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Sizing of Thermal Storage Under the Eco-Exergetic Operation Optimization for District Energy Networks: Application to a Real Case Study in Italy

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ABSTRACT

District energy networks (DENs) are recognized crucial to contribute to the carbon neutrality target by 2050, thanks to the possibility to integrate renewables at the local level in the heating and cooling sector beyond the electricity one. Thermal energy storage (TES) allows DENs to be more flexible by managing the temporal gap between supply and demand. The identification of the TES size in a DEN is challenging, depending on several variables as energy loads and prices, the coupling of energy processes within the DEN, and the different economic or sustainability priorities. The contribution of this paper is to present an optimization model for sizing TES under the eco-exergetic operation optimization of DENs. The model is based on mixed-integer linear programming and aims to determine the optimal operation strategies of the DEN and the optimal TES capacity with the goal to maximize the economic/exergetic performance of the network. As case study, a real DEN located in Torino is considered. From the comparison with the results obtained with the current case in the absence of the TES, it emerges that the optimization tool brings valuable economic and exergetic benefits to the DEN, thanks to the identification of the optimal TES capacity.

1. INTRODUCTION

District energy networks (DENs) are recognized crucial to contribute to the carbon neutrality target by 2050, thanks to the possibility to integrate renewables at the local level in the heating and cooling sector beyond the electricity one [1-5]. Looking at the thermal part of DESs, they are usually characterized by a gap between production and consumption leading to a waste of thermal energy. Thermal energy storage (TES) allows DENs to be more flexible by managing the temporal gap between supply and demand [6-8]. The identification of the TES size in a DEN is challenging, depending on several variables as energy loads and prices, the coupling of energy processes within the DEN and the different economic or sustainability priorities to consider [9-12].

The contribution of this paper is to present an optimization tool for sizing TES under the eco-exergetic operation optimization of DENs. The optimization model, based on mixed-integer linear programming (MILP), aims to determine the optimal operation strategies of a DEN and the optimal TES capacity with the goal to maximize the economic/exergetic performance of the network, by using a multi-objective approach. The economic objective is to maximize the annual profit of the DEN operator, whereas the exergetic objective is to maximize the total exergy efficiency of the system by minimizing the total annual primary exergy input to the system. Exergy analysis, applied to DENs, contributes to obtaining a more rational use of energy resources, taking into consideration the different levels of energy quality (exergy) both on the supply and on the demand side [13, 14]. In the context of buildings, energy demand is characterized by different levels of energy quality, given the different temperature levels associated with thermal energy demand [15, 16]. Since the temperatures required for space heating/cooling are low (20-26°C), the quality of the energy required for these applications is also low. The quality of the energy necessary for the production of domestic hot water is slightly higher, given the water temperature level to be ensured, generally equal to 55-60°C. Instead, for electrical appliances, the highest quality of energy is required. Exergy analysis, based on the balancing of exergy levels between supply and demand, applied to DENs, allows increasing the sustainability of these systems, through a more efficient use of energy resources. In fact, by promoting the use of low exergy resources, such as solar thermal or heat recovered from power generation processes, to satisfy low temperature thermal demands, the waste of resources with a high exergy content, such as electricity or fossil fuels as natural gas, is reduced [17-19].

To optimize both the economic and exergetic performances of the considered DEN, a multi-objective approach is implemented by using the weighted-sum method, and the MILP-type optimization problem has been solved by using the branch-and-cut, implemented in the IBM ILOG CPLEX Optimization Studio optimization software.

The proposed optimization tool is applied to a real DEN located in Torino, composed by a combined heat and power (CHP) system, a condensing boiler and two traditional boilers, and an absorption and an electric chiller. The users are an office building, a cinema hall, and a cluster of 31 residential buildings connected through a district heating network (DHN). The constraints of the model are defined by taking into account the real constraints of the technologies and the DHN, as well as the energy balances to be respected to satisfy the hourly electrical and thermal loads of the users. From the comparison with the results obtained with the current case in the absence of the TES, it emerges that the optimization tool brings economic and exergetic benefits to the DEN, thanks to the optimal TES capacity. The greatest benefit of the TES to the economic performance of the network lies in the possibility of exploiting a larger quantity of thermal energy recovered from the CHP, that leads to an increase of electricity sold on the upstream grid, while also leading to higher number of the Italian White Certificates incentive obtained. The optimal capacity of the TES allows also increasing the total exergy efficiency. This is mainly due to the possibility of better exploiting the thermal energy from the CHP, resulting in a reduction in the use of boilers and natural gas used.

