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Conversion of Existing District Heating into Solar District Heating

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ABSTRACT

Solar District Heating (SDH) systems combined with Seasonal Thermal Energy Storage (STES) are one of the most interesting available strategies to decarbonize the residential sector in Europe, where most of the energy is presently provided by fossil fuels. The present work analyses both technically and economically the retrofitting of an existing district heating based on a biomass boiler into a SDH with STES, comparing two different SDH configurations: a single network, and few separated smaller networks, both serving the same actual heat demand. Dynamic modelling of both systems was carried out using TRNSYS (TRaNsient SYstem Simulation) software. The results of the simulations are then presented and discussed.

Keywords: Solar District Heating, Seasonal Thermal Energy Storage, TRNSYS, buildings, Parabolic Trough Collectors

NOMENCLATURE

Abbreviations	
DHN	District Heating Network
DNI	Direct Normal Irradiance
PTC	Parabolic Trough Collector
SDH	Solar District Heating
STES	Seasonal Thermal Energy Storage
RES	Renewable Energy Sources
SF	Solar Fraction

1. INTRODUCTION

The energy consumption of residential and service sector buildings has significantly increased in past decades [1]. In the European Union (EU) in particular, all buildings are responsible for around 40% of total consumption [2], and the residential sector for 26% [3]. The vast majority (78%) is used for space heating and domestic hot water [3]. In 2019, most energy for heating and cooling was produced from fossil fuels (75% of the total), while renewable sources only provided 22%. In order to reduce fossil fuel consumption and greenhouse gas emissions in the residential sector, the EU is pursuing several strategies, notably: more extensive use of photovoltaic panels and solar thermal collectors by households [4], the electrification of heating through the use of highly-efficient heat pumps [2], the renovation of existing energy-inefficient buildings [2] and the implementation of district heating networks fed by waste heat and renewable sources [5]. Solar thermal collectors, in particular, are very interesting, as most household energy is needed for heating. These systems are characterized by their scalability, ranging from small installations for single-family houses to large-scale plants. Large-scale applications, covering thousands of square meters, can satisfy the thermal needs of an entire small town or urban quarter, via a district heating network. In recent years, several of these solar district heating (SDH) systems have been implemented in the EU [6-10]. Nevertheless, the impact of solar thermal technologies remains limited: for instance, in 2019, in Italy they met only 0.4% of heating and cooling demand [11]. Solar district heating systems are in general realized in association with seasonal thermal energy storage (STES); STES allows storing the excess of heat produced by solar thermal collectors during spring and summer when the thermal needs are low, and to deliver it during winter when the heat demand is high. SDH combined with STES is one of the most interesting available strategies to decarbonize the residential sector [6]. The introduction of solar technologies in existing district heating could be extremely interesting for Italy since many Italian cities already have district heating nets that are 75% fed by fossil fuels [12] and the solar resource is

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higher than in northern Europe. In general, to be cost effective, the implementation of solar technologies inside existing district heating aims to cover a large amount of heat requested (at least 40%). However, not always this hybridization is feasible.

The present paper presents the analysis of retrofitting an existing and running district heating network fed by a biomass boiler, into a Solar District heating with Seasonal Thermal Energy Storage. Two different SDH concepts are analysed. The first one is represented by the traditional configuration, i.e. a district heating net that delivers to all the households the heat produced by the unique solar field, which is placed in a unique area. Close to the solar field, a large seasonal storage is installed. The configuration with few separated smaller solar district heating nets, each of them characterized by its own solar field and seasonal storage represents the second concept. This solution can allow using piping of lower dimension therefore reducing piping heat losses. On the other hand, the amount of STES heat losses is expected to increase.

The goal of the present paper is to compare these two concepts from an energy point of view and to discuss the feasibility of the hybridization for a third generation district heating (supply temperature above 80°C).

