible form [2]. There are four main types of sensible seasonal energy storage in operation. Based on a comprehensive literature review, Rad and Fung [4] concluded that Borehole Thermal Energy Storage (BTES) has the most favorable condition for long-term energy storage thanks to the large amounts of energy involvement and relatively low cost of storage media. In a BTES, the underground is used as the storage material; heat is charged or discharged by vertical or horizontal Borehole Heat Exchangers (BHE) which are installed into boreholes with a depth of typically 30 to 100 m below the ground surface. BHEs can be single- or double-U-pipes or concentric pipes mostly made of synthetic materials; a certain number of BHEs can be hydraulically connected in series to a row and a certain number of rows can be connected in parallel.

Compared to conventional heating plants, District Heating (DH) systems have a number of advantages: (i) they have overall better efficiencies; (ii) they provide a platform for a flexible choice of energy resources; (iii) they make it easier to have control over the maintenance and keep the efficiency on the designed condition; (iv) they improve energy supply security. However, DH plants require a significant initial investment for the infrastructure and piping system.

Several recent studies have discussed the application of seasonal thermal energy storage when integrated into district heating systems based on solar systems [1, 4-10], both on large and small scales. All these studies come to the conclusion that the so-called Central Solar Heating Plants with a Seasonal Storage (CSHPSS) can play a significant role in the implementation of future smart energy systems thanks to the fact that they have a higher efficiency and are more environmentally beneficial when compared to individual heating systems. However, in order to be able to fulfil its role, these systems must be further developed to decrease grid losses, exploit synergies, and thereby increase the overall system efficiency [11].

The above-mentioned studies reveal that very few and dated investigations on CSHPSSs have been performed under the climatic conditions of Italy [12]. In addition, it should be noted that the performance of these systems has been analyzed under climatic conditions that are very different from those of Naples (central Italy) in terms of both Heating Degree-Days as well as availability of solar energy. Moreover, it should be highlighted that the influence of solar collectors area, short-term buffer tank volume and long-term buffer tank volume on the energy and economic performance of the systems has not been investigated in the above-mentioned Italian cases study. Thus further investigations for Italian applications are required.

In this paper a central solar district heating system based on the utilization of a seasonal borehole thermal energy storage has been modelled, simulated and analysed by means of the TRaNsient SYStems (TRNSYS) software platform (version 17) [13] over a 5-year period. The system is devoted to satisfy the heating demand and domestic hot water requirements of 6 typical single-family houses and 3 typical schools under the climatic conditions of Naples (center Italy). The plant is mainly composed of a solar collectors array, a short-term buffer tank, a long-term borehole thermal energy storage, an auxiliary natural gas-fired boiler and a heat distribution network for heating purposes (domestic hot water (DHW) is produced by individual natural gas-fired boilers installed inside the single houses). A sensitivity analysis has been carried out by simulating 27 different configurations characterized by different values of the following main design ratios:

- gross solar collectors area per unit annual space heating demand;
- short-term buffer tank volume per unit annual space heating demand;
- long-term buffer tank volume per unit gross solar collectors area.

The simulation results have been analyzed in terms of solar fraction, primary energy consumption, operating costs as well as simple pay-back period according to the Italian scenario. The data have been compared with those associated to a conventional decentralized heating system (only consisting of individual natural gas-fired boilers installed inside the single houses).

2. DESCRIPTION OF THE DISTRICT

The district served by the proposed plant is composed of 6 typical Italian single-family residences and 3 typical schools located in Naples (latitude = 40° 51' 46" 80 N; longitude = 14° 16' 36" 12 E; Heating Degree-Days = 1,034; Italian climatic zone = C). Three different typologies of residential buildings (A, B and C) and three different schools (Nursery (N), Nursery School (NS) and Elementary School (ES)) have been considered. In particular, the district is composed of 2 residential buildings for each typology. Tables 1 and 2 summarize the characteristics of end-users composing the district.