In the following, the Italian DEN, object of the case study, is described in Section 2. Section 3 is dedicated to the description of the optimization model formulation, whereas Section 4 discusses the optimization results obtained for the current DEN configuration and the case in which the sizing of the TES is investigated. Conclusions of the work are presented in Section 5.

2. DESCRIPTION OF THE ITALIAN DEN

The DEN, shown in Figure 1, is located in Torino and consists of a CHP with an internal combustion engine as prime mover powered by natural gas, a condensing boiler and two traditional boilers, also powered by natural gas, and an absorbtion and an electric chiller, with the technical data shown in Table 1 [20].

The users of the DEN are an office building owned by the DHN operator (that is also assumed as the DEN operator), a cinema hall and a cluster of 31 residential buildings (640 houses), connected to the DEN via the DHN. This network is of the direct mesh/branched type and is connected to the DEN via a heat exchange station.

As shown in Figure 1, the electrical load of the office building can be satisfied by the CHP in the DEN and the distribution grid, while both the cinema hall and the residential buildings are not electrically served by the DEN. The thermal load of the office building and the cinema hall can be satisfied by the CHP and the boilers, while the cooling load can be satisfied by the absorption and the electric chillers. With reference to the cluster of residential buildings, the thermal load can be satisfied by the CHP and boilers through the DHN. In the summer period, these users are not served by the DEN. Furthermore, the electricity produced by the CHP can also be fed back to the grid, thereby representing a source of revenue for the DEN operator.

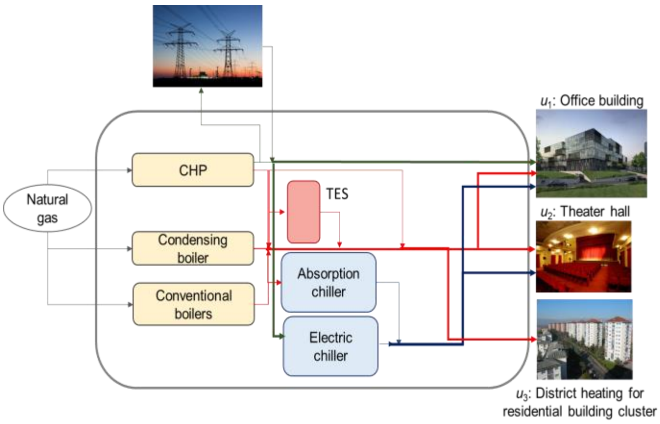

Figure 1. Scheme of the DEN in Torino

The maximum overall thermal power that can be transported in the DHN, taking into account the thermal losses in the network itself and the simultaneity coefficient evaluated on the basis of experiences gained in similar plants, is equal to 13.10 MW_{th} [20].

In the current configuration of the DEN, the TES is absent, and the related sizing is object of this study. The TES to be sized allows the thermal energy recovered from the CHP to be stored, thus decoupling the energy production from the demand of the users served by the DEN.

Table 1. Characteristics of technologies in the DEN

Technology	Size	Efficiency	
		Electric	Thermal
CHP (Internal Combustion Engine) *DEUTZ TCG 2020K*	970 kW_e	0.386	0.463
Condensing boiler *Viessmann Vitocrossal 300*	895 kW_t	-	0.930
Traditional boilers (2) *Viessman Vitomax 200*	2600 kW_t (2)		0.90 (2)
Single-stage absorption chiller *BROAD BDH20*	195 kW_f		4.4
Electric chiller *TRANE RTWB 214*	435 kW_f		0.75

3. OPTIMIZATION MODEL FORMULATION

3.1 Description of the optimization model

The goal of the proposed optimization model is to determine, in addition to the optimal hourly operating strategies of the real DEN under consideration, also the optimal capacity of the TES which allows maximizing the economic/exergetic performance of the system.

The model developed is based on a multi-objective optimization model of MILP type, formulated taking into account the real constraints of the DHN and technologies in the DEN. The decision variables of the optimization problem include both binary and continuous decision variables and are listed below:

- On/off status of each technology.
- Electrical, heating and cooling power provided by each technology.
- Electricity purchased from the grid.
- Electricity fed back to the grid.

- Capacity of the TES.
- Charging and discharging heat rates to/from TES.

The on/off state of each technology represents a binary decision variable, while all other decision variables listed above are continuous.