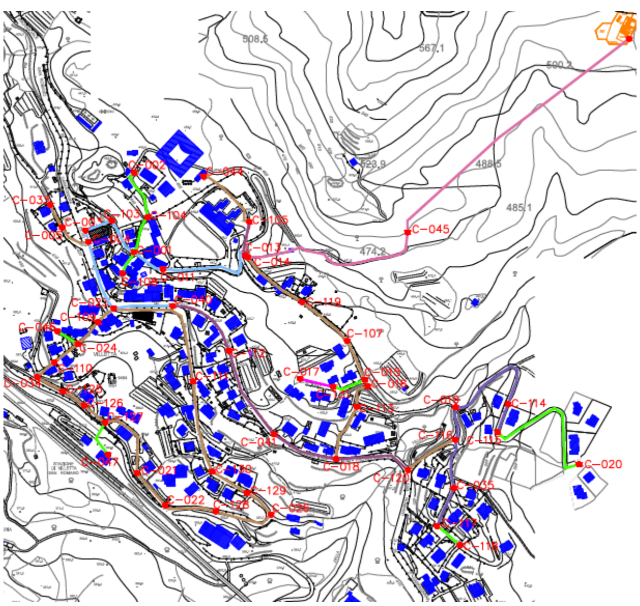

Fig 1 District heating network

2. DEFINITION OF THE CASE STUDY

The District Heating Network (DHN) studied is in a small town in the Garfagnana area in Tuscany, Italy (DNI=1400 kWh/m^2/year). The supplied buildings are 115, with a total plant area of 24806 m^2. Figure 1 shows a schematic aerial view of the existing district heating network.

Diameter $[mm]$	Length $[m]$
200	800
150	385
100	963
80	3271
65	731
50	1048
40	92

Tab 1 Nominal diameter and length of the Villetta DHN pipes

Currently, the district heating network is fed by a boiler with a storage that acts as a "buffer", to compensate the transients in demand. The thermal power plant is installed 1 km far away from the town. Table 1 shows the diameter of the insulated pipes that make up the network and the overall length for each type.

The DH is a third generation district heating with a supply temperature of 85°C/70°C (winter/summer) and return temperature of 70°C/50°C. Table 2 summarizes the main parameters of the network derived from the final design and measured data in past years.

Network length [m]	7290
Users plant area [m^2]	24806
Users Heat Demand [MWh/y]	3421
Space heating period demand [MWh/y]	2964
Pipe losses [MWH/y]	1060
Network mass flow [kg/h]	34000
Flow temperature [°C] (Winter / summer)	85 ÷ 70
Return temperature [°C] (Winter / summer)	70 ÷ 50

Tab 2 Main data of the district heating network

About a quarter of the heat produced by the boiler is dissipated in the pipes. Indeed, during the summer months more than half of the heat is lost, due to the low demand and the high supply temperature, equal to $T_{supply} = 70°C$. The input terminals for the utilities are radiators, which work with a $T_{in} = 70°C$ and $T_{out} = 50°C$. During summer, when the space heating is turned off, temperature drops to $T_{in} = 45°C$ and $T_{out} = 15°C$. The solar systems used to integrate RES in the plant are parabolic trough made by Solitem, with the technical characteristics available in [13].

3. DINAMIC MODEL

The software used for the dynamic modelling of the district heating network is TRNSYS (TRaNsient SYstem Simulation), which allows describing complex dynamic systems of different nature. Two models have been realized (figure 2). The first one describes the district heating network and it is used to calculate the pipe losses of the system. The second one describes the heating plant with the integration of concentrating collectors and seasonal storage.

Piping losses are calculated in TRNSYS taking into account the temperature variation of the fluid along the circuit, the heat flow in radial and circumferential direction and the thermal accumulation of the ground. The model of the heating plant is composed by three different circuits: the solar loop, the storage loop and the user loop. The pressurized water in the Parabolic Trough Collectors (PTCs) circuit flows if the radiation is greater than a threshold of 250 W/m^2 (otherwise the plant is switched off). The water inside the storage tank is limited to a temperature of 95°C, instead, since it is not pressurized. That component is connected with the district heating directly and with the solar field through a heat exchanger. In general, the return flow from the district network is heated by the circulation inside the STES. In case the level of temperature is not suitable to satisfy the demand, the biomass boiler integrates the thermal energy necessary to maintain the flow temperature at the desired value at the district network input.

