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Energy, Environmental, and Economic Analyses of a District Heating (DH) Network from Both Thermal Plant and End-Users' Prospective: An Italian Case Study

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Abstract: District heating (DH) is an alternative technology to Individual Heating (IH) for satisfying end-user's needs. This paper assesses the competitiveness of a DH network in the center of Italy from energy, environmental, and economic points of view considering both thermal power plant and end-users' sides. On the thermal power plant side, the energy analysis considers the Primary Energy Saving (PES) and the specific energy (E_{sp}) of the fuel actually exploited in the thermal power plant compared to its Low Heating Value (LHV), while the environmental analysis considers the avoided CO_2 and the economic analysis considers the Energy Efficiency Certificates (EECs). Results showed that the current thermal power plant configuration with two boilers and a Combined Heat and Power (CHP) unit reaches a yearly PES of 21.3% as well as 1099 tCO_2 avoided. From the economic analysis of the thermal power plant side, 829 EECs with an economic return of 207,222€ are obtained, while from the end-users' side the DH network is cheaper than IH in 84.7% of the cases. Further technologies are also studied to enhance the CHP unit flexibility.

Keywords: cogeneration plant; district heating network; economic analysis; energy efficiency; environmental analysis; heat pump; thermal energy storage

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1. Introduction

Climate change has become a serious issue that is affecting the whole world. Nowadays, increasingly stringent strategies and solutions are needed more than ever to tackle this problem. Energy-consuming technologies, as well as the use of conventional fossil fuel sources, have a fundamental impact on the global environment: indeed, the previous decade was the warmest period ever recorded so far, with a global average temperature of 1.1 °C above pre-industrial levels [1]. Currently, global warming, caused by human activities, is continuously rising by 0.2 °C per decade, and this will lead to considerable impacts on both Earth's environment and living beings when an overall increase of 2 °C compared to the temperature in pre-industrial times will be achieved [1]. Nevertheless, cities and municipalities that occupy only 3% of the Earth's surface consume 75% of the natural resources and produce 60–80% of the global greenhouse gas emissions [2]. With firstly the Paris Agreement and then the Clean Energy Package, Europe has committed itself to achieve by 2030 the ambitious goal to increase energy efficiency up to 32.5%, the exploitation of renewables up to 32%, and reduce greenhouse gas emissions down to at least 40% [3]. Renewable energy can therefore be considered fundamental for feeding current and future energy systems in a cleaner way, bringing both economic and environmental benefits, as well as social benefits by improving the environment quality and fulfilling people requirements [4]. Furthermore, renewable energy is expected to be widely used in electricity, heating, cooling, and transportation by 2050, also creating about 10 million additional direct jobs within the EU countries [5–7].

In such a context, District Heating (DH) networks are considered one of the best solutions in future energy systems together with a high share of renewables to maximize energy conservation and to abate environmental pollution [8,9]. Indeed, over the last few decades, DH networks have become more efficient from the energy point of view [10], thus reducing emissions in cities and supplying both domestic hot water and thermal heating to the end-users properly [11]. In addition, a DH network can provide several advantages from the end-users' point of view, both in terms of maintenance and harmful emissions controls. In the latter case, the control of the thermal plant chimneys is more rigid and frequent than those in the Individual Heating (IH) systems. Furthermore, thanks to the chimneys' height and the best filtering systems, the density of polluting emissions is sensibly lower. From the production side, instead, a DH network offers the same advantages as those in traditional systems such as calorimeters together with operating time and temperature control systems. In terms of safety, the risk of explosion and smoke poisoning are eliminated by distributing hot water and not gas [12].

Both buildings and DH networks have become nowadays even more energy efficient. The development of DH networks has led, over the years, to a classification in accordance to the heat transport fluid typology (hot water and air), energy transported (heating, cooling, and both), and used heat resource (fossil fuels, nuclear power, waste heat, cogeneration, solar thermal energy, ground source heat pumps, and biomass) [10].