3.2 Objective functions

3.2.1 Economic objective

The economic objective function is formulated as the total daily profit of the DEN operator to be maximized, taking into account: (1) the revenues obtained from the sale of the electricity produced by the CHP fed back to the grid; (2) the revenue obtained from the sale of thermal energy to users; (3) the revenue related to the sale of white certificates (WC); (4) the costs incurred for the purchase of electricity from the grid and natural gas to power the CHP and boilers; (5) the annualized investment cost of the TES.

This objective function is defined below:

$$\text{Prof} = R^{Sell,grid} + R^{Sell,users} + R^{WC} - C^{Energy} - C^{Inv,TES} \tag{1}$$

with all the terms specified below:

$$R^{Sell,grid} = \sum_t \left(E_{CHP,t}^{Sell} \Pi_t^{DA}\right) Dt \tag{2}$$

$$R^{Sell,users} = \sum_t \sum_{\substack{u \\ u \neq u_1}} (H_{u,t}^{Dem} \Pi_{heat}^{Dem})\, Dt \tag{3}$$

$$R^{WC} = WC\Pi^{WC},$$
$$WC = \sum_t (E_{CHP,t}/\eta_{ref,e} + H_{CHP,t}/\eta_{ref,th} - G_{CHP,t}^{Buy} LHV_{gas}) cK \tag{4}$$

$$C^{Energy} = \sum_t [E_t^{Buy} \Pi_t^{Grid} + \sum_i (G_{i,t}^{Buy} \Pi^{Gas})] Dt,$$
$$i \in \{CHP, CondBoil, ConvBoil_1, ConvBoil_2\} \tag{5}$$

$$C^{Inv,TES} = CRF_{TES}\left(C_{c,TES} Cap_{TES}\right),$$
$$CRF_{TES} = r(1+r)^{N_{TES}}/[(1+r)^{N_{TES}} - 1] \tag{6}$$

In Eq. (4), $\eta_{ref,e}$ and $\eta_{ref,th}$ represent the reference electrical and thermal efficiency for the separate generation, assumed to be equal to 0.46 and 0.90 respectively, the c factor takes into account the conversion from kWh to TOE, while K is a coefficient which varies depending on the size of the CHP, which, in the analyzed case, is assumed to be equal to 1.4.

In Eq. (6), CRF_{TES} is the capital recovery factor of TES; $C_{C,TES}$ is the specific investment cost (€/kWh); r is the interest rate; and N_{TES} is the lifetime of the TES technology, expressed in years.

3.2.2 Exergetic objective

The exergetic optimization applied to DEN is based on the balancing of exergy levels between supply and demand, and allows minimizing the quantity of exergy input to the system, thereby minimizing the consumption of fossil fuels, for the same of energy needs of the users to be satisfied. This, in fact, leads to an increase in the sustainability of the energy supply system, through a rational use of the energy resources input to the system. Consistent with the optimization model proposed by Di Somma et al. [8], the exergetic objective is to maximize the total exergy efficiency of the system, defined as the ratio between the total exergy required to satisfy the electrical and thermal needs of the DEN users and the total primary exergy input to the system. The total exergy required to satisfy these loads is known on the basis of the experimental data available for the DEN under consideration (electrical and thermal demand for DHW and SH and temperature levels associated to thermal demand). Therefore, the maximization of the total exergy efficiency of the system is achieved by minimizing the net daily total primary exergy input to the DEN, which is defined as the difference between: (1) the total primary exergy input to the DEN; and (2) the exergy associated with the share of electricity produced by the CHP fed back to the grid.

The exergetic objective function is thus formulated as:

$$Ex_{net,in} = Ex^{in} - Ex^{Sell,grid} \tag{7}$$

that can be further specified as:

$$Ex_{net,in} = \sum_t \left(Ex_{j,t} - Ex_{CHP,e,t}^{Sell}\right) Dt$$
$$j \in \{Grid, NGas\} \tag{8}$$

In Eq. (8) $Ex_{j,t}$ represents the exergy relating to the energy carrier j, that can be specified for the electricity from the grid and natural gas as indicated below, respectively:

$$Ex_{Grid,t} = E_t^{Buy}/\varepsilon_{gen} \tag{9}$$

$$Ex_{Ngas,t} = G_{i,t}^{Buy} \varsigma_{Gas} LHV_{Gas} \tag{10}$$

In Eq. (9), the electricity from the grid is seen as an energy carrier supplied by power generation plants and the relative exergy thus depends on the exergy efficiency of these plants, ε_{gen}. In Eq. (10), the exergy associated to natural gas depends on the specific chemical exergy of the fuel, through the exergy factor of natural gas ς_{NGas}.