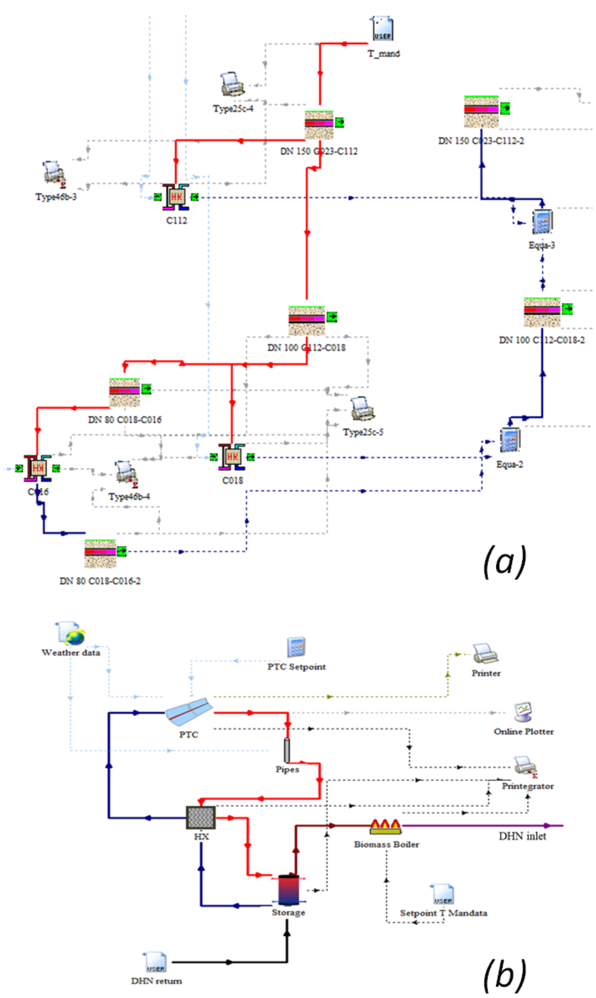

Fig 2 (a) model of the DH. (b) model of the heating plant

4. SDH WITH CENTRALISED STES

The centralized STES and its solar field would be realized close to the thermal heating plant, 1 km away from the town. At first, the goal of the hybridization of the district heating with the solar technologies aimed at a solar fraction (SF) close to 40% (i.e. the ratio between the useful thermal energy supplied by the solar field and the heat demand), in order to reduce the use of biomass. Several simulations were carried out to perform a parametric analysis, varying the area of the solar field (A_{total}) and the volume of the storage ($V_{storage}$). The target was reached with:

$$A_{total} = 3555\ m^2;\ V_{storage} = 28500\ m^3$$

obtaining the following results:

$$Q_{solar} = 1927\ \frac{MWh}{y} \Longrightarrow \mathrm{SF} = \frac{Q_{solar}}{Q_{DHN}} = \frac{1927}{4481} = 43\%$$

Figure 3 shows the main energy variables of interest during the year: from May to September, the solar field

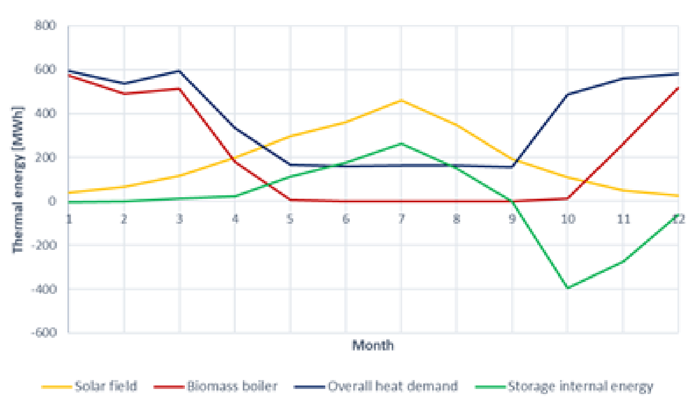

Fig 3 Monthly trend of the main plant parameters

(yellow line) produces more energy than required (blue line); the surplus of energy is transferred to the STES (green line) by increasing its internal energy. Therefore, the boiler can be switched off. From October to December, storage releases the stored heat (negative here for convention), contributing to satisfy the thermal demand, with a decrease in the use of the biomass boiler.

However, the capacity of STES is only partially exploited because of the high return temperature from the network. In fact, the STES temperature range is limited between 60°C and 90°C, strongly reducing its capacity and the solar fraction of the heating plant.

5. DECENTRALISED SOLUTIONS

A second hypothesis of solution consists in dividing the current network into 5 smaller energy districts as presented in Figure 4. Five solar district heating have been designed; the diameter for the pipes have been calculated for each distribution system.

The main boundary conditions are the same of the previous case (Total heated area: $24806\ m^2$, $T_{supply} = 85°C \div 70°C$; $T_{return} = 70°C \div 50°C$. Table 3 reports the heated area and DH length for each district heating.

Piping heat losses have been calculated for each district adapting the model in TRNSYS. The global grid flowrate was split considering the useful area of the building involved in the specific zone as a weight.

Then, another parametric analysis has been conducted to properly size the STES and the solar field for each district keeping the goal of solar fraction equal to 40%; the results are shown in table 4.