Historically, the first Generation of District Heating (1GDH) was developed in the late 1800s in the United States [9]. Over the years, new generations of DHs have been developed, reaching currently the fifth generation: the substantial differences between the different DH networks can be classified from carrier fluid temperature and energy source points of view. In terms of carrier fluid temperature, it has been reduced from steam (1GDH) to near-ground water temperature (5GDH), passing through superheated water (2GDH), hot water (3GDH), and water at low temperature (4GDH) [13]. From the energy source point of view, coal was the first and most used source that has characterized the development of the first two DH generations, and it is still used in energy districts in China [9]. Fossil fuels are largely used in the 3GDH, although there were some exceptions, such as Sweden, in which a sustainable 3GDH network with non-fossil resources has been developed [13]. One of the substantial differences of 4GDH with respect to the previous generations is the balancing of the energy supply with better energy exploitation using renewables [14]. The lower temperatures in 4GDH enabled low-temperature heat sources to deliver more heat with lower investments with respect to the other DH generations [15–17].

Not only the new generations of DH have led to an improvement in performance, but scientific literature has also shown increasing interest in finding several criteria for improving existing and future DH networks. For instance, Ljubenko et al. [18] presented an exergy-based analysis of a DH network in Slovenia, showing that there are important differences in energetic and exergetic efficiencies of heating supply in different parts of the network. It has also been shown how (i) the supply temperature reduction, (ii) the pipe sizes reduction, and (iii) the increasing of the heat supplied to the network affect the exergetic efficiency optimization procedures. Marina Domingo et al. [19], instead, investigated the reduction of the energy consumption before and after the installation of a DH network in a Spanish University Campus in terms of historical consumption and climate variables data. The results obtained with the DH network were (i) energy savings higher than 21% for 33% of the campus buildings, (ii) increase in consumption of 20% in 17% of the buildings, and (iii) no significant differences in the remaining buildings. Neirotti et al. [20] studied two different approaches for decreasing the DH operating temperatures, starting from a different control strategy involving night-time operation to avoid the morning peak demand, and the partial insulation of the buildings to decrease the operating temperatures without modifying the heating system of the end-users. In the first approach, it was possible to decrease the network temperature down to 50–60 °C without compromising the comfort and the end-users' energy consumption increased by 3.5% with respect to the reference case due to the continuous operation of the heating system, although the network losses decreased. In the second approach, it has been shown the great benefits due to the energy efficiency interventions in buildings; however, the network temperature must be at least 60 °C to guarantee an acceptable comfort level.

While in North and Central Europe the DH networks are widely developed, the current Italian situation is well displayed in Figure 1: in the regions of northern and central Italy, characterized by a colder climate, many DH and cooling (DHC) networks have been built so far.

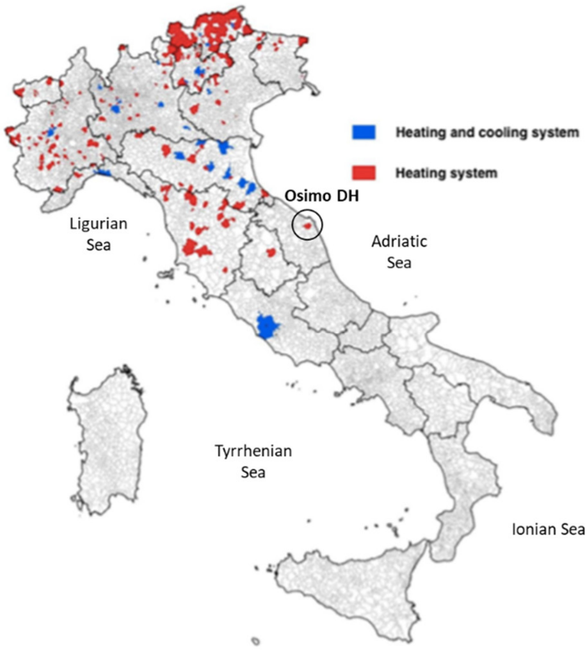


Figure 1. Heating and cooling systems in Italy, in which the Osimo DH network has been highlighted.

