A solar assisted seasonal borehole thermal energy storage system for a non-residential building in the Mediterranean area

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***Abstract*—Solar heating and cooling technologies are feasible solutions among clean energy technologies. Indeed, solar thermal devices help reduce primary energy consumption and can reduce electricity demand, thus representing one of the best options for satisfying heating and cooling energy supply. Among the various storage technologies, Borehole Thermal Energy Storage (BTES) is the most promising because the size of the storage can be easily extended by drilling additional boreholes and simply connecting the pipes to the existing boreholes; the overall energy efficiency of this system is about 40–60%. In this paper, the authors present an application of this technology for the heating system of a school building located in the Southern part of Italy. Two different seasonal storage schemes are presented: a school equipped with a low enthalpy radiant floor heating system and a school building with a high temperature heat pump system. All simulations were performed in dynamic state by using TRNSYS software. The results of the analysis assessing the energy performance of the two systems highlight the advantages and disadvantages of the different BTES applications.**

Keywords—thermal energy storage; BTES; flat solar collector; school building; heating system

I. Introduction

The building sector accounts for about 40% of the total energy use in European Union (EU) countries [1] and solar thermal energy can represent an important renewable source which can contribute to reducing the heating demand of buildings toward a net zero energy building target [2].

When solar thermal collectors are used, there is an inconstant availability of the solar energy; nevertheless, a reliable source of energy is required for the heating and/or cooling system. During the day, or even the season, there are periods in which solar energy is not needed or thermal energy production is more than the actual demand. In order to capture the thermal energy produced during such times, thermal energy storage could represent an efficient solution.

In thermal solar systems part of the incoming solar radiation can be stored as heat in the soil; in this case the utilization of heat flows and stored heat may be direct if the desired temperature is no higher than that of the storage system. The seasonal thermal energy storage systems (STES) have the possibility to offset the mismatch between solar energy availability and thermal energy demand, improving the efficiency of the heating/cooling systems of buildings [3].

The thermal energy stored could be used during the winter or during the night when the solar fraction is low; it could also balance the community energy demand versus thermal heat generation through solar collectors [4] in the case of district heating systems. Furthermore, a STES is a way to increase the thermal inertia [5] of a building-plant system, allowing the reduction of the air conditioning system size.

In the Combined Heat and Power (CHP) system, thermal energy storage could decouple thermal production from electricity production. While the CHP system generates heat and electricity simultaneously, the unwanted or surplus heat production can be stored and saved for when the thermal energy is required [6]. The first solar thermal plant was constructed in Sweden in 1978/79 [7,8]. Since 1979 several countries have participated in the construction of central solar heating plants with seasonal storage, collaborating under the International Energy Agency (IEA) Task VII. In Germany, the first seasonal heat storage system was built at the University of Stuttgart in 1985 [9]. Solar heat is collected by a large area of solar collectors and then transferred to the central heating plant. The excess heat from solar panels, in summer, is deviated to the thermal storage unit. In the heating season, the stored heat will be directed to the central plant to supply the district heating system. A detailed review of advances in seasonal thermal energy storage in Germany is described in [10,11].

It is possible to identify four types of sensible seasonal energy storage: Hot Water Thermal Energy Storage (HWTES); Aquifer Thermal Energy Storage (ATES); Gravel-Water Thermal Energy Storage (GWTES) and Borehole Thermal Energy Storage (BTES) [6]. Among the STES plants the BTES represents a promising technology. In the last 15 years, large application projects of solar assisted BTES plants, used for central solar heating in Northern European countries, have been built [12]. In BTES systems the geological formation plays a significant role in defining the thermal capacity of the storage; normally rock- or water-saturated soils are the most suitable [6,13]. In each borehole, the heat is exchanged through a double or single U-pipe or a concentric pipe. The fluid in the pipes is mostly water, sometimes mixed with ethanol or glycol to prevent freezing. The boreholes' heat transfer properties have been studied theoretically in [14] and [15], in which the authors have tested them in the laboratory [16] and in the field [17].