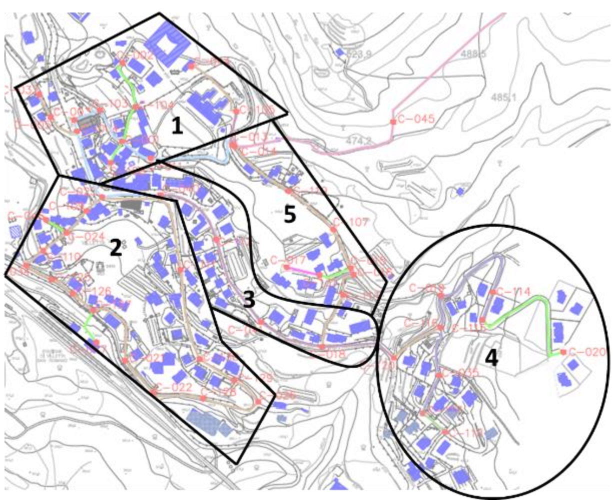

Fig 4 The partition into 5 district heating

For what concerns the heat piping losses, in the decentralized layout, they decreased by 418 MWh/y, about 40% less compared to the centralized one. The reason is related to the smaller diameter used for piping. Furthermore, the heat loss in the centralized system network accounts for 24% of the global heat demand, while, for example in zone 1, the heat losses weight for 11%.

As can be seen from table 4, the necessary storage volume and the total surface area of the solar field are quite the same amount in order to reach around 40% of solar fraction. In the decentralized case, the STES heat losses are higher as expected compared to the centralized case due to the bigger surface area of the storage. However, for the centralized case, the volume of the storage (higher than 25000 m^3) is very large. Assuming the cylindrical shape (with the diameter equal to height to minimize the surface), both dimensions arise more than 31 m, which means the storage is actually unfeasible from an executive point of view. However, it is also difficult to build the storages of the decentralized solution due to the limitation in space inside the urban contest, even if they are much lower compared to the centralized one (diameter and height of 19 m in the average case). In any case the total volume requested for the thermal storage in both the two cases is strongly oversized because of the non-optimal boundary conditions of the network. In particular, the high supply temperature (imposed by the radiators as final utilities) and consequently the high return temperature in the network plays a key role in the overall behaviour of the entire system. The thermal capacity of the STES is indeed strongly limited fixing the operative temperature between 50 and 95°C. Thus, both solutions are not interesting from an energy point of view.

	$Heated\ area\ [m^2]$	$DH\ length\ [m]$
Zone 1	5510	1082
Zone 2	5731	2300
Zone 3	4335	898
Zone 4	7440	1420
Zone 5	1790	790
Total	24806	6490

Tab 3 Local district heating networks

6. ECONOMIC ANALYSIS

An economic analysis has been developed to compare the different investments. Assuming that the cost for the solar field is 500 €/m^2 (balance of plant included) and the cost for STES goes from 100 to 230€/m^3 depending on the volume of the single STES [14]. The capex expenditure is respectively 3.9M€ for the centralized case and 4.4 M€ for the decentralized case.

discharging the STES and maximising its capacity, should be considered to make the implementation of solar based technology solutions profitable from both an energy and economic point of view.

Decentralized solar district heating							
	Storage Volume $[m^3]$	Solar field [m^2]	Heat demand $[MWh/y]$	Piping heat loss $[MWh/y]$	STES heat loss $[MWh/y]$	Heat to users from STES $[MWh/y]$	Solar fraction [%]
Zone 1	6900	751	845	99	126	345.9	37
Zone 2	5200	733	706	219	104	362	39
Zone 3	4000	495	526	79	88	214	35
Zone 4	9200	1008	1098	158	152	480	38
Zone 5	1700	275	247	86	50	124	37
Total	27000	3261	3421	642	521	1527	37
Centralised							
Zone	28500	3555	3421	1060	316.4	1927	43
	Storage Volume $[m^3]$	Solar field [m^2]	Heat demand $[MWh/y]$	Piping heat loss $[MWh/y]$	STES heat loss $[MWh/y]$	Heat to users from STES $[MWh/y]$	Solar fraction [%]

Tab 4 Results of the simulations for decentralized and centralized DH

The costs are higher for the decentralized case due to the higher cost for the storages (3.6 M€, 1.3 M€ higher than the centralized one).

Considering the annual cash flow, an interest rate of 2.5%, O&M costs (1% of the realization cost) and also the presently available incentives, the payback time for the two cases is higher than 20 years which is in general the lifetime of the heating plant.

7. CONCLUSIONS

Solar district heating is a key strategy to decarbonize the residential sector. District heating networks, fed by fossil fuels, are widespread in Italy; thus, the introduction of solar technologies in existing plants can be evaluated. This paper, which reports an energetic and economic comparison between two different solutions of district heating (centralized case versus decentralized one), clearly shows that it is not always profitable from both the energy and economic point of view the conversion of existing third generation DH into a solar district heating. Boundary conditions (for instance the supply and return temperature of the network) play a crucial role to determine if the retrofitting is meaningful. Some mandatory actions such as the substitution of users heating system in a low temperature systems (such as fancoil or radiant heating) or the use of a heat pump

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