A multi-objective optimization analysis to assess the potential economic and environmental benefits of distributed storage in district heating networks: a case study

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A multi-objective optimization analysis to assess the potential economic and environmental benefits of distributed storage in district heating networks: a case study

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ABSTRACT

Conventionally, District Heating (DH) networks have been developed with a centralized logic, with large generation units designed to provide space heating to distributed users. Some networks have already evolved to a stage in which multiple generation units are distributed throughout the network and are supplying heat from different sources and with different schedules. ICT technologies can be the basis for a live optimization of the network, which can be implemented by minimizing energy supply cost for the users or minimizing greenhouse gases emissions.

This paper proposes an optimization analysis of the energy generation in a real distributed energy system (DES) coupled to a District Heating (DH) in Turin by maximizing the DES operator profit and minimizing greenhouse gases emissions. The results show the limited effect of the demand profile variation in comparison with the potential benefits of optimization strategies against the current operation of the case study under analysis, the main reason being the good flexibility of the available heat generation units. Thus, the installation of distributed storage units should be preferred in DH networks characterized by a large share of non-flexible generation options, such as solar energy or waste heat from industries, or where the energy prices show large variations over the day.

Keywords:

District Heating Networks;
Renewable Energy Sources;
Distributed Generation;
Energy Storage;
Sector Coupling;

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1. Introduction

In recent years, the energy policies have focused on the improvement of energy efficiency, reduction of carbon emissions and reliability of the energy supply. In this context, District Heating (DH) can contribute significantly to use more efficiently the energy sources and at the same time to integrate renewable energy in the heating sector. DH is a technology that has evolved considerably over the last years, as demonstrated by analysis on Low Temperature District Heating [1,2] and on the role of the 4th generation DH in the future smart energy systems [3]. In addition, the centralized logic of DH, characterized by large generation units designed to provide space heating to distributed users, is giving the floor to new thermal grids in which multiple generation units are distributed throughout the network. These multiple units are called Distributed Energy Systems (DESs) and they have been recognized to have a key role

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Abbreviations

CHP	Combined heat and power
DA	Day-ahead market
DES	Distributed Energy System
DH	District Heating
DHN	District heating network
ICT	Information and Communication Technologies
MOLP	Multi-Objective Linear programming
ToU	Time of Use
WC	White certificates

Nomenclature

c	Constant in Eq. (12) (kWh/€)
CI_{gas}	Carbon intensity of natural gas ($kgCO_2/Nm^3$)
CI_{grid}	Carbon intensity of power grid ($kgCO_2/kWh$)
DR	Maximum ramp-down rate (kW)
F	Objective function of the multi-objective optimization problem
F^C	Cost function (€)
$F_{CO_2}^{Avoid}$	Avoided CO_2 emissions ($kgCO_2$)
$F_{CO_2}^{Oper}$	CO_2 emissions related to the DES operation ($kgCO_2$)
F^R	Revenue function (€)
G	Natural gas volumetric flow rate (Nm^3/h)
H	Heat rate (kW)
K	Coefficient in Eq. (12)
LHV_{gas}	Lower heat value of natural gas (kWh/Nm^3)
$NetCO_2$	Net CO_2 emissions ($kgCO_2$)
P	Electric power (kW)
$Prof$	Total operator's profit (€)
UR	Maximum ramp-up rate (kW)
x	Binary decision variable

Greek symbols

Δ_t	Length of the time interval (h)
η	Efficiency
Π	Energy price (€/kWh) - (€/Nm^3)
Π_{WC}	White certificate price (€/WC)
ω	Weight in Eq. (17)

Superscript/subscripts

CHP	Combined heat and power
d	Index of day
DA	Day-ahead market
dem	Demand
DHN	District heating network
e	Electric
energy	Energy
gas	Natural gas
grid	Power grid
heat	heat
i	Index of technology
max	Maximum
min	Minimum
ref	reference
Self	Self-consumption
Sold	Sold
t	Index of time
th	Thermal
u	Index of user
users	Final users
WC	White certificates

in the future energy system [4]. Consequently, a new network configuration with multiple energy sources from decentralized locations allow considering new operation logics such as demand side management, that is well explained by Cai et al. [5], and that actually include also a new actor of the energy market: the "prosumer" defined as a unit/member, which both consumes and produces energy. Initially, the concept of prosumer was strictly related to power grids but the role of thermal prosumers in DH is enhancing thanks to the integration of DES in the heating network.

DES are usually characterized by small-size technologies providing electrical and thermal energy close to end-users [6]. The benefits of DES are multiple: economic in view of their potentiality to reduce energy costs; environmental on account of their possibility to integrate several energy resources, including renewables, and to maximize the energy efficiency of the entire system in view of the reduction of network losses thanks to production of energy close to end-user, or avoiding the waste of energy due to distributed energy storages. [7–9]. On the other hand, in order to better exploit these benefits, an optimized daily operation management is fundamental, and it has to take into account several challenges concerning with the unbalance among supply and demand sides. This unbalance is given by the typical instantaneous variation of user energy demand, and the limited operation flexibility of certain technologies within the system to deal with the fluctuation in energy demand [10–12]. The integration of energy storage systems is a key aspect in supporting the demand and supply matching in DES [13].

In the literature there are several works focusing on the operation optimization of DES through formulating mixed-integer optimization models for scheduling multiple energy devices with the aim to minimize the daily energy cost [14–23] . However, the economic benefits are valid for the short run and they cannot be pursued without considering the environmental problems, such as reducing CO_2 emissions, in order to guarantee the sustainability of energy supply in the long term. On account of that, Alarcon et al. [24] show that global warming and environmental problems are essential drivers in the decision-making process for DES integration. As a result both economic and environmental aspects have to be considered for the DES effective integration, but it is challenging since the economic and environmental objectives can be conflicting [11]. The multi-objective approach has been widely investigated in the context of DES [25–27]. With specific reference to the DES operation optimization, a multi-objective optimization model was proposed in [10] with the aim to achieve the optimal operation strategies of a DES by considering minimization of energy costs and environmental impacts in terms of CO_2 emissions, and the Pareto frontier was found by using the compromise programming method. A stochastic multi-objective optimization model was developed in [12] to find the optimal operation strategies of a DES on the Pareto frontier, by taking into account both energy costs and CO_2 emissions. The Pareto frontier was found through the weighted-sum method, and the problem was solved by using branch-and-cut. A mixed-integer model was proposed in [28] for the optimal scheduling of distributed energy resources supplying energy to a building cluster while considering both economic and environmental aspects, and the multi-objective optimization problem was solved by using the surrogate Lagrangian relaxation method.