As it can be noticed, there is only one DH network in the Marche region, which is in the center of Italy, the Adriatic (East) coast (see Figure 1). In this work, an Italian case study related to the city of Osimo (AN) is investigated, being an interesting case study that has been already analyzed in other works [21–24] due to the use of multiple technologies and energy vectors involved, besides the geographical location that makes these energy efficiency interventions interesting. In Osimo (AN) there is a multi-energy system constituted by electricity, Natural Gas (NG), DH, and a 23% share of non-controllable Renewable Energy Sources (RES) capacity, mostly PhotoVoltaic (PV) panels. In particular, studies on Water Supply System (WSS) [21], Electric Vehicles (EVs) [22,23], and the CHP-DH plant [24] have been carried out. In the latter, Comodi et al. [24] described the old CHP-DH plant in Osimo based on a Steam Injection Gas Turbine (STIG) that has been nowadays replaced with a cogeneration gas engine. Different scenarios were analyzed by introducing an Internal Combustion Engine (ICE), a high-temperature Heat Pump (HP), and a Thermal Energy Storage (TES) to increase the CHP flexibility, which will extend its operating hours at rated conditions. Results showed that the best option was the new cogeneration gas engine sized on the baseload thermal demand, thus allowing both improvements of both Primary Energy Saving (PES) and economic revenues. The configuration with the heat pump, instead, affects positively the profitability, but not the energetic efficiency as well as that one with the TES.

The current configuration of the CHP-DH plant (3GDH) of Osimo is here studied. Both energy and environmental analyses are carried out and a comparison between the reference scenario (no DH network) and the current one is performed. In particular, the analysis is divided by production and end-users' sides to better analyze and discuss the performance of the overall DH network (thermal plant plus end-users).

Based on the literature analysis of DH networks studies carried out so far and to the authors best knowledge, it has emerged that simulated data have been mostly used to carry on feasibility studies [25–27]. Others, on the other hand, used historical data without going into details on the economic analysis related to the end-users' side with real thermal bills data [27,28], as well as without comparing the DH with the reference scenario (no DH) to highlight possible benefits in energy, environmental, and economic terms for both thermal power plant and users' side [29,30]. In particular, Yoon et al. [29] evaluate and compare the economic value that consumers place on different types of convenience between IH and DH, and provide practical policy information without analyzing what a current DH user would pay with the IH. Cao et al. [30], instead, compare the thermal comfort between DH and IH from the perspective of the adaptation of occupant's point of view. In contrast to the IH, the DH considered in this study does not allow end-users to choose the operating heating hours, as well as to choose the internal temperature inside the buildings on their own. This monitoring system is now obsolete since nowadays each DH end-user can set the internal temperature via thermostat to improve the thermal comfort, and only the thermal energy currently consumed by each DH end-user is counted in the bill. Wang [31] investigates the competitiveness of the DH with large HPs compared to IH in the United Kingdom in terms of environmental and economic advantages. This study shows the environmental benefits of the DH in contrast with IH, and its economic disadvantages as well. However, there is not any comparison with other existing technologies to support and enhance the deployment of a DH network to make it economically competitive compared to IH. Because of these considerations, a more in-depth study on the cost comparison of DH and IH, as well as an update of the technical aspects that can be implemented in a DH, are necessary and of great interest.

Accordingly, a comprehensive study with real data, comprising energy, environmental, and economic analyses of both thermal plant and end-user sides, has not been investigated in detail so far.

The present paper aims to present (i) the current configuration of the DH network with respect to the reference case, (ii) energy and environmental analysis from both thermal plant and end users' points of view by comparing the DH network with the individual heating, (iii) the energetic analysis from the production side through the calculation of the PES and the specific energy consumption obtained by a cubic meter of NG used to feed the heating generation technologies available in the thermal plant, (iv) the economic analysis from the end-users' point of view by comparing the DH network and the IH, (v) the economic analysis from the production side considering the grid losses and the simultaneous production of heat and electricity by the CHP unit, (vi) both pros and cons of the DH network considering the geographical and social context in which the DH network is placed, (vii) possible improvements of the thermal power plant to increase the flexibility of the CHP unit installed in the thermal plant with the use of a HP and/or TES, which have been partially discussed in [24] assuming different scenarios, and (viii) lessons learned from the Osimo case study, generalized to be widened in other CHP-DH plants to be a starting point to improve other existing plants from the energy, environmental, and economic points of view.

This paper is structured as follows: Section 2 presents an overview of the case study related to a DH network located in Osimo (AN) in the center of Italy, providing detailed information about the cogeneration plant and the DH networks well. Section 3 describes the methodology used to carry out energy, environmental, and economic analysis from both production and the end users' sides. Section 4 discusses the results obtained from the methodology explained in the previous section, showing also possible solutions like the installation of an HP or a TES [24] to increase the flexibility of the CHP unit. Section 5 summarizes and generalizes lessons learned from the Osimo case study. Finally, Section 6 reports the conclusions of the work.