Table 1. Characteristics of buildings

	Residential building typology			**School typology**		
	A	B	C	N	NS	ES
Number of buildings (-)	2	2	2	1	1	1
Floor area (m^2)	60	78	114	780	670	1340
Windows' area (m^2)	84	102	230	387	743	670
Volume (m^3)	230	370	448	2480	2203	4470
Maximum number of simultaneous occupants (-)	3	4	5	98	115	145

For each residential building typology, an annual stochastic profile (composed of 365 different daily stochastic profiles) at a one-minute time resolution has been considered for defining the number of active occupants as well as the power required for both lighting and domestic appliances as a function of the time; these annual stochastic profiles have been obtained by using the models developed by Richardson and Thomson [14]. The occupancy profile as well as the power demand for both lighting and domestic appliances have been defined for the school buildings according to the schools' timetables.

Table 2. Energy demands of buildings

	6 Residential Buildings (2A+2B+2C)	**3 Schools (N+NS+ES)**
Energy demand for heating (MWh/year)	13.54	11.11
Energy demand for DHW (MWh/year)	8.97	0
Electric energy demand (MWh/year)	14.98	12.46

In order to be compliant with the Italian legislation requirements [15], the thermal transmittance of the building envelope 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.

Several sets of yearly load profiles for the domestic hot water demand have been specified within the IEA-SHC Task 26 [16]. 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 residential building typologies A and B, while a demand profile with an average basic load of 200 l/day in the time scale of 1 min has used for residential building typology C. The DHW demand associated to the school buildings was not considered.

3. DESCRIPTION OF THE PROPOSED CSHPSS

The schematic of the proposed CSHPSS is reported in figure 1. In this figure, the following main components of the system can be identified: end-users, solar field collectors (SFC), heat dissipator (HD), short-term thermal energy storage (STTES), borehole thermal energy storage (BTES) with vertical double-U-pipes borehole heat exchangers, main natural gas-fired back-up boiler (MB), heat exchangers (HE1 and HE2), local individual boilers (B), fan-coils (FC), pumps (P), 3-way valves and pipes. In the figure, the following three main circuits are highlighted: SFC circuit, BTES circuit, heat distribution network.

The fluid flowing inside all the components is a mixture of water and ethylene glycol (40 % by volume) with a saturation temperature of 105°C at ambient pressure. The solar energy captured by the solar thermal collectors is first transferred, through a 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 another heat exchanger (HE2) into the distribution network, and then to the end-users for space heating. Every building is equipped with a group of fan-coils, supplied by the STTES.

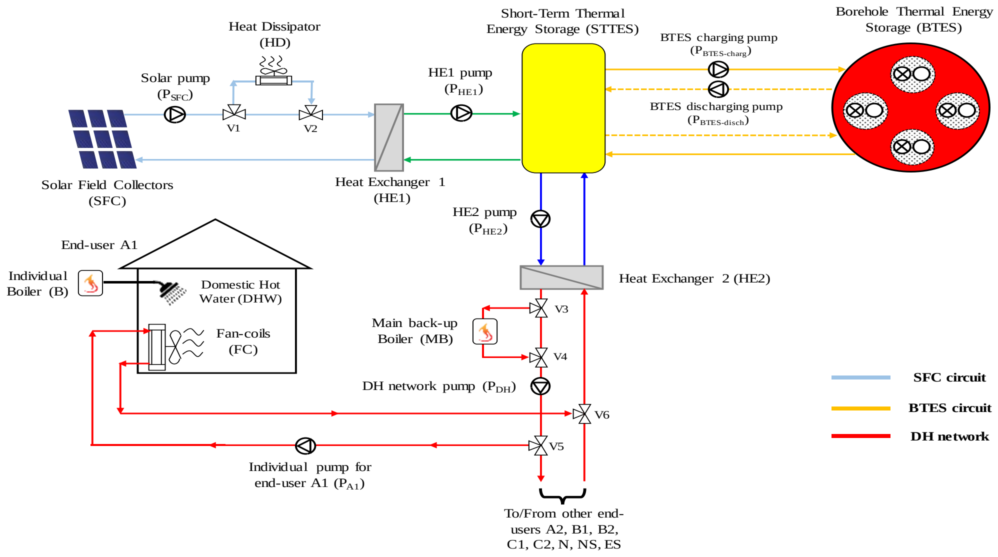


Figure 1. Schematic of the proposed central solar heating plant with seasonal thermal energy storage