The storage volume of BTES compared to HWTES is much bigger in size. Depending on the soil characteristics, BTES should be three to five times larger than a HWTES [13]. Unused or rejected heat is injected into hot fluid circulation in the boreholes and transferred to the soil, where it is stored. BTES works in seasonal and periodic modes. When the stored heat is needed, cold fluid is circulated to absorb the required heat. The best and most efficient BTES is when a high thermal conductivity soil formation surrounds the boreholes and less thermal conductivity away from the storage volume with no ground water flow [18]. Soil formations with lower thermal conductivity, in fact, reduces the storage heat losses. The storage efficiency, defined here as the ratio of the annual energy injected into and extracted from the soil, ranges from 40–60% in the most BTES systems [19-21]. One of the advantages of BTES compared to other types of storage system is that the size of the storage can be easily expanded by drilling additional boreholes.

Concerning applications of BTES in the Mediterranean area, where the cooling energy demand is more prevalent and the solar energy resource is greater, generally there are no available studies. Instead, the BTES could represent an opportunity to improve the energy efficiency of Heating Ventilating and Air Conditioning (HVAC) systems of all buildings being prevalently used in winter, even in mild climates. This paper presents an application of the BTES technology for the heating system of a school building located in Palermo (Italy) and a preliminary assessment of the related energy performances.

II. Case study

The energy efficiency of buildings, particularly public buildings, is a major concern for all European governments, since they are responsible for a large part of the total energy costs of each member state. School buildings contribute significantly to these costs [22]. The application of two different seasonal storage schemes in a school building located in the city of Palermo, characterized by a Mediterranean climate with mild-wet winters and warm-hot dry summers, are investigated in this study. In winter the average temperatures range from 8 to 14°C and rarely drop to 0°C. Snowfall and fog are extremely improbable. The average temperature during the summer varies from 21 to 28°C. During a summer day the temperature can frequently rise to 33°C, and even temperatures of up to 42°C have been recorded. Average air humidity is about 70% year round [23].

Palermo is characterized by 751 Heating Degree Days (HDD) and, according to the national guidelines, is located in the B climate zone. The heating runs from 1st December to 31st March and lasts for 8 hours a day (from Monday to Friday, from 06:00 to 12:00 and from 15:00 to 17:00, not considering weekends and holidays).

A typical school building [24,25] has been considered in this study:

- heated volume of 14500 m^3;
- 600 kW conventional thermal plant;
- normalization factor for heating consumption of 13 $Wh/m^2DDyear$; which represents a sufficient thermal quality class.

An array of thermal flat solar collectors has been used to charge the BTES system and investigating two different plant layouts:

- Case A: the school is equipped with a low enthalpy radiant-floor heating system and an auxiliary heating device used to keep the fluid temperature above 35°C, whenever the temperature of the fluid returning from the BTES is below the required minimum during the winter discharge phase (Fig. 1)

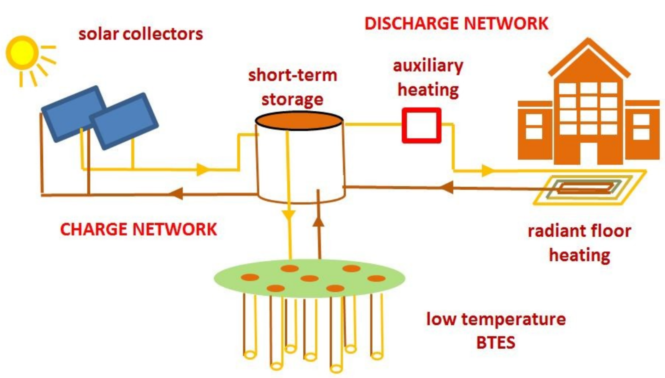

Fig. 1. Schematic representation of the CASE A: solar thermal field, BTES, high soil temperature,

- Case B: the school is heated by radiators and a high temperature heat pump is interposed between the short-term storage and heat distribution systems. (Fig. 2)

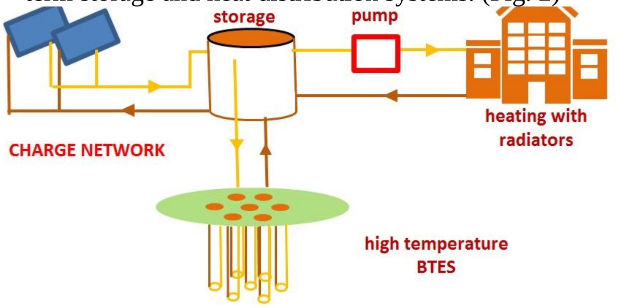

Fig. 2. Schematic representation of the CASE B: solar thermal field, BTES, low soil temperature