The main benefit of using a multi-objective approach consists of finding trade-off solutions for the diverse stakeholders participating in DES management. In such a context, the objectives can be formulated from different perspectives, e.g., the DES operator who is interested in maximizing his profit, and the civil society, which is interested in minimizing the environmental impact. These two objectives can be conflicting, and there is no one single solution that can satisfy all the stakeholders. Moreover, from a high-level perspective, a multi-objective approach in this context can provide essential information on the benefits and impacts related to DES deployment, by also fostering incentives and polices to encourage DES local integration and facilitating collective decisions.

The aim of this work is to study the effects on an existing DH network when distributed heat storage systems are installed. DH users usually show a "standard" heat load profile, leading to a standard aggregated profile for the network. Due to the progressive upgrade from consumers to prosumers, thanks to the introduction of distributed storage or generation capacity, the demand profile is potentially changing, thus leading to a different aggregated load profile. The present article evaluates the consequences due to that changing considering both economic and environmental optimization strategies thanks to the use of the multi-objective optimization model described in Paragraph 2.2 – Optimization Model. It allows finding the optimal operation strategies of the DES, which maximize the DES operator's profit while also reducing the CO_2 emissions, thanks to identification of different trade-off points on the Pareto front. The extreme points of Pareto front have been obtained under the economic optimization for one side and the environmental optimization for the other side, while all the internal points, corresponding to the trade-off points between economic and environmental objectives, have been obtained by subdividing the weight interval into 100 equally-spaced points. As a result, several operation solutions to the DES operator are offered according to his economic/environmental priority. A sensitivity analysis has been also performed to evaluate the effects of the variation of key factors such as day-ahead (DA) market price and the natural gas price on the optimized operation of the DES.

2. Methodology

This section firstly describes the problem and defines the system layout; furthermore, the optimization model is explained focusing on problem constraints and objective functions. Finally, the real case study for the application of the model is presented illustrating technical characteristics of the technologies and heat load profiles.

2.1. Problem description

The main research question of this work is to evaluate the economic and environmental effects of different operation logics of distributed storage systems and of the generation units, to meet the optimized the supply-demand matching.

In this paper different configurations are compared, by analysing the economic incomes for the DES operator, which is generally the main driver in real applications, and the calculated CO_2 emissions of the system, which are used to estimate the environmental impact of the DES. A simplified layout of the system is reported in Figure 1.

The current operation of the DES is compared to an economic optimization (maximizing the DES operator profit) and to an environmental optimization (minimizing the CO_2 emissions). These three strategies are evaluated in the system without heat storage and in two additional heat storage operation logics that will be explained in detail in the following sections.

2.2. Optimization model

The optimization model allows identifying the optimal operation strategies of the DES by considering both economic and environmental aspects. The aim is to maximize the DES operator's profit, while also minimizing the net CO_2 emissions in the hourly operation schedule of the DES on annual basis. The optimization problem is formulated as a multi-objective linear programming problem (MOLP), which is solved through the weighted-sum method by using branch-and-cut.

In the following, the operation constraints related to the energy technologies in the DES and the DHN, as well as the energy balances constraints are defined. Then, the objective functions and the optimization method are described.

2.2.1. Problem constraints

For all the technologies present in the DES, the common constraint is the capacity constraint, formulated below for the CHP:

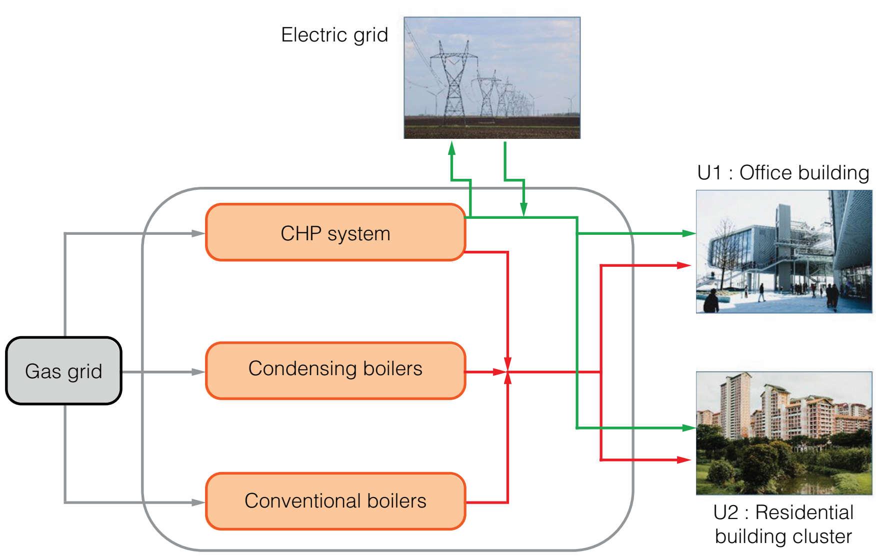

Figure 1: Layout of the DH generation plant and network

$$P_{CHP}^{min} x_{CHP,t,d} \leq P_{CHP,t,d} \leq P_{CHP}^{max} x_{CHP,t,d} \ \forall t, d \quad (1)$$

In this constraint, the power provided by the CHP at time t in day d (a continuous decision variable) is bounded by the minimum rated power and maximum power, if the CHP is on (the binary decision variable is equal to 1, $x_{CHP,t,d} = 1$).