2. Case Study

2.1. Thermal Power Plant

This work analyses the use of a DH network installed in a small town, named Osimo (AN), located in the Center of Italy. It is the only DH network installed in the Marche region and supplies 3% of the total heat demand to both residential and industrial end-users. The town belongs to the climatic zone D (Degree Day 2.073) where the minimum temperature is −2 °C during the winter season and the highest is 34 °C in the summer season, as shown in Figure 2. Heat and electricity are produced through a CHP unit composed of a Natural Gas (NG) fuelled ICE. The rated electrical power is 1.2 MWel, while the heating one is 1.3 MWth. The CHP unit provides flexibility to both DH network and the electricity grid. The thermal energy is used to supply the DH network. The CHP unit operates by following the heat demand of the end-users that will be described in detail in the next Section 2.2: it can modulate the thermal load to produce the required thermal energy.

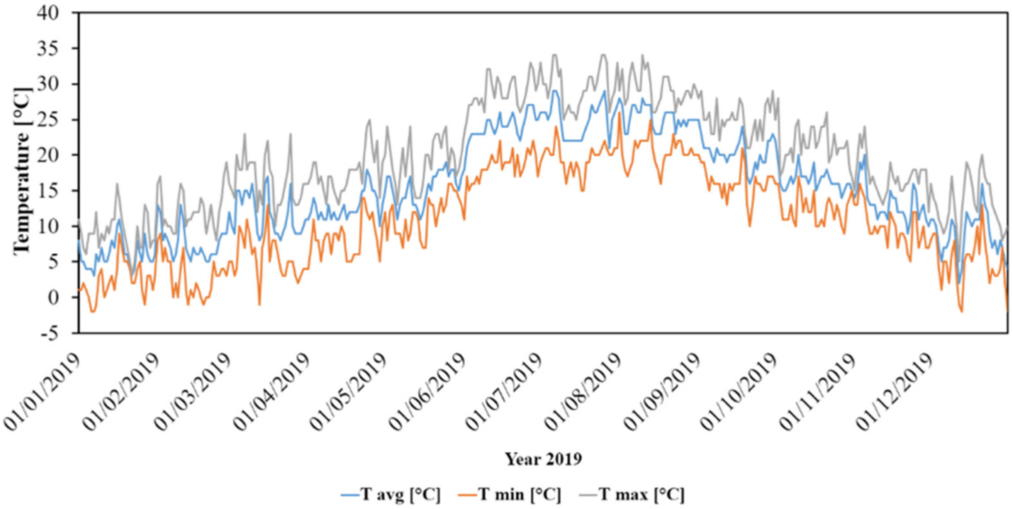


Figure 2. Temperature profiles recorded in Osimo (year 2019).

However, the CHP unit is not the only piece of equipment installed in the thermal power plant connected to the DH network under investigation. Indeed, the plant has also NG boilers (2 boilers having 4.6 MWth and 1 boiler with 4.2 MWth, one of them used as back-up) that provide additional thermal energy when the demand exceeds the CHP unity capacity. Figure 3 shows the layout of the thermal plant where both CHP unit and boilers are presented [32].

The CHP unit is connected in series with the boilers, which are connected in parallel. The main technical data of both CHP unit and boilers are listed in Table 1.

Table 1. Technical data of the CHP unit and boilers.

Magnitude [Unit of Measure]	Values
CHP unit rated electric power [MW]	1.2
CHP unit rated thermal power [MW]	1.3
Boilers rated thermal power [MW]	13.4
$\eta_{th,CHP}$ [-]	0.42
$\eta_{e,CHP}$ [-]	0.41
$\eta_{th,boil}$ [-]	0.962

The operating principle of the thermal power plant, which is mostly used in the winter season, is here described: the water flow rate comes back to the plant through the return pipelines of the DH network, having a temperature of about 60 °C, and then goes to the cooling circuit of the CHP unit, as well as through a heat exchanger to cool down its exhausts. For clarity, the cooling circuit plus the heat exchanger on the CHP unit side is named "CHP circuit" hereinafter. In the end, the flow rate elaborated by the CHP circuit is increased from 60 °C to about 75–76 °C. During the winter season, if the output temperature of the flow rate exiting the CHP circuit is lower than the setpoint one in the boilers, all the flow rate is elaborated by the boilers to reach the set value, keeping in mind that one or two boilers can operate, while the other one is used as a backup.

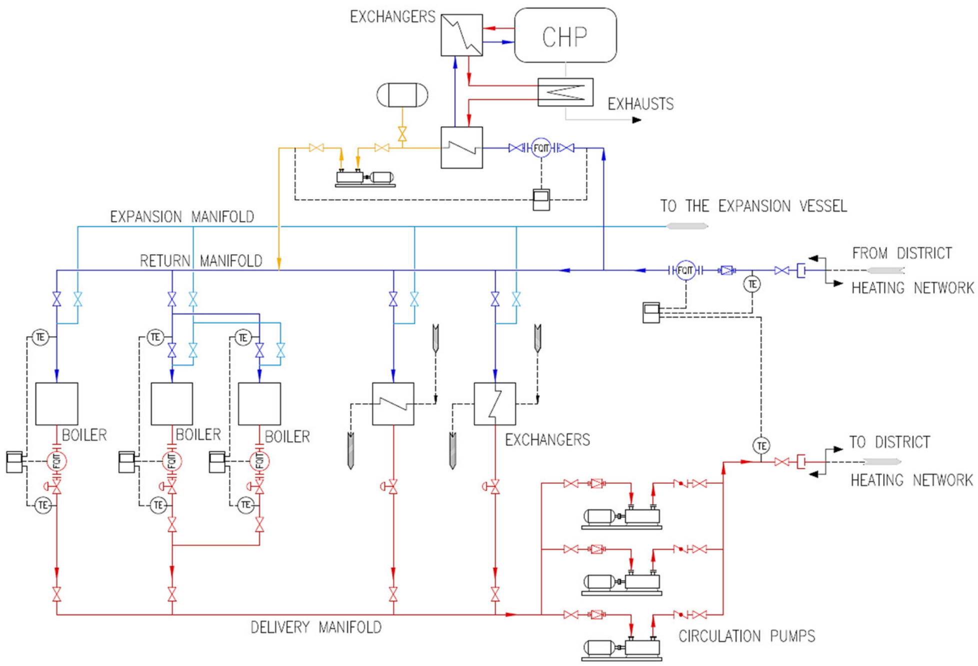


Figure 3. Scheme of the thermal plant connected to the analyzed DH network [32].

2.2. District Heating (DH) Network

The DH network is constituted by 45 km of insulated polyurethane pipelines, namely 22.5 km of supply pipelines plus 22.5 km of return ones, provided with external mechanic protection in polyethylene. It supplies room heating and domestic hot water to about 1278 end-users, namely 1204 residential buildings and 74 public or commercial customers. The DH network is composed of two main circuits: the first circuit is directly connected to the thermal power plant and supplies heat to the end-users located at altitudes between 90 and 190 m a.s.l., while the secondary one is physically disconnected from the primary one through two plate exchangers located in a pumping station (old town center) and serves end-users placed between 180 and 255 m a.s.l as shown in Figure 4.

The commercial end-users account for 51% of the total thermal demand, while the residential ones constitute the remaining 49%.

The DH supply temperature varies depending on the season: the time range in which thermal demand peaks are recorded are the same in all the seasons, mainly from 7:00 to 9:00 and from 18:00 to 20:00, with greater intensity in the winter season. During the winter season, the supply temperature varies from a minimum of 66.1 °C to a maximum of 99.1 °C, in the mid-season it varies from 58.3 °C to 90.8 °C, and during the summer season it varies from 40.4 °C to 87.4 °C. The return temperature, instead, in the winter season varies from 55.2 °C to 66.8 °C, in the mid-season it varies from 53.1 °C to 71.5 °C, and in the summer season it varies from 30.4 °C to 64.4 °C.

Table 2 lists the monthly heat losses in the DH network (year 2019) together with the incidence of the heat losses on the total thermal energy produced, showing how the incidence of the heat losses is much higher in the summer season, where the thermal demand is lower, and reaches the maximum value of 62.1% in August, compared to the winter season where the minimum value of 16.6% is recorded in January.