A short-term thermal storage unit (a water tank) acts as a hydraulic disconnector between the three elements: the solar plant, the BTES and the discharge network, in order to allow for different flow rates of the heat transfer fluid in the three hydraulic circuits. The BTES is made up of different groups of geothermal borehole exchangers connected in series. During the summer charging phase the hot water coming from the solar collectors is injected into the head borehole of each series and extracted from the more peripheral ones. During the winter discharging phase, the direction of the water flux is reversed and the cold water coming from the heating distribution system is injected into the peripheral boreholes and extracted from the central ones. Using this procedure, it is possible to generate a radial gradient of temperatures inside the soil, and reduce the thermal losses of the BTES.

III. BUILDING-PLANT SIMULATION MODEL

The heating system, as well as the thermal loads of the building, have been simulated with TRNSYS software [26] where the BTES response is modelled by the Duct Ground Heat Storage Model (DST) and the thermal resistance of the borehole is numerical estimated by a finite element model. The soil thermal properties and the climate data used for the simulations are characteristic of the urban area of Palermo. Table 1 shows the principal characteristics of the BTES.

The school building model has been modelled considering: thermal environment, orientation, climate, energy demand, water use, occupancy, and thermo-physical properties of opaque and glass envelopes [27]. Furthermore, the dynamic model of the building has been calibrated with real data set recorded during over several months of the building monitoring.

Figure 3 showed the TRNSYS model of the studied system

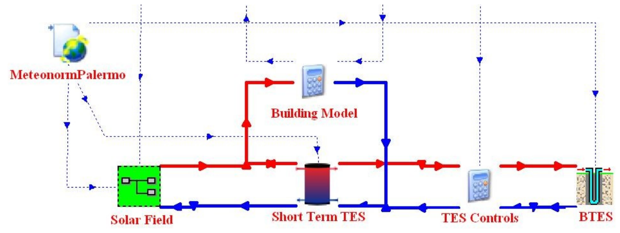

Fig. 3. TRNSYS model.

TABLE I. BTES CHARACTERISTICS

Parameter			
		unit	***Value***
Soil	Thermal conductivity	[W/mK]	1.67
	Thermal capacity	[kJ/m³K]	2723
	Inizial temperature	[°C]	18
Top insulation over the BTES	Thickness	[m]	0.20
	Thermal conductivity	[W/mK]	0.043
Borehole	Heigh	[m]	30
	Diameter	[m]	0.14
	Header depth	[m]	0.60
	Thermal resistance	[mK/W]	0.13

In both cases, the solar field is constituted by 30 flat plat solar thermal collector (HT-A 35-10 [28]) and the BTES system is realized by 45 boreholes distributed in 15 subsets, each of them constituted by 3 boreholes connected in series . In Case A the water temperature entering the building heating system is 35°C and the flow rate is 15000 kg/m^3. In Case B the water temperature flowing to the radiators is 80°C and the COP curve of the high efficiency heat pump is showed in Fig. 4.

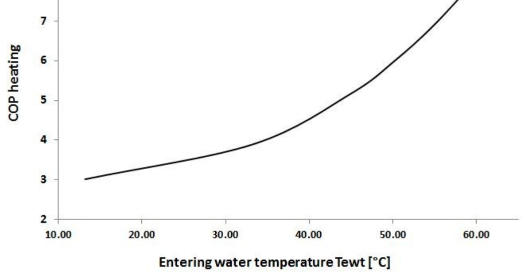

Fig. 4. Heating COP trend [29].

IV. BUILDING-PLANT SIMULATION RESULTS

A detailed parametric analysis of the two cases were carried in order to find the optimum sizes of the short thermal TES and the BTES system. In these analysis, the variables are: the "short-term" tank volume and the borehole distances. Both parameters significantly modify the behaviour of the system. The tank volume changes the temperature of the water flowing into the heating system; the borehole distance greatly influences the thermal field inside the geothermal reservoir. In the following tables (Table 2 and 3) the results of 24 simulations for both cases A and B are shown; in each table the renewable contribute to total thermal loads are reported. In the same tables the maximum values of the solar fraction is underlined.