The total power provided by the CHP consists of the sum of power provided for self-consumption and power sold back to the grid:

$$P_{CHP,t,d} = P_{CHP,t,d}^{self} + P_{CHP,t,d}^{Sold} \ \forall t, d \quad (2)$$

Moreover, for the CHP, the ramp-rate constraint is also included. This constraint allows limiting the variation in power generation between two successive time-steps within the ramp-down and ramp-up limits:

$$DR_{CHP} \leq P_{CHP,t,d} - P_{CHP,t\text{-}1,d} \leq UR_{CHP} \ \forall t, d \quad (3)$$

The amount of natural gas consumed by the CHP is formulated as:

$$G_{CHP,t,d} = P_{CHP,t,d} / (\eta_{CHP,e} LHV_{gas}), \forall t, d \quad (4)$$

where $\eta_{CHP,e}$ is the electrical efficiency of the CHP and LHV_{gas} is the lower heat value of natural gas. The heat rate recovered by the CHP is formulated as:

$$H_{CHP,t,d} = P_{CHP,t,d} \eta_{CHP,th} / \eta_{CHP,e}, \forall t, d \quad (5)$$

where $\eta_{CHP,th}$ is the thermal efficiency of the CHP.

As for the condensing and conventional boilers, the amount of gas consumed by them can be formulated similarly to Eq. (4), by considering the thermal efficiency values of the different types of boilers.

The operation constraint related to the DHN limits the heat rate transported by the DHN by considering the maximum heat rate allowable for the DHN to satisfy the DH users (user 2) load [29]:

$$H_{i,u2,t,d} \leq H_{DHN}^{max} \forall t, d, i \in \{CHP, ConvBoil1, ConvBoil2, CondBoil\} \quad (6)$$

Energy balances allow to satisfy the users electrical and thermal demand. The electricity balance for the office building (user 1) is formulated as:

$$P_{u1,t,d} = P_{CHP,t,d}^{Self} + P_{Grid,t,d}, \forall t, d \quad (7)$$

The thermal energy balance is formulated as:

$$H_{u,t,d} = \sum_i H_{i,u,t,d}, \forall u, \forall t, d, i \in \begin{Bmatrix} CHP, ConvBoil1, \\ ConvBoil2, CondBoil \end{Bmatrix} \quad (8)$$

2.2.2. Objective functions and multi-objective optimization method

The economic objective is formulated as the annual DES operator profit to maximize. It is related to the total revenue for selling power from CHP back to the grid, for selling thermal energy to the DH users and for getting white certificates (WC) derived by the related Italian incentive scheme (for CHPs with a size lower or equal to 1 MWe and a primary energy saving higher than 0, the incentive scheme is based on white certificates (WC), each certificate attests the saving of a TOE and has an economic value), and to the total energy cost for buying grid power as well as gas for the boilers:

$$Prof = F_{Sell,grid}^{R} + F_{Sell,users}^{R} + F_{WC}^{R} - F_{Energy}^{C} \quad (9)$$

where the various functions for revenues and costs are formulated below:

$$F_{Sell,grid}^{R} = \sum_d \sum_t (P_{CHP,t,d}^{Sold} \Pi_{t,d}^{DA}) \Delta t \quad (10)$$

$$F_{Sell,users}^{R} = \sum_d \sum_t (H_{u3,t,d} \Pi_{Heat}^{Dem}) \Delta t \quad (11)$$

$$F_{WC}^{R} = \sum_d \sum_t (WC \, \Pi_{WC}) \Delta t, with WC = \sum_d \sum_t (P_{CHP,t,d} / \eta_{ref,e} + H_{CHP,t,d} / (\eta_{ref,th} - G_{CHP,t,d} LHV_{gas}) CK \quad (12)$$

$$F_{Energy}^{C} = \sum_d \sum_t (P_{Grid,t,d} \Pi_{t,d}^{Grid} + G_{i,t,d} \Pi^{Gas}) \Delta t, \ i \in \{CHP, ConvBoil1, ConvBoil2, CondBoil\} \quad (13)$$

The environmental objective is formulated as the annual net CO_2 emissions to minimize, consisting of the emissions related to grid power and gas consumption and the avoided emissions related to power sold back to the grid [25]:

$$NetCo_2 = F_{Co_2}^{Oper} - F_{CO_2}^{Avoid} \quad (14)$$

where:

$$F_{CO_2}^{Oper} = \sum_d \sum_t (P_{Grid,t,d}\, CI_{Grid} + G_{i,t,d} CI_{Gas})\Delta t, i \in \{CHP, ConvBoil1, ConvBoil2, CondBoil\} \quad (15)$$

$$F_{CO_2}^{Avoid} = \sum_d \sum_t (P_{CHP,t,d}^{Sold} CI_{Grid})\Delta t \quad (16)$$

The optimization problem involves two objective functions, which are the annual operator's profit to maximize and the annual net CO_2 emissions to minimize. The weighted-sum method is used to solve this multi-objective optimization problem, through formulating one single objective function as a weighted sum of the minus-profit (*-Prof)*, and the net CO_2 emissions, $NetCO_2$, to be minimized:

$$F = c\omega(-Prof) + (1\text{-}\omega)NetCO_2 \quad (17)$$

It should be noted that the weighted-sum method is highly indicated for these types of problems, since it is easy to implement and allows to find all the solutions belonging to the Pareto front in case of convex problems and in the presence of two objective functions [24,30]. In Eq. (17), when ω=1, the solution that minimizes the minus-profit (maximizes the operator's profit) is found, whereas when ω=0, the solution that minimizes the net CO_2 emissions is found. For ω varying in the interval 0–1, the trade-off solutions between the economic and environmental objectives can be found on the Pareto front. These trade-off solutions represent the set of non-dominated solutions of the multi-objective optimization problem, known as the Pareto front. When an optimization problem has a single objective, the definition of "best solution" is one-dimensional and there is only a single best solution (or none, eventually). Conversely, a multi-objective optimization problem has no a single solution, but a set of non-dominated solutions belonging to the Pareto front. A solution belongs to the Pareto front if no improvement is possible in one objective without losing in any other objective [24].

The problem formulated is linear and involves both discrete and continuous variables. This mixed-integer linear problems is solved by using branch-and-cut. Mixed-integer linear programming problems are usually hard to solve since a set of decision variables is restricted to integer values. Branch-and-cut as a powerful instrument for mixed-integer linear problems is therefore used. In this method, all integrality requirements on variables are first relaxed, in order to solve the relaxed problem by using a linear programming method. If the values of all integer decision variables turn out to be integers, the solution of the relaxed problem is optimal to the original problem. If not, the convex hull (the smallest convex set that contains all feasible integer solutions in the Euclidean space) is needed since once it is obtained, all integer decision variables of the linear programming solution are integers and optimal to the original problem. The process of obtaining the convex hull, however, is problem dependent, and can itself be NP hard. Valid cuts that do not cut off any feasible integer solutions are added, trying to obtain the convex hull first. If the convex hull cannot be obtained, low-efficient branching operations may then be needed on the variables whose values in the optimal relaxed solution violate their integrality requirements. The objective value of the current optimal relaxed solution is a lower bound, and can be used to quantify the quality of a feasible solution. The optimization stops when CPU time reaches the pre-set stop time or the relative gap falls below the pre-set stop gap [7].