The exergy associated with the share of electricity produced by the CHP fed back to the grid is formulated as [8]:

$$Ex_{CHP,e,t}^{Sell} = E_{CHP,t}^{Sell} \tag{11}$$

3.3 Constraints

The constraints of the optimization model consist of:

- Operation constraints of DEN technologies.
- Constraints relating to the DHN operation.
- Energy balance constraints for satisfying the hourly electrical and thermal loads of the users.

3.3.1 Operation constraints of the DEN technologies

With reference to the operation constraints of the DEN technologies, to maintain the linearity of the optimization model, the hypothesis of constant efficiency for each technology is made, therefore assuming that it does not vary with the load.

The main constraints are defined below:

<u>*CHP system*</u>

The total power is limited by the minimum and maximum rated output, if the device is on:

$$E_{CHP}^{min} x_{CHP,t} \leq E_{CHP,t} \leq E_{CHP}^{max} x_{CHP,t}, \forall t \quad (12)$$

where, the total power provided by the CHP is equal to the sum of the power for self-use and the power sold back to the grid:

$$E_{CHP,t} = E_{CHP,t}^{Self} + E_{CHP,t}^{Sell}, \forall t \quad (13)$$

For all devices in the DEN, the capacity constraint can be formulated as in (12). The amount of natural gas required by the CHP is formulated as:

$$G_{CHP,t}^{Buy} = E_{CHP,t}/(\eta_{CHP,e} LHV_{gas}), \forall t \quad (14)$$

The heat rate recovered by the CHP is formulated as:

$$H_{CHP,t} = E_{CHP,t}\eta_{CHP,th}/\eta_{CHP,e}, \forall t \quad (15)$$

In the winter period, the thermal energy recovered by the CHP can be used to satisfy the thermal demand of the office building, the theater hall, and the building clusters (through the DHN), whereas, in the summer period, it can be used to power the absorption chiller.

Condensing and conventional boilers

The amount of gas required by the condensing boiler is formulated as:

$$G_{CondBoil,t}^{Buy} = H_{CondBoil,t}/(\eta_{CondBoil,th} LHV_{gas}), \forall t \quad (16)$$

The amount of gas required by the conventional boilers can be formulated as in Eq. (16). Similarly to the CHP, also for the boilers, in the winter period the thermal energy provided can be used to satisfy the thermal demand of the three users, whereas, in the summer period, it can be used to power the absorption chiller.

Absorption chiller

In the summer period, the cooling rate provided by the absorption chiller is formulated as:

$$C_{AChil,t} = COP_{AChil} \sum_i H_{i,t}^{Cool} \quad i \in \{CHP, CondBoil, ConvBoil_1, ConvBoil_2\}, \forall t \quad (17)$$

Electric chiller

In the summer period, the power required by the electric chiller is formulated as:

$$E_{EChil,t}^{Req} = C_{EChil,t}/COP_{EChil}, \forall t \quad (18)$$

Thermal energy storage

The state dynamic of the TES is formulated as:

$$H_{TES,t} = H_{TES,t-1}(1 - \varphi_{TES}(D_t)) + (H_{TES,t}^{in} - H_{TES,t}^{out})D_t \quad (19)$$

3.3.2 Operation constraints for the DHN

In the winter period, the sum of the heat rates provided by the CHP and boilers has to be lower or equal to the maximum heat rate allowable for the DHN:

$$\sum_i H_{i,u,t} \leq H_{DHN}^{max} \quad i \in \{CHP, CondBoil, ConvBoil_1, ConvBoil_2\}, \forall t \quad (20)$$

where, $H_{i,u,t}$ is the share of the heat rate provided by the device i at time t for the user 3 (district heating for the residential building cluster). In the summer period, the residential building cluster is not served by the DEN operator.

3.3.3 Energy balance constraints

Energy balance constraints are necessary to ensure that assigned users loads are met. With reference to the electricity balance, during the winter period, the electricity load of the office building must be satisfied by the electricity supplied by the CHP and the electricity from the network:

$$E_{u,t}^{Dem} = E_{CHP,u,t}^{Self} + E_{u,t}^{Buy}, u = u_1, \forall t \quad (21)$$

Both the cinema hall and the residential users are not electrically served by the DEN. The constraint in Eq. (21) also applies to the summer period, with the addition of the electrical power required by the electric chiller which represents a load for the DEN.