Table 3. Main characteristics of the proposed CSHPSS

Solar field collectors (SFC) [17]	
Collector typology	Flat plate
Apertura area of a single collector (m^2)	2.31
Tilted angle	30°
Orientation	South
Boreholes thermal energy storage system (BTES)	
Number of boreholes	1
Borehole radius (m)	0.15
Inner radius of U-tube pipe (m)	0.01372
Outer radius of U-tube pipe (m)	0.01669
U-pipe spacing (m)	0.01752
Thermal conductivity of soil (W/mK)	1.5
Thermal conductivity of grout (W/mK)	1.3
Main back-up boiler (MB) and Individual Boiler (B)	
Fuel	Natural gas
Rated capacity (kW)	26.6
Efficiency at rated capacity (-)	0.9213
Solar pump and HE1 pump	
Nominal flow rate (kg/hm^2)	19.06
HE2 pump and Distribution pump	
Minimum nominal flow rate (kg/h)	497.7
Maximum nominal flow rate (kg/h)	18,015.7

If the solar energy is not immediately required for heating purposes, it can be moved from short-term thermal energy storage to the long-term thermal energy storage system during the whole year ("BTES charging mode"): in this case, the heat carrier fluid is taken at the top of STTES, circulated through the BTES and then re-entered at the bottom of the STTES. During the heating season, thermal energy stored in the BTES field can return into the STTES ("BTES discharging mode") to eventually supplement additional thermal energy. During the charging, 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.

A natural gas-fired boiler is used to supplement the space heating demand when the solar energy collected and stored in the short- and long-term storage systems cannot meet the energy requirements.

A natural gas-fired boiler has also been installed inside each single residential building specifically devoted to the domestic hot water production.

All the electric requirements are satisfied with the electric energy supplied by the central national grid.

In Table 3, the main characteristics of each component of the proposed CSHPSS are indicated.

3.1 Simulation models

The TRaNsient SYStems (TRNSYS) software platform [13] is one of the most popular advanced dynamic energy systems simulation programs [18,19]; in this study it has been used to model and simulate the proposed CSHPSS. Table 4 highlights the component modules (called "Types" in TRNSYS terminology) selected for this project.

Table 4. "Types" used in the TRNSYS project

Buildings	Type 56
Solar collectors	Type 1b
Heat dissipator (HD)	Type 753e
Short-Term Thermal Energy Storage (STTES)	Type 534
Borehole Thermal Energy Storage (BTES)	Type 557a
Main back-up boiler (MB)	Type 700
Heat exchangers (HE1 and HE2)	Type 5b
Individual Boilers (B)	Type 659a
Fan-coils (FC)	Type 753e
Pumps (P)	Type 656
Climatic data	Type 15
3-ways valves	Type 647
Pipes	Type 31
Controllers	Type 2

3.2 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 heat carrier fluid flows through the fan-coils only in cases when there is a call for heat triggered by a thermostat installed in each building. The room temperature is targeted to be kept at 20 °C (according to Italian Law [20]) only in the case of at least one occupant being inside the building, otherwise the indoor air temperature is not controlled. When the room temperature is lower than 19.5 °C, it calls for heat from the STTES; the call for heat signal will be disabled when the room temperature reaches 20.5 °C. When there is no heat demand, the DH network pump operates with the minimum flow rate to avoid a significant temperature drop in the district heating network.

The flow rate on the source side of the heat exchanger HE2 is set to the same value of the load side.

The solar energy recover is mainly based on the comparison between the current values of temperature at node 10 (lower part) of STTES and the temperature of the fluid exiting the solar collector field.

In more detail, 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, the temperature in the center of BTES field as well as the room target temperature (20 °C). 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.

It should be also highlighted that the set-point for the DH supply temperature is 55 °C; So the target of the main back-up boiler thermostat is fixed at 55 °C with a dead band of 5°C.

The DHW temperature is assumed to be produced at 45 °C.