The flowchart summarizing the methodology used to find the optimized operation strategies of the DES is shown in Figure 2. Given the input data, such as the energy demand, the energy prices, the carbon intensity values and the technical characteristics of the technologies in the DES, by solving the optimization problem above, it is possible to find the Pareto front consisting of the best possible trade-offs between the economic and environmental objectives. Considering that each point on the Pareto front corresponds to a different operation strategy for the DES, the operator can choose it based on his economic and environmental priorities.

2.3. Description of the case study

The case study presented in this work is based on an existing DH system in the city of Turin, where around 240,000 m^3 of residential buildings and 50,000 m^3 of offices are heated by a central plant, which is supplying around an annual average of 11 GWh of heat to the users. A natural gas engine is in operation to supply mostly of the heat demand, while backup and integration natural gas boilers are available to provide additional capacity for the peak loads. The same heating plant is also supplying heat to a large office building.

Data about the analysed DH system are referred to the AIRU (Italian Association of Urban Heating –

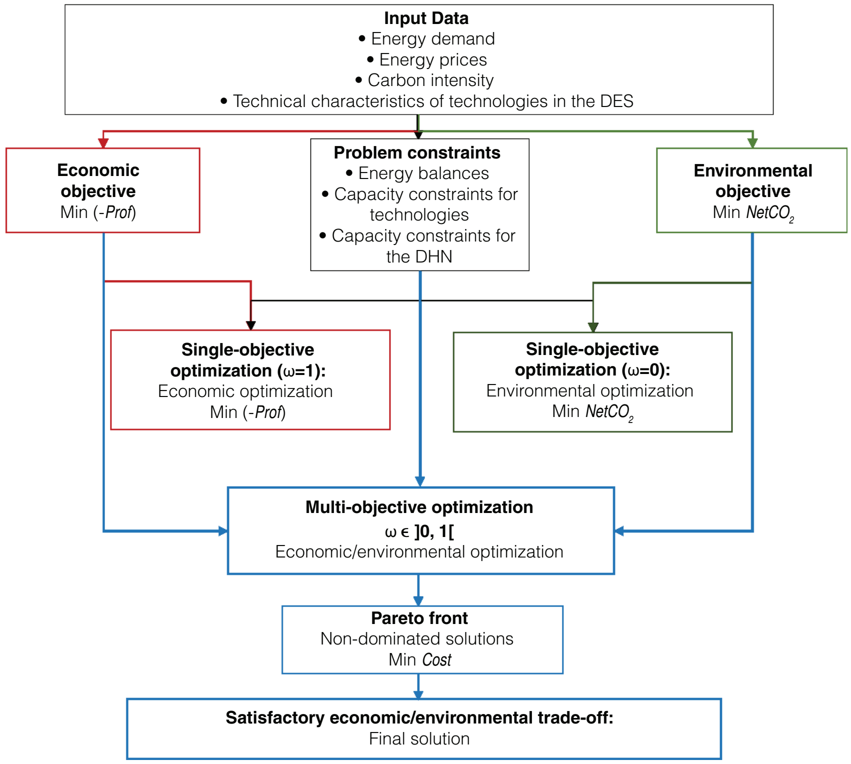

Figure 2: Flowchart of the multi-objective optimization model

Table 1: Technical characteristics of technologies in the DES

Technology	Size	Efficiency	
		Electrical	Thermal
CHP *DEUTZ TCG 2020K*	970 kW_e	0.386	0.463
Condensing boiler *Viessmann Vitocrossal 300*	895 kW_{th}	–	0.93
Conventional boilers 2x *Viessman Vitomax 200*	2x 2600 kW_{th}	–	0.90 (2)

2016) [31]. The share of heat production is split by 42% from CHP and 58% from boilers (there is currently no information on the share for each boiler). The technical characteristics of the technologies in the DES are shown in Table 1. The CHP is a natural gas engine with a rated nominal electric power of 970 kW_{el} and a nominal heat output of 1,163 kW_{th}; it consumes 13.69 GWh of natural gas for the production of 5.25 GWh of electricity and 5.02 GWh of heat. Information about the annual amount of excessive thermal energy produced by CHP are not provided, but since the CHP runs only for around 5,000 hours, the engine is never used to produce electricity only. The condensing boiler and the two conventional boilers reach a cumulated heat output of 895 kW_{th} and 2,600 kW_{th} respectively. The network losses of the DH network are 11.9%.

The total heat demand profiles were obtained by considering three years of operation data (2015–2017), for which an hourly measure of the heat consumption of the buildings was available. The analysis presented in this work has been performed on average monthly profiles, for three main reasons: (1) to limit the influence of the periods of missing data points and measurement errors, (2) to obtain acceptable computational times for the optimization tool and (3) to obtain a representation that could be generalized to other similar situations.

The simulation of the distributed heat storage systems has been performed by considering a cumulated available heat storage of 1,600 kWh for the residential buildings (corresponding roughly to 70 m^3 when considering 20°C of temperature difference) and 1,000 kWh for the office building (equal to 42 m^3). The heat storages have been designed starting from the heat profiles of the users and the operational logics to be implemented. The resulting sizes (1,600 kWh for residential and 1000 kWh for the office) are in accordance with usual design logics for heat storage systems. An average value of heat losses for the charge/discharge cycles of 1% has been considered, with reference to daily operation cycles of the heat storage systems

Figure 3 shows the comparison between the current heat loads of the users (Case 0), with two alternative charge-discharge logics: one to flatten the heat load profile (Case 1) and the other one which is following the average DA electricity market price on the market to support the CHP operation (Case 2). The reason of this choice is to evaluate potential strategies to exploit available storage driven by the traditional approach of avoiding significant peak loads (Case 1) or try to maximize the CHP operation during the hours in which the economic benefit is higher (Case 2).