As for the thermal energy balance, it is formulated as:

$$H_{u,t}^{Dem} = \sum_i (H_{i,u,t}) + H_{TES,t}^{out} - H_{TES,t}^{in}, \forall u, t \quad i \in \{CHP, CondBoil, ConvBoil_1, ConvBoil_2\} \quad (22)$$

where, the thermal load of user 3 refers to the thermal power required on the secondary side of the heat exchanger between the DEN and the DHN. This thermal load takes into account the losses in the DHN pipes.

In the summer period, the cooling demand for users 1 and 2 can be satisfied by the absorption and the electric chillers:

$$C_{u,t}^{Dem} = \sum_i C_{i,u.t}, i \in \{AChil, EChil\} \quad u \in \{u_1, u_2\}, \forall t \quad (23)$$

3.4 Multi-objective optimization method

The optimization model includes two objectives: maximizing the operator's total daily profit and minimizing the total daily net primary exergy input to the network. Using the weighted sum method, which is simple to implement and effective for convex problems with two objectives, the economic objective is reformulated as the negative profit (-Prof) to convert it into a minimization problem.

$$OF = c\omega(-Prof) + (1 - \omega)Ex_{net,in} \quad (24)$$

By varying the weight ω in the interval 0 – 1, it is possible to find the Pareto frontier, which includes the possible trade-off solutions between the economic and exergy objectives. The extreme points can be found by posing $\omega=1$ and $\omega=0$ (economic and exergetic optimization).

The linear optimization problem, involving binary and continuous variables, is solved using the branch-and-cut algorithm, which is efficient for MILP models.

4. IMPLEMENTATION OF THE OPTIMIZATION MODEL TO THE REAL CASE STUDY

4.1 Input data

On the basis of the available experimental data, the hourly electrical and thermal load profiles related to the DEN users have been identified with reference to 12 representative days of the 12 months of the year. The number of days for each month has been defined based on the characteristics of the reference climatic zone and the period established by law in which it is possible to turn on the heating systems in that climatic zone. On the basis of this assumption, and considering that from the month of May to the month of September, the DEN is not in operation and the cooling energy technologies are turned off, Table 2 shows the annual energy demand of the DEN users, with reference to electricity and space heating.

Table 2. Annual energy demand of users served by the DEN (GWh)

User	Electricity	SH
Office building	0.53	0.99
Theater hall	-	0.082
DHN for the residential building cluster	-	4.03

For the purchase of electricity from the grid, the BTA6 tariff for industrial uses of the Time-of-Use (TOU) type (three-hourly tariff) has been considered. Also for the natural gas, the tariff for industrial uses has been considered. In both cases, only the energy quotas have been considered. The day-ahead market price has been considered for evaluating the economic value of the electricity produced by the CHP fed back to the grid. The sales price of thermal energy to users has been assumed equal 0.089 €/kWh (single-hourly tariff), based on the district heating tariff data available in reference [20]. The specific investment cost for the TES has been assumed equal to 20 €/kWh, with a lifetime of 20 years.

The exergy efficiency of power generation plants has been assumed to be equal to 0.40, with reference to the Italian situation relating to the energy mix for electricity generation and the average efficiency of plants powered by fossil fuels [20], while the exergy factor of natural gas has been set equal to 1.04.

4.2 Optimization results

The optimization model has been implemented considering the experimental data of the DEN in Torino, with reference to an entire year, and has been implemented using IBM ILOG CPLEX Optimization Studio Version 12.6 optimization software. The optimization problem can be solved in a few hours using a PC with 2.60 GHz (2 multi-core processors) Intel® Xeon® E5 CPU with 32G RAM.

The results obtained by implementing the optimization model for the current DEN configuration in the absence of the TES and with the optimal size of the TES are discussed below.

4.2.1 Optimization results for the current DEN configuration in the absence of TES

Figure 2 shows the Pareto frontier obtained from the implementation of the optimization model for the current configuration of the DEN in the absence of the TES. In the case of economic optimization (point *a*), the operator's annual profit is maximum and equal to €147493, while the total annual net primary exergy input to the DEN, also maximum, is equal to 7.447 GWh. In the case of exergetic optimization (point *b*), the total annual net primary exergy is minimum and equal to 6.543 GWh, while the operator's annual profit, also minimum, is equal to €82174.5.