4. METHODS OF ANALYSIS

Table 5. Matrix of 27 simulation cases

Simulation cases	SCA (m^2/MWh)	SSV (m^3/MWh)	SLV (m^3/m^2)
Case 1	2.27	0.22	1.8
Case 2	2.27	0.22	3.6
Case 3	2.27	0.22	7.2
Case 4	2.27	0.39	1.8
Case 5	2.27	0.39	3.6
Case 6	2.27	0.39	7.2
Case 7	2.27	0.69	1.8
Case 8	2.27	0.69	3.6
Case 9	2.27	0.69	7.2
Case 10	3.25	0.22	1.8
Case 11	3.25	0.22	3.6
Case 12	3.25	0.22	7.2
Case 13	3.25	0.39	1.8
Case 14	3.25	0.39	3.6
Case 15	3.25	0.39	7.2
Case 16	3.25	0.69	1.8
Case 17	3.25	0.69	3.6
Case 18	3.25	0.69	7.2
Case 19	4.22	0.22	1.8
Case 20	4.22	0.22	3.6
Case 21	4.22	0.22	7.2
Case 22	4.22	0.39	1.8
Case 23	4.22	0.39	3.6
Case 24	4.22	0.39	7.2
Case 25	4.22	0.69	1.8
Case 26	4.22	0.69	3.6
Case 27	4.22	0.69	7.2

Twenty-seven simulation cases, characterized by different combinations of the following design parameters, have been simulated and investigated in this paper:

- specific solar collectors area (SCA) = gross solar collectors area/annual space heating demand;
- specific short-term thermal energy storage volume (SSV) = STTES volume/annual space heating demand;
- specific long-term thermal energy storage volume (SLV) = BTES volume/ gross solar collectors area.

In particular, 3 different values of SCA (2.27, 3.25, 4.22 m^2/MWh), SSV (0.22, 0.39, 0.69 m^3/MWh) and SLV (1.8, 3.6, 7.2 m^3/m^2) have been considered. The variation ranges of SCA, SSV and SLV have been defined according to the design guidelines suggested by Pahud [21]. The other system parameters have been assumed to be the same; in this way, the impact from the configuration change alone can be evaluated.

In Table 5, the values of SCA, SSV and SLV are reported for the 27 investigated configurations. The configurations indicated in this table have been simulated over a period of 5 year with a one-minute simulation time-step by means of TRNSYS [13].

The simulation results have been analyzed and compared with those associated to a traditional Italian domestic heating system (serving the same buildings/loads) assumed as a reference in order to assess the suitability of the proposed CSHPSS.

4.1 Reference system

A typical decentralized conventional heating system has been considered to be compared with the proposed CSHPSS. In the reference system, each building is equipped only with a natural gas-fired boiler (characterized by a constant efficiency of 90 %) used for both space heating and domestic hot water production. All the electric requirements are satisfied with the electric energy supplied by the central national grid (characterized by an average power plant efficiency equal to 42 % (including transmission losses) according to the Italian scenario [22]. The reference system is compared with the proposed CSHPSS from the energy and economic points of view by adopting the approach/parameters defined in the following two sub-sections.

4.2 Energy analysis

The energy analysis has been first carried out by calculating the so-called Solar Fraction (SF) defined as the amount of thermal energy provided by the solar source divided by the total thermal energy required for heating purposes [22].

$$SF = \frac{E_{th,HE2}}{E_{th,HE2} + E_{th,MB}} \tag{1}$$

where $E_{th,HE2}$ is thermal energy supplied to the district network through HE2 and $E_{th,MB}$ is thermal energy produced by the main back-up boiler. The solar fraction ranges from zero (for no solar energy utilization) up to 1.0 (in the case of all energy provided by solar source).

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):

$$PES = \frac{\left(E_{p,TOT}^{CS} - E_{p,TOT}^{CSHPSS}\right)}{E_{p,TOT}^{CS}} \quad (2)$$

where $E_{p,TOT}^{CSHPSS}$ is the primary energy associated to the proposed system and $E_{p,TOT}^{CS}$ is the primary energy associated to the conventional system. The power plant average efficiency is assumed equal to 0.42, including transmission losses, according to the Italian scenario [22]; the efficiency of the main boiler has been calculated according to the manufacturer performance data [23] as a function of the thermal output.

4.3 Economic analysis

The economic analysis has been performed in terms of both capital and operating costs.

The capital cost of the proposed CSHPSS has been evaluated according to the following formula:

$$CC_{CSHPSS} = CC_{SFC} + CC_{STTES} + CC_{BTES} + + CC_{DH} + CC_{MB} + \sum_{1}^{6} CC_{B} \quad (3)$$

where:

- CC_{SFC} is the capital cost of the solar field collectors;
- CC_{STTES} is the capital cost of the short-term thermal energy storage;
- CC_{BTES} is the capital cost of the long-term thermal energy storage;
- CC_{DH} is the capital cost of the distribution network.
- CC_{MB} is the capital cost of the main back-up boiler;
- CC_{B} is the capital cost of a single individual boiler.

CC_{SFC} has been assumed equal to 360.00 €/m^2 according to the value suggested by Angrisani et al [24]. The capital cost associated to the distribution network has been considered equal to 10.55 €/m according to the Italian price list of public works for Naples [25]. The values of CC_{STTES} and CC_{BTES} have been evaluated by using the specific cost functions suggested by Pahud [21] based on which CC_{STTES} depends on the volume of the thermal energy storage, while CC_{BTES} is affected by the number of boreholes, the depth of boreholes, the borehole spacing, the depth of the top soil layer covering the thermal storage, the ground area as well as the length of the connection between the boreholes. CC_{MB} and CC_{B} have been assumed equal to 759.0 € according to manufacturer data [23]. The maintenance costs have been neglected in this study.

It can be noticed that 25-50 % of total capital costs comes from the solar collectors, 15-35 % form the BTES and the remaining cost (6-20 %) from STTES.

The operating costs of the proposed system have been compared with those of the conventional system by means of the following parameter:

$$\Delta OC = \frac{\left(OC^{CS} - OC^{CSHPSS}\right)}{OC^{CS}} \quad (4)$$

where OC^{CSHPSS} are the operating costs associated to the proposed system and OC^{CS} are the operating costs associated to the conventional system. The values of OC^{SHPSS} and OC^{CS} used in Eq (4) have been computed as reported in [22] and considering the lower heating value of natural gas LHV_{ng} equal to 49,599 kJ/kg [26] and the density of natural gas ρ_{ng} equal to 0.72 kg/m^3 [26].

The tariffs of both the electric energy as well as the natural gas have been kept up-to-date according to the Italian scenario [27]; in Naples it ranges from 0.466 €/Sm^3 to 0.848 €/Sm^3.

The unit cost of electric energy purchased from the Italian grid is a function of the time of the day, the day of the week and the level of cumulated electric energy consumption; in Naples it ranges from 0.121 €/kWh to 0.301 €/kWh [27].

In order to evaluate the feasibility of the proposed system, the Simple Pay-Back (SPB) period has also been evaluated according to [24]. This economic parameter represents the amount of time required to recover the extra cost of the proposed system thanks to the reduction of operating costs in comparison to the reference system. In calculating the values of SPB periods, the Italian economic incentives for promoting the use of renewable energy-based technologies associated to thermal energy production have been taken into account [22].

5. RESULTS AND DISCUSSION

The simulation results highlight that the values of SF, PES and ΔOC increase with time assuming the maximum value during the 5th year of operation, whatever the simulation case is; this is thanks to the fact that the average temperature of the long-term thermal energy storage becomes higher and higher, allowing for a more effective exploitation of solar energy. In particular, they mainly increase from the 1st to the 2nd year of operation and then become substantially constant. Therefore, their values corresponding to the 5th year of operation ($SF^{5th\text{-}year}$, $PES^{5th\text{-}year}$, $\Delta OC^{5th\text{-}year}$) can be assumed as asymptotic values.

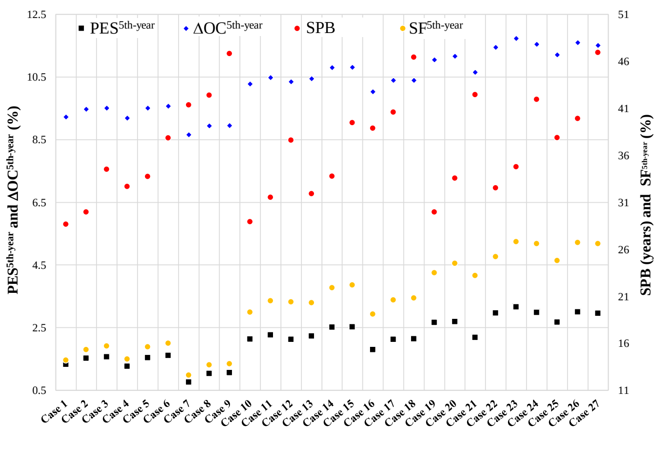


Figure 2. Simulation results in terms of $SF^{5th\text{-}year}$, $PES^{5th\text{-}year}$, $\Delta OC^{5th\text{-}year}$ and SPB

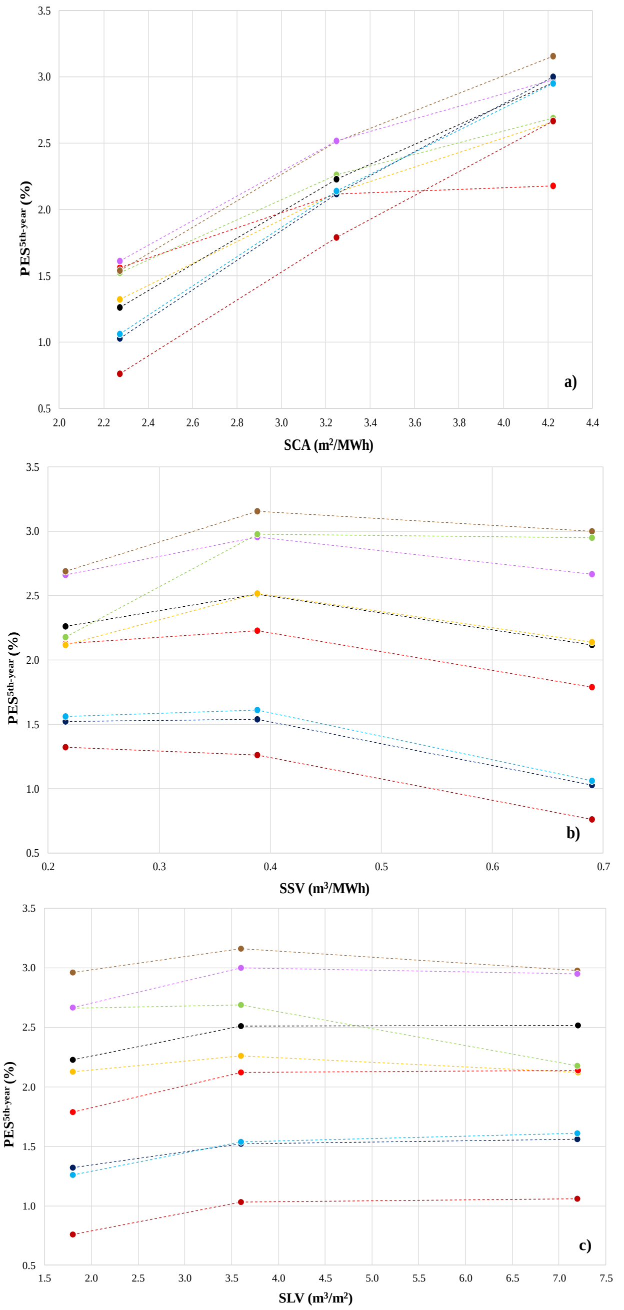
Figure 2 reports the values of $SF^{5th\text{-}year}$, $PES^{5th\text{-}year}$, $\Delta OC^{5th\text{-}year}$ referred to the 5th year of simulation and SPB period as a function of the simulation case.

This figure indicates that:

- the values of $SF^{5th\text{-}year}$ are between 12.6 % (case 7) and 26.8 % (case 23);
- the values of $PES^{5th\text{-}year}$ are always positive, whatever the simulation case is. In particular, $PES^{5th\text{-}year}$ ranges between 0.76 % (case 7) up to 3.16 % (case 23). The best case in terms of $PES^{5th\text{-}year}$ is related to the configuration with SCA=4.22 m^2/MWh, SSV=0.39 m^3/MWh, SLV=3.6

m^3/m^2;

- the values of $\Delta OC^{5th\text{-}year}$ are always positive, whatever the simulation case is. In particular, $\Delta OC^{5th\text{-}year}$ is between 8.7 % (case 7) and 11.7 % (case 23). The best case in terms of $\Delta OC^{5th\text{-}year}$ corresponds to the configuration 23 (SCA=4.22 m^2/MWh SSV=0.39 m^3/MWh, SLV=3.6 m^3/m^2);
- the values of SPB range from 28.7 and 46.9 years. The lowest value of SPB is obtained in the case 1 corresponding to the smallest solar collector area, SSTES volume as well as BTES volume (SCA=2.27 m^2/MWh, SSV=0.22 m^3/MWh, SLV=1.8 m^3/m^2). The worst SPB period (46.9 years) corresponds to the configuration 27 (SCA=4.22 m^2/MWh, SSV=0.69 m^3/MWh, SLV=7.2 m^3/m^2) characterized by the biggest solar collectors area, STTES volume as well as BTES volume (this is the reason why the simulations have been limited to the above-specified variation ranges of SCA, SSV and SLV in order to avoid larger/unacceptable values of SPB).



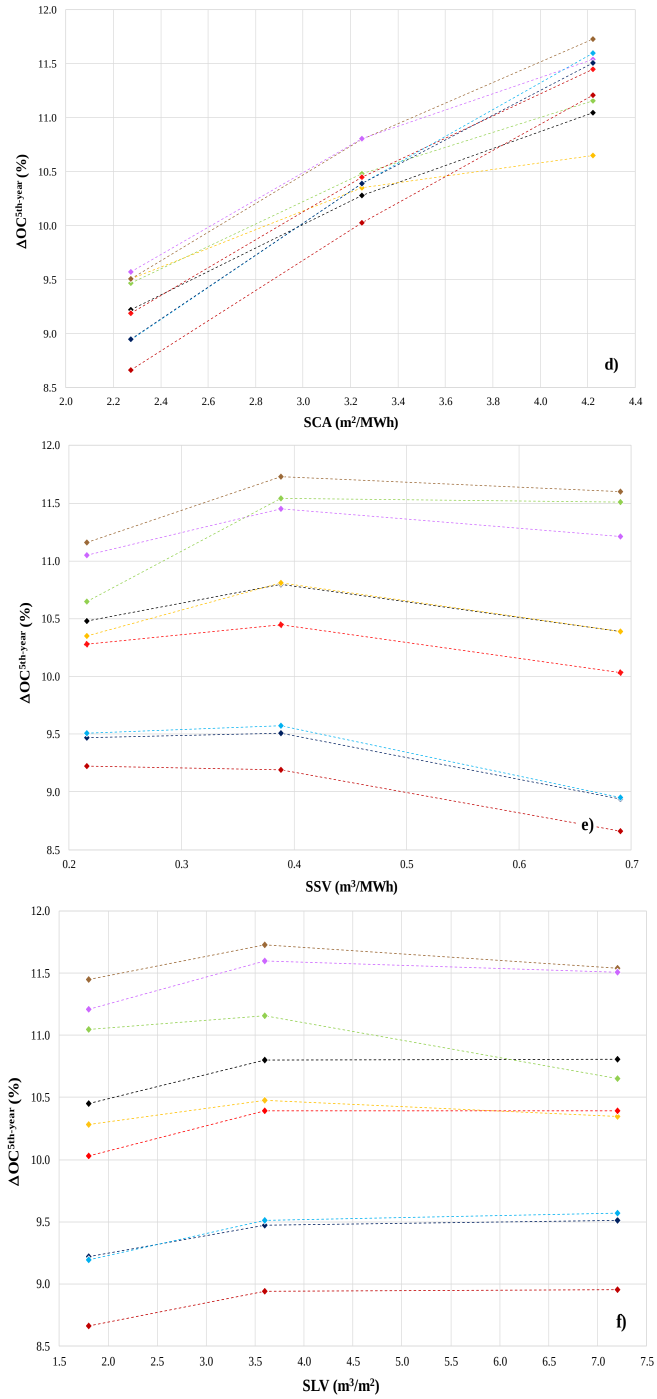


Figure 3. Values of $PES^{5th\text{-}year}$ and $\Delta OC^{5th\text{-}year}$ as a function of SCA, SSV and SLV

Figures 3a, 3b and 3c report the values of $PES^{5th\text{-}year}$ as a function of SCA (a), SSV (b) and SLV (c). In these figures the symbols/configurations with identical parameters, apart from the one varied, are connected by lines.

Within the ranges of variation of SCA, SSV and SLV investigated in this study, figures 3a, 3b and 3c show that:

- the values of $PES^{5th\text{-}year}$ increase with SCA (figure 3a); in particular, the biggest increment of $PES^{5th\text{-}year}$ upon varying SCA is around 1.9 % when SCA varies from 2.27 m^2/MWh to 4.22 m^2/MWh;
- whatever the values of SCA and SLV, $PES^{5th\text{-}year}$ decrease with SSV in the cases of SSV increases from 0.39 m^3/MWh to 0.69 m^3/MWh (Figure 3b); when SLV increases from

0.22 m^3/MWh to 0.39 m^3/MWh, the values of $PES^{5th\text{-}year}$ slightly increase or remain almost constant (Figure 3b);
- whatever the values of SCA and SSV are, $PES^{5th\text{-}year}$ increase with SLV in the cases of SLV increases from 1.8 m^3/m^2 to 3.6 m^3/m^2 (Figure 3c); when SLV increases from 3.6 m^3/m^2 to 7.2 m^3/m^2, the values of $PES^{5th\text{-}year}$ slightly decrease or remain almost constant (Figure 3c). It can be also noticed that the influence of SLV on $PES^{5th\text{-}year}$ is less relevant than that one of SCA.

Figures 3d, 3e and 3f report the values of $\Delta OC^{5th\text{-}year}$ as a function of SCA (d), SSV (e) and SLV (f).

Within the ranges of variation of SCA, SSV and SLV investigated in this study, figures 3d, 3e and 3f show that the trends are very similar to those referring the values of $PES^{5th\text{-}year}$:
- the values of $\Delta OC^{5th\text{-}year}$ increase with SCA (figure 3d), in particular, the biggest increment of $\Delta OC^{5th\text{-}year}$ upon varying SCA is around 2.5 % when SCA changes from 2.27 m^2/MWh to 4.22 m^2/MWh;
- whatever the values of SCA and SLV, $\Delta OC^{5th\text{-}year}$ decrease with SSV in the cases of SSV increases from 0.39 m^3/MWh to 0.69 m^3/MWh (Figure 3e); when SLV increases from 0.22 m^3/MWh to 0.39 m^3/MWh, the values of $\Delta OC^{5th\text{-}year}$ slightly increase or remain almost constant (Figure 3e);
- whatever the values of SCA and SSV are, $\Delta OC^{5th\text{-}year}$ increase with SLV in the cases of SLV increases from 1.8 m^3/m^2 to 3.6 m^3/m^2 (Figure 3f); when SLV increases from 3.6 m^3/m^2 to 7.2 m^3/m^2, the values of $\Delta OC^{5th\text{-}year}$ slightly decrease or remain almost constant (Figure 3f). It can be also noticed that the influence of SLV on $\Delta OC^{5th\text{-}year}$ is less relevant than that one of SCA.

6. CONCLUSIONS

In this paper a solar district heating system using a seasonal borehole thermal energy storage (BTES) has been analyzed by means of dynamic simulations over a 5-year period. The operation of the plant has been investigated while serving a small-scale district composed of 6 typical single-family houses and 3 typical schools under the climatic conditions of Naples (center Italy, Heating Degree-Days = 1,034).

A sensitivity analysis has been carried out by simulating 27 configurations obtained by varying three main design parameters: (i) solar collectors area; (ii) volume of STTES; (iii) volume of BTES.

The simulations results have been analyzed according to the Italian scenario and compared with those associated to a conventional heating system in terms of solar fraction, primary energy consumption, operating costs and simple pay-back period.

With reference to the simulated climatic/operating conditions and components size, the study revealed that the proposed CSHPSS:

(1) is potentially able to enhance the exploitation of solar energy allowing to obtain solar fraction values up to 26.8 %;

(2) allows to attain a reduction in terms of primary energy consumption (up to 3.16 %) as well as operating costs (up to 11.7 %);

(3) is characterized by a simple pay-back periods varying between 28.7 years and 46.9 years depending on the components sizes.

The influence of the solar collectors area, STTES volume as well as BTES volume on the system performance has been analyzed by highlighting that the energy results are mainly affected by the solar collectors area.

Simple rules for the initial design of the plant were established. In particular, it was deduced that the best configuration depends on the evaluation criteria (energy or economic). From an energy point of view (largest $PES^{5th\text{-}year}$), the best case is that one characterized by 4.22 m^2 of solar collectors per MWh of annual heating demand, 0.39 m^3 of STTES per MWh annual heating demand and 3.6 m^3 of BTES per m^2 of solar collectors; from an economic point of view (lowest SPB period), the best case is that one characterized by 2.27 m^2 of solar collectors per MWh of annual heating demand, 0.22 m^3 of STTES per MWh annual heating demand and 1.8 m^3 of BTES per m^2 of solar collectors.

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