The other input data for the optimization tool refer to the energy prices and carbon intensity values. Based on the Italian BTA6 tariff for industrial use [32], the time of use (ToU) tariff varies in the range 0.074-0.096 €/kWh. The tariff for industrial use is also adopted for the unit price of natural gas assumed as 0.343 €/Nm^3. For both the prices, reference is made to the energy quotas. The DA market price is built based on [33]. The price for selling thermal energy to end-users is assumed as 0.089 €/kWh. Moreover, with reference to the white certificates, according to the Italian regulation, each certificate attests the saving of a TOE, and its value is assumed as 100 €. Finally, the carbon intensities of the power grid and natural gas are equal to 0.330 $kgCO_2$/kWh and 0.202 $kgCO_2$/kWh (1.927 $kgCO_2/Nm^3$), respectively [34].

3. Results and discussion

The optimization model has been implemented by using IBM ILOG CPLEX Optimization Studio Version 12.6. The problem can be solved in a few minutes with a PC with 2.60 GHz (2 multi-core processors) Intel® Xeon®

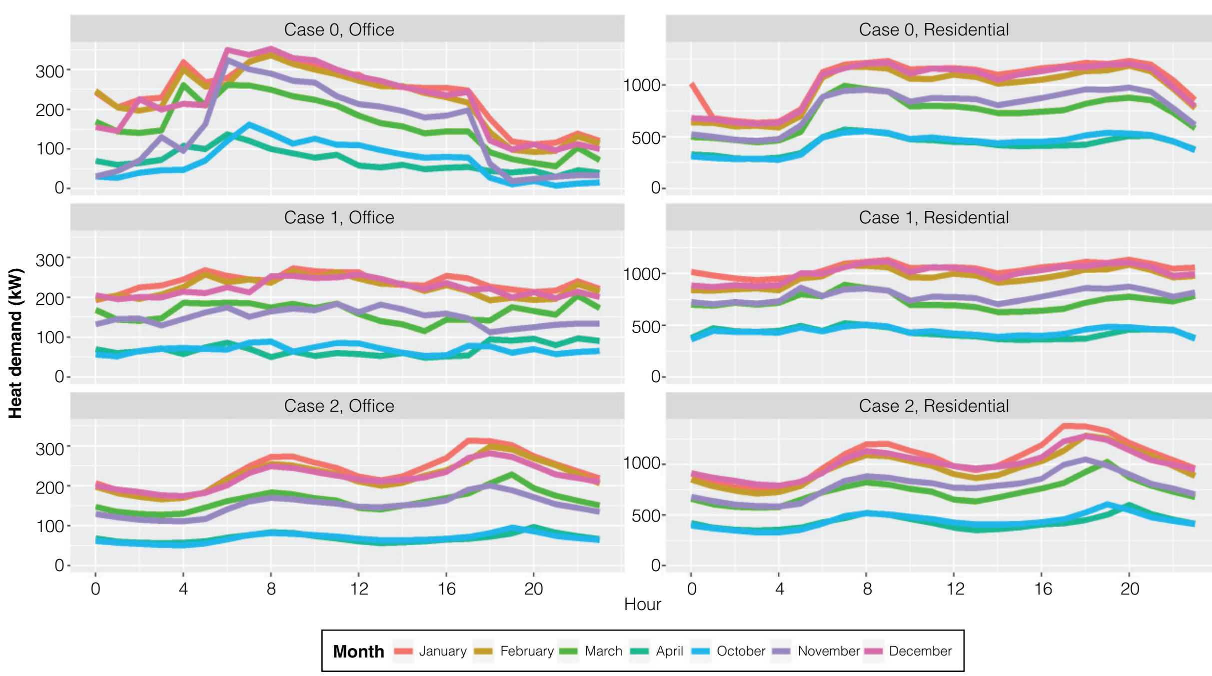

Figure 3: Average monthly heat loads for the offices and the residential buildings

E5 CPU and 32G RAM. A comparison of the economic and environmental results of the simulations is reported in Table 2. By comparing the results, a strong difference emerges from the optimized operation of the DES in comparison with the current DES operation strategies. These latter are based on the common practice logics and ON/OFF operation of the CHP unit with a rather fixed time schedule, which is shown for the illustration purpose in Figure 4 for the month of January.

In real applications small plants are rarely equipped with advanced control logics that allow a dynamic regulation based on the market prices for electricity, especially for DES that have many years of operation. However, some applications are available in newer systems, especially in Denmark and Sweden [35–37]. These applications are also depending on the economic trade-off between exploiting the potential of price differences among hours, and the additional installation and operational costs for such systems.

Considering the results of Table 2, in the current operation logic the use of distributed storage leads to a reduction of net CO_2 emissions as well as of economic profits (up to a decrease of around 10% for both indicators). However, the optimized operation strategies of the DES lead to a significant increase of economic profits from 21% to 37%, and a considerable decrease of net CO_2 emissions in the range 53%–59% when compared to the current operation of the different cases. In detail, the best economic performances of the DES are attained for Case 2 under the economic optimization. In this case, the users heat loads follow the trend of the average DA electricity market price to support the CHP operation. Therefore, in correspondence of high DA market prices, a large amount of electricity from the CHP is sold back to the grid, by allowing maximizing the revenue for the operator. Moreover, this type of operation strategy allows to cover the peak users heat loads with the thermal energy recovered from the CHP, and reduce the usage of boilers, thereby minimizing the energy costs. Conversely, the best environmental performances of the DES are attained for Case 1 under the environmental optimization. In this case, the DES operation strategies are not sensitive to the electricity prices, and the CHP is fully committed to satisfy the users electrical and thermal loads, by avoiding the usage of grid power and minimizing the usage of boilers, thereby minimizing the CO_2 emissions. Moreover, a large amount of electricity from the CHP is sold back to the grid, and as shown in Eq. (16), this allows increasing the amount of CO_2 emissions avoided. Therefore, in this case, the DES optimized operation strategies allow minimizing the net CO_2 emissions.