The various cost, revenue and exergy items are shown in Table 3, with reference to the extreme points of the Pareto frontier. The revenue for selling thermal energy to the end-users is equal in all points of the Pareto frontier to €293509, as this term is not subject to optimization (and thus excluded from the table). It is noted that in the case of economic optimization, the revenue linked to the sale of electricity fed back to the grid plays a fundamental role in maximizing the operator's profit. This revenue becomes very small in the case of exergetic optimization, as the CHP is mainly used for self-consumption, as also demonstrated by the value of the exergy relating to the electricity fed back to the grid, equal to 0.098 GWh, compared to 10.34 GWh obtained in the case of economic optimization.

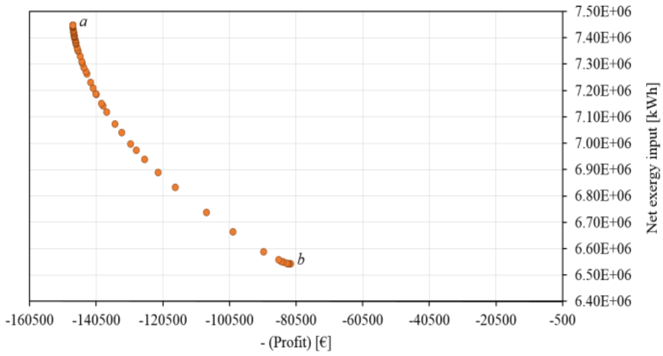

Figure 2. Pareto frontier obtained for the current configuration of the DEN in the absence of the TES

Table 3. Optimized annual cost, revenue and exergy items obtained in the current configuration

Point	Revenues (€)		Costs (€)	Exergy (GWh)	
	$R^{Sell,grid}$	R^{WC}	C^{Energy}	Ex^{in}	$Ex^{Sell,grid}$
a	135976	75437.9	357429	10.34	2.89
b	4982.5	13037.3	229354	6.64	0.098

4.2.2 Optimization results for the DEN with optimal sizing of TES

Table 4 compares the optimization results obtained in the two aforementioned cases.

In the case of economic optimization, the optimal capacity of the TES is equal to approximately 690 kWh. The operator's profit is equal to €148849, while the total annual net primary exergy is equal to 7.487 GWh. It is noted that, although the operator's profit takes into account the annualized investment cost of the TES, it increases by approximately by 1% as compared to the current case in the absence of TES. The greatest benefit brought by the TES to the economic performance of the DEN lies in the possibility of exploiting a larger quantity of the thermal energy recovered from the CHP to satisfy the thermal needs of the users, while also reducing the use of boilers. This, in fact, leads to an increase both in the quantity of electricity sold on the electricity grid, and in the quantity of total electricity produced by the CHP and, consequently, in the number of white certificates obtained.

In the case of exergetic optimization, the optimal capacity of the storage system is equal to approximately 1373 kWh. In this case, the operator's profit is equal to €80064, while the total annual net primary exergy is equal to 6.540 GWh. It is therefore noted that the presence of the TES allows the net annual primary exergy input to be reduced compared to the current case in the absence of TES. The slight reduction in the net primary exergy input is mainly due to the possibility of better exploiting the thermal energy recovered from the CHP to satisfy the thermal needs of the DEN users, resulting, in fact, in a reduction in the use of boilers and therefore the quantity of natural gas used. It is therefore clear that the optimal sizing of the TES entails both economic and exergetic benefits for the performance of the DEN.

The various cost, revenue and exergy items are shown in Table 5, with reference to the extreme points of the Pareto frontier. Also in this case, the revenue for selling thermal energy to the end-users is equal in all points of the Pareto frontier to €293509, as this term is not subject to optimization (and thus excluded from the table).