TABLE II. SOLAR FRACTION CASE A

"Short-term" tank volume [m³]		Boreholes Distance [m]			
		2	**3**	**4**	**5**
	200	0,806	0,825	0,764	0,687
	300	0,818	0,844	0,784	0,706
	400	0,824	0,851	0,793	0,715
	500	0,825	**0,853**	0,796	0,717
	600	0,824	0,851	0,795	0,717
	700	0,823	0,849	0,793	0,714

TABLE III. SOLAR FRACTION CASE B

"Short-term" tank volume [m³]		Boreholes Distance [m]			
		2	**3**	**4**	**5**
	200	0,782	0,777	0,756	0,732
	300	0,787	0,782	0,761	0,737
	400	0,788	0,783	0,762	0,739
	500	0,789	0,782	0,763	0,740
	600	0,789	0,782	0,762	0,741
	700	**0,790**	0,782	0,762	0,741

The results show that in the first case, the best solution is characterized by a TES volume of 500 m3 and borehole distances of 3 m, corresponding to a solar fraction of 85%. In the second case, instead, the performance of the system is less dependent on the TES volume and a solar fraction of about 78% is achieved with borehole distances of 2-3 m. In Fig.5 the typical trend of the average BTES temperatures for Case A (blue curve) and Case B (red curve) are shown for the first 10 years of the operation.

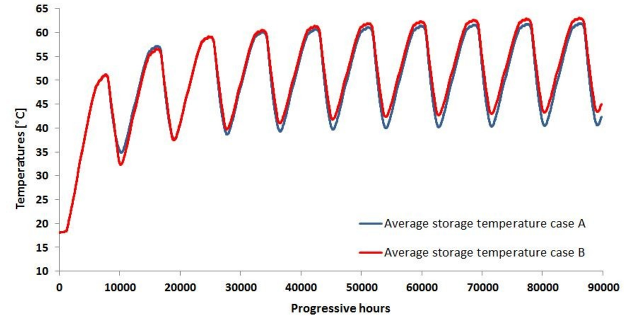

Fig. 5. BTES and short term TES temperatures variations in the first 10 years of operation.

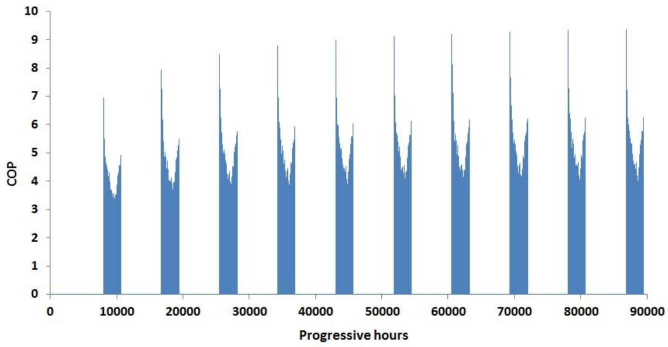

Fig. 6. Heating COP trend.

In Case B the only important parameter that affects the system efficiency becomes the average temperature of the geothermal field, closely linked to the distance of the probes: the shorter the distance among the probes the greater the temperature of geothermal field and the higher the COP of the heat pump. For these reasons, the optimization of Case B can not ignore the evaluation of the costs of short-term reservoir. It is also to underline that the minimum distance among the boreholes can not fall below a minimum value because of drilling.

V. CONCLUSIONS

The presented study examines the exploitation of solar thermal energy and the possibility of thermal accumulation in the soil. Two different concept layouts have been examined, each providing a Short Term Storage System (issuing a thermal flywheel effect) consisting of a separated water tank. The evaluation of energy performance was carried out by means of a set of TRNSYS models. The plants were located in Palermo, South Italy and the climatic peculiarities of the chosen location make the study particularly interesting for a possible application in the Mediterranean countries, characterized by high summer insolation. The implementation of the plant was coupled to a non-residential building used as school.

Preliminary results show that the application of these environmentally friendly technologies, in terms of CO_2 production and fossil fuel consumption, may be a viable option in the case of medium-large users, even in locations characterized by mild winters.

The maximum solar fraction in case A is achieved with a tank of 500 m^3 and a distance among boreholes of 3 m.. In case B, it should be noted that the solar fraction remains practically constant with the tank volume: in this case the optimization of these parameters can not disregard of economic evaluations related to the installation costs.

It also should be noted that the coupling with a high temperature heat pump allows to achieve extremely high COP. The carried out simulations confirm that the adoption of these technologies can be extremely advantageous also for buildings with intermittent load (non-residential) and located in areas where typically the peak of energy consumption is in summer.

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