Table 2: Synthesis of the main results of the annual simulation

	Economic profits (€)			**Net CO_2 emissions (t)**		
	Case 0	**Case 1**	**Case 2**	**Case 0**	**Case 1**	**Case 2**
Current operation	83,210	78,099	75,237	2,188	2,042	1,977
Economic optimization	102,394	102,285	103,034	933	931	930
Environmental optimization	100,691	100,100	101,221	900	892	897

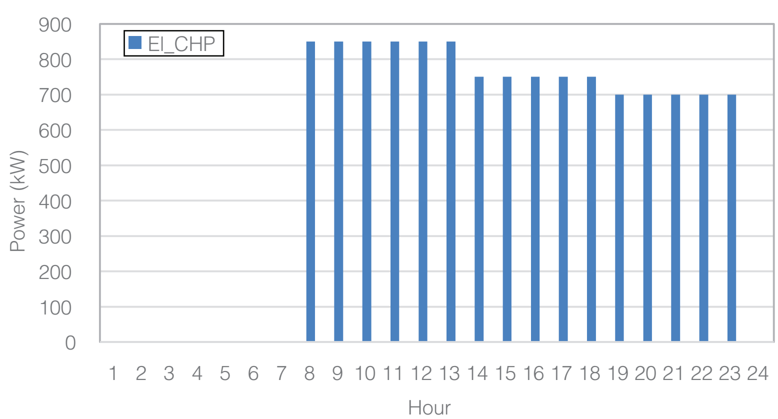

Figure 4: Current operation strategies of the CHP unit (month of January)

On the other hand, it can be noted that there are no significant differences when comparing the optimized operation strategies across cases, as the final values for economic profits and emissions show differences under 1%. This finding suggests that the use of distributed storage systems is not providing significant benefits in comparison with generation plant optimization in the case study evaluated in this work, when considering economic revenues and net CO_2 emissions as indicators. However, the availability of other energy sources characterized by a strong variability (e.g. solar energy, waste heat from industries with an irregular production cycle) could lead to a better exploitation of these systems. In the analysed case study, the installation of solar collectors would be limited by the reduced available space, and consequently its integration to the system should have a negligible contribution.

Thus, the installation of energy storage systems should be preferred in DH networks with a low flexibility of the supply side. Heat storage systems may also become a key component in case of strong energy price fluctuations within the same day, but tailored operational strategies are needed to fully exploit their potential. The availability of distributed energy storage systems could also lead to a decrease of the peak demand on the DH network, if operated with proper logics. To fully exploit their potential, their management should be coordinated by a common platform, which should be able to provide live information on optimized operation based on the heat demand and generation costs.

3.1. Focus on optimization logics

The optimization tool, as described in the Methodology section, defines the operation of the generation plant by choosing the load of each component to produce the amount of electricity and heat required by the users, by taking into account the network losses. An example of the hourly thermal energy supply strategy for the month of January is reported in Figure 5, in the case of the environmental optimization considering the demand profile with distributed storage (Case 1). The largest amount of heat is produced from CHP. This result highlights the importance of CHP for the environmental purpose, since it offers the possibility to exploit the thermal energy recovered for meeting the thermal users' demand. When the thermal energy recovered by the CHP is not enough to satisfy the demand, the condensing boiler is preferred to the conventional ones due to the higher conversion efficiency.

The corresponding optimized operation strategies of the DES for electricity, with DA market price and Time of Use (ToU) electricity tariff are illustrated in Figure 7, for the same month and the same simulation hypotheses. It can be noted that the operation strategies are not sensitive to the electricity prices. In detail, grid power is never used to satisfy the electrical load of the office building, and a large amount of electricity provided by the CHP is sold back to the grid, independently from the DA market price. As shown in Eq. (16), selling a larger electricity back to the grid allows increasing the amount of CO_2 emissions avoided, thereby minimizing the annual net CO_2 emissions.

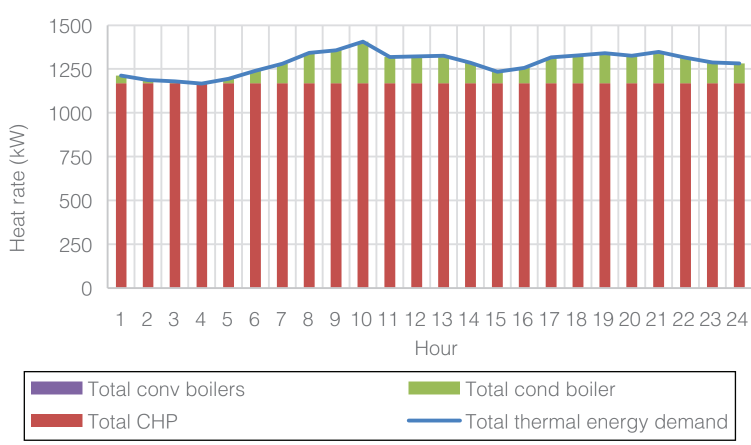

Figure 5: Thermal energy balance, Environmental optimization – Case 1 (month of January)

The hourly thermal energy supply strategy for the month of January is reported in Figure 8, in the case of the economic optimization considering the demand profile with distributed storage (Case 2). It can be noted that the CHP is mostly used during the hours corresponding to the users peak loads. This operation strategy mostly depends on the operation strategies of the DES for electricity shown in Figure 8.

The optimization strategies for the other cases show some slight differences in specific hours, but a predominant use of CHP is common across the scenarios.

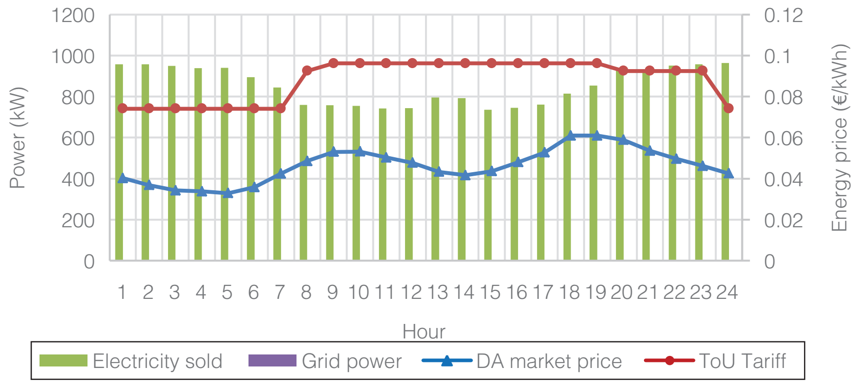

Figure 6: Optimized operation strategies of the DES for electricity, Environmental optimization – Case 1 (month of January)

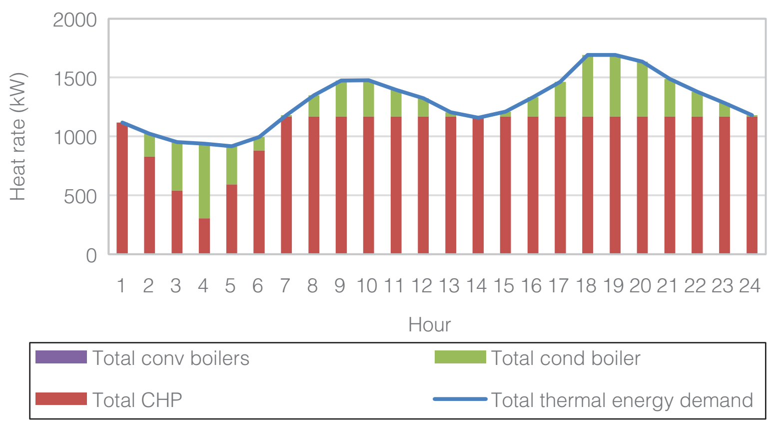

Figure 7: Thermal energy balance, Economic optimization – Case 2 (month of January)

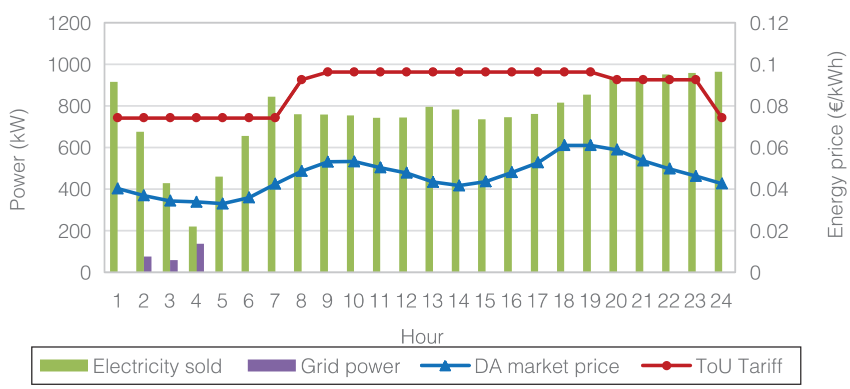

Figure 8: Optimized operation strategies of the DES for electricity, economic optimization – Case 2 (month of January)

Figure 9 shows the comparison of the Pareto fronts for the three cases discussed above, where economic and environmental optimization points are the limits of these fronts. The extreme points on the left side of Pareto fronts have been obtained under the economic optimization, where the economic objective function (-*Prof*) is minimum, thereby corresponding to the maximum annual operator's profit. Conversely, the annual net CO_2 emissions are maximum. Instead, the extreme points on the right side of the Pareto fronts have been obtained under the environmental optimization, where the economic objective function (-*Prof*) is maximum, thereby corresponding to the minimum annual operator's profit, and, conversely, the annual net CO_2 emissions are minimum.

All the internal points of the Pareto fronts, which correspond to trade-off points between the economic and environmental objectives, have been obtained by subdividing the weight interval into 100 equally-spaced points.

3.2 Sensitivity analysis

A sensitivity analysis has been performed to evaluate the effects of the variation of key factors such as DA market price and the natural gas price on the optimized operation of the DES for all the three cases analysed.

Figure 10 shows the comparison of Pareto fronts in the three cases analysed obtained with the current DA market price, and by considering an increase and decrease of the market price equal to 25%.

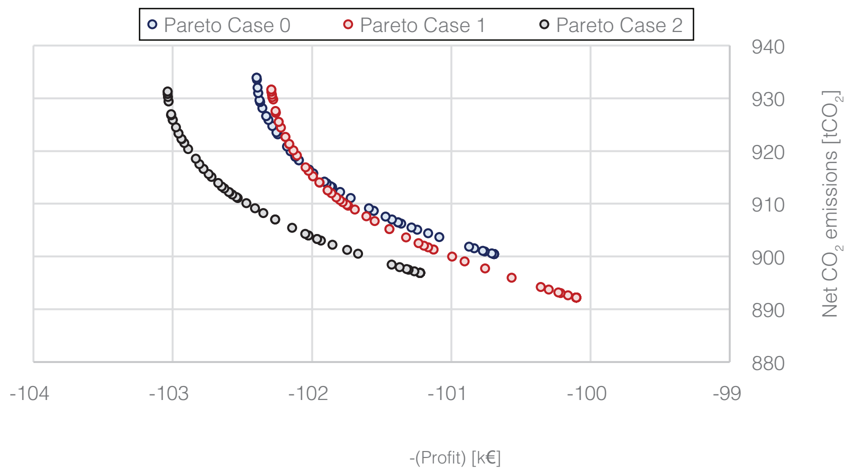

Figure 9: Comparison of Pareto fronts for the different cases analysed

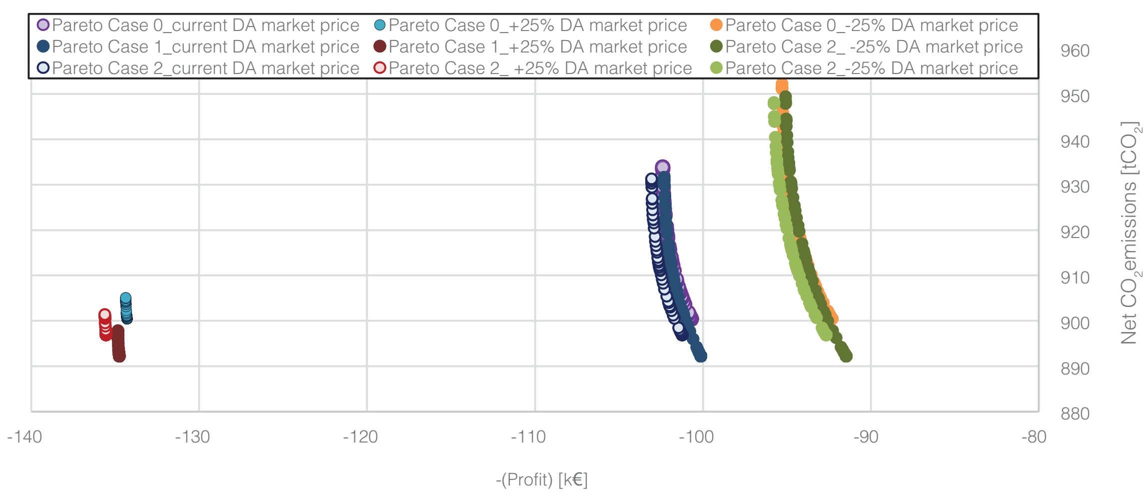

Figure 10: Comparison of Pareto fronts for the three cases analysed and with different DA market prices