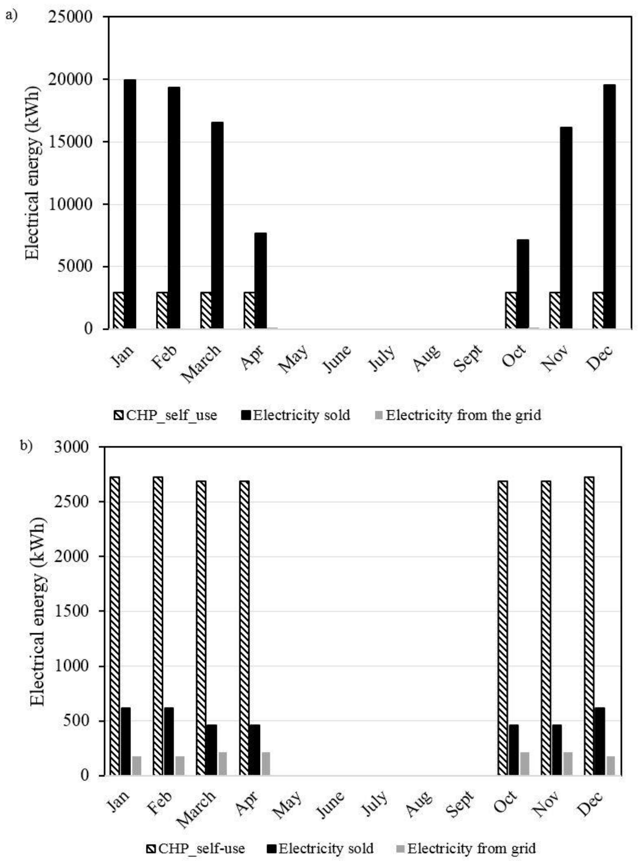

Figure 3. DEN operation strategies for electricity in the case of a) economic optimization and b) exergetic optimization

These results are similar to those obtained in the previous case, and the same comments are valid. A higher annualized investment cost for the TES is also noted in the case of exergetic optimization considering the larger installed capacity compared to the case of economic optimization.

Figure 3 shows the operation strategies of the DEN for electricity obtained in the case of economic and exergetic optimization, for a representative day of each month. The results presented in the previous table are confirmed by the operation strategies of the DEN. In fact, it is noted that, in the case of economic optimization, a large part of the electricity supplied by the CHP is fed back to the grid. On the contrary, in the case of exergetic optimization, the total electrical energy produced by the CHP is drastically reduced and a large part of it is used for self-consumption.

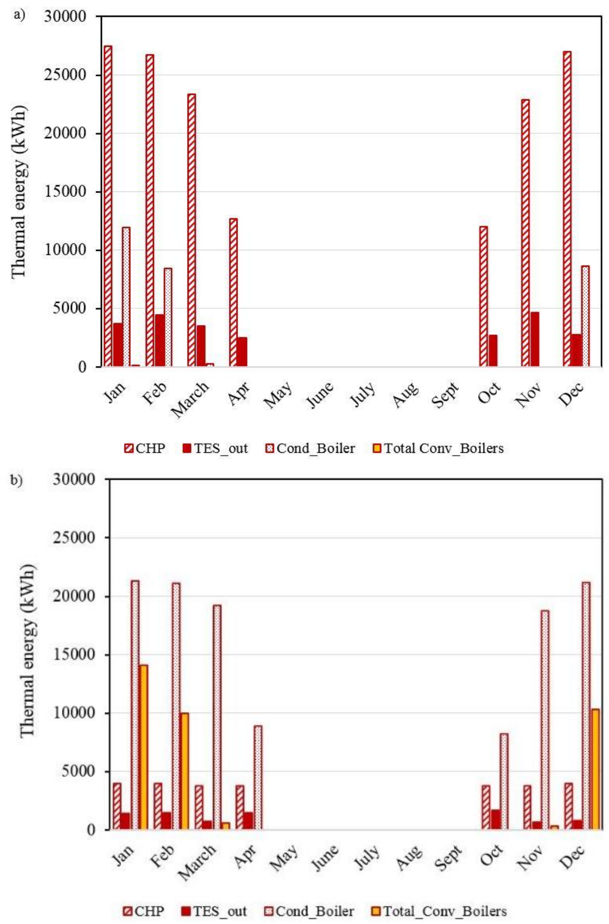

Figure 4. DEN operation strategies for thermal needs in the case of a) economic optimization and b) exergetic optimization

Table 4. Comparison of optimization results in the two analyzed cases

Case	Type of Optimization	Annual Profit (€)	Annual Net Primary Exergy (GWh)	TES Optimal Capacity (kWh)
Current configuration	Eco	147493	7.447	-
	Ex	82174.5	6.543	-
Presence of TES	Eco	148849 ↑	7.487 ↑	690
	Ex	80064 ↓	6.540 ↓	1373

Table 5. Optimized annual cost, revenue and exergy items obtained for the DEN with optimal TES capacity

Point	Revenues (€)		Costs (€)		Exergy (GWh)	
	$R^{Sell,grid}$	R^{WC}	C^{Energy}	$C^{Inv,\ TES}$	Ex^{in}	$Ex^{Sell,grid}$
a	141092	77715.6	362361	1106.6	10.48	2.99
b	4982.5	13037.3	229268	2196.8	6.64	0.097

Figure 4 shows the thermal operation strategies of the DEN for a representative day of each month, obtained in the case of economic and exergetic optimization. It is noted that, in the case of economic optimization (Figure 4(a)), a large part of the thermal needs of the users is satisfied by the thermal energy supplied by the CHP, consistently with the operation strategies for electricity presented in Figure 3(a). The presence of the TES allows reducing the use of the boilers compared to the current case in the absence of TES. However, the condensing boiler remains a preferable option compared to conventional boilers due to its greater conversion efficiency.

In the case of exergetic optimization (Figure 4(b)), it is noted that the presence of the TES allows the use of conventional boilers to be reduced compared to the case in the absence of TES. However, similarly to the case in the absence of storage, it is noted that a large part of the thermal needs of the users are satisfied by the condensing boiler and not by the CHP. The almost exclusive use of the CHP for self-consumption of electricity (as shown in Figure 3(b)) means that the amount of thermal energy recovered is not sufficient to cover the thermal loads.

5. CONCLUSIONS

This paper presents an innovative tool for sizing TES under the eco-exergetic operation optimization of DENs. The optimization model, based on mixed-integer linear programming, aims to determine the optimal operation strategies of a DEN and the optimal TES capacity with the goal to maximize the economic/exergetic performance of the network, by using a multi-objective approach. The economic objective function represents the annual DEN operator's profit to maximize, whereas the exergetic objective is to maximize the total exergy efficiency of the system by minimizing the total annual primary exergy input to the DEN. The proposed optimization tool is applied to a real DEN located in Torino, composed by CHP system, a condensing boiler and two traditional boilers, and an absorption and an electric chiller. The users are an office building, a cinema hall, and a cluster of 31 residential buildings connected through DHN. The constraints of the model are defined by taking into account the real constraints of the technologies and the DHN, as well as the energy balances to be respected to satisfy the hourly electrical and thermal loads of the users. The optimization model is implemented in IBM ILOG CPLEX environment. The results obtained with the current case in the absence of the TES are compared to the case in which the TES capacity is optimized, and it has emerged that the optimization tool brings economic and exergetic benefits to the DEN, thanks to the identification of the optimal TES capacity. The greatest benefit of the TES to the economic performance of the network lies in the possibility of exploiting a larger quantity of thermal energy recovered from the CHP, that leads to an increase of electricity sold on the upstream grid, while also leading to higher number of the Italian White Certificates incentive obtained. The optimal capacity of the TES allows also increasing the total exergy efficiency. This is mainly due to the possibility of better exploiting the thermal energy from the CHP, resulting in a reduction in the use of boilers and natural gas.

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NOMENCLATURE

c	Constant in Eq. (24) (kWh/€)
Cap_{TES}	TES capacity (kWh)
$C_{C,TES}$	TES specific investment cost (€/kWh)
C^{Energy}	Total cost of input energy carriers (€)
CRF_{TES}	Capital recovery factor
C_t	Cooling rate (kW)
D_t	Time step (h)
E_t	Electrical power (kW)
Ex	Exergy (kWh)
Ex_t	Exergy per unit time (kW)
G_t	Volumetric flow rate of natural gas (Nm^3/h)
H_t	Heat rate (kW)
K	Coefficient in Eq. (4)
LHV_{NGas}	Lower heat value of natural gas (kWh/Nm3)
N_{TES}	Lifetime of the TES technology (years)
$Prof$	Total profit of the DEN operator (€)
R	Total network operator revenue (€)
r	Interest rate
WC	Number of white certificates
x_t	Binary decision variable

Greek symbols

Π^{WC}	Price of each WC (€/WC)
φ_{TES}	Thermal loss fraction of TES
ε_{gen}	Exergetic efficiency of power generation
η	Conversion efficiency
Π	Price of the energy carrier (€/kWh) - (€/Nm3)
ς_{NGas}	Exergetic factor of natural gas
ω	Weight factor in Eq. (24)

Subscripts

AChil	Absorption chiller
CondBoil	Condensing boiler
Cool	Spance cooling
DA	Day-ahead market
EChil	Electric chiller
i	Technology index
in	Input
j	Input energy carrier index
max	Maximum
min	Minimum
out	Output
u	User index