It can be noted that for all the three cases, when the DA market price increases by 25%, the annual operator's profits significantly increase at all points of the Pareto fronts as compared with those obtained with the current DA market price. This is mostly due to the increase of revenue related to the electricity provided by the CHP sold back to the grid. Conversely, the net CO_2 emissions significantly reduce as compared with those obtained with the current DA market price. This result is due to the fact that a larger amount of electricity from the CHP is sold back to the grid, thereby increasing the amount of CO_2 avoided.

The contrary occurs when the DA market price decreases by 25%, since the annual operator's profits reduce at all points of the Pareto fronts as compared with those obtained with the current DA market price, whereas the annual net CO_2 emissions increase. When the DA market price reduces, a lower amount of electricity from CHP is sold back to the grid. This leads to a reduction in the related revenue for the operator. From the environmental perspective, this leads to a lower amount of CO_2 emissions avoided, as well as to a lower amount of thermal energy made available from CHP to meet the thermal user demand, which in turn leads to a larger usage of boilers, with consequently higher CO_2 emissions.

Figure 11 shows the comparison of Pareto fronts in the three cases analysed obtained with the current natural gas price, and by considering an increase and decrease of the gas price equal to 25%.

It can be noted that for all the three cases, when the gas price increases by 25%, the annual operator's profits decrease at all points of the Pareto fronts as compared with those obtained with the current gas price. This is mostly due to the increase of the energy cost related to the operation of the CHP. Moreover, with a higher gas price, the CHP results to be less convenient, thereby leading to a lower revenue related to selling electricity back to the grid and to WC incentives. This operation strategy also leads to an increase in the net CO_2 emissions as compared with those obtained with the current gas price. The lower amount of thermal energy made available from the CHP leads to a larger usage of boilers, with consequent higher CO_2 emissions.

Conversely, when the gas price decreases by 25%, for all the three cases analysed, the Pareto front reduces to a single point, showing that the optimized operation strategies are the same for all the points of the Pareto front, and correspond to those found under the environmental optimizations. The reduction of gas price leads to a very high economic convenience in the usage of the CHP, which leads to achieve the best environmental performances of the DES as well.

4. Conclusions and future work

This paper presents an analysis to assess the effect of the installation of distributed heat storage systems in an existing District Heating network. A simulation based on real demand profiles for the users is used to compare different optimization strategies with the current operation logics, by including some potential profile variations obtained through the management of the heat storage systems.

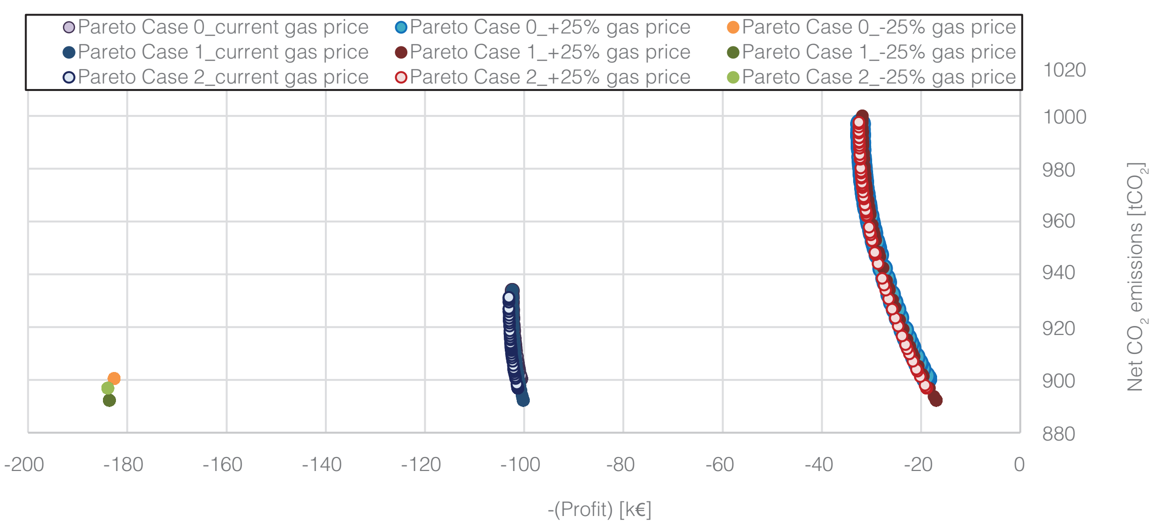

Figure 11: Comparison of Pareto fronts for the three cases analysed and with different natural gas prices

The results of the study show a large potential for both reducing the CO_2 emissions and increasing the revenues for the DES operator by applying optimization logics to the current operation of the system. This result is in line with previous works that have been carried out on this topic [10,12]. On the other hand, the presence of the distributed storage systems appears to have little effect on the achievable performance, due to the fact that the potential modifications on the heat demand profile have no significant impact on the optimization strategies of the generation plant.

The sensitivity analysis confirms the major contribution of optimization logics compared to distributed heat storage systems. The DES operator's profits are tightly related to both the natural gas prices and the electricity prices, the latter being the crucial driver for the CHP operation strategies under the economic optimization.

These results suggest that for a small DES characterized by flexible generators based on the same input fuel, and with relatively stable heat profiles, the installation of distributed heat storage systems provides little benefits when considering economic revenues and net CO_2 emissions. Different outcomes can be expected in DH systems based on variable heat sources availability, such as solar source and waste heat with variable flows over time. Thus, the installation of distributed storage should be preferred in DES characterized by a large share of non-flexible generation options, or where the infra-day energy prices show large variations.

The model developed in this work will be the basis for further research on more complex case studies, to evaluate the effect of other energy sources and heat demand profiles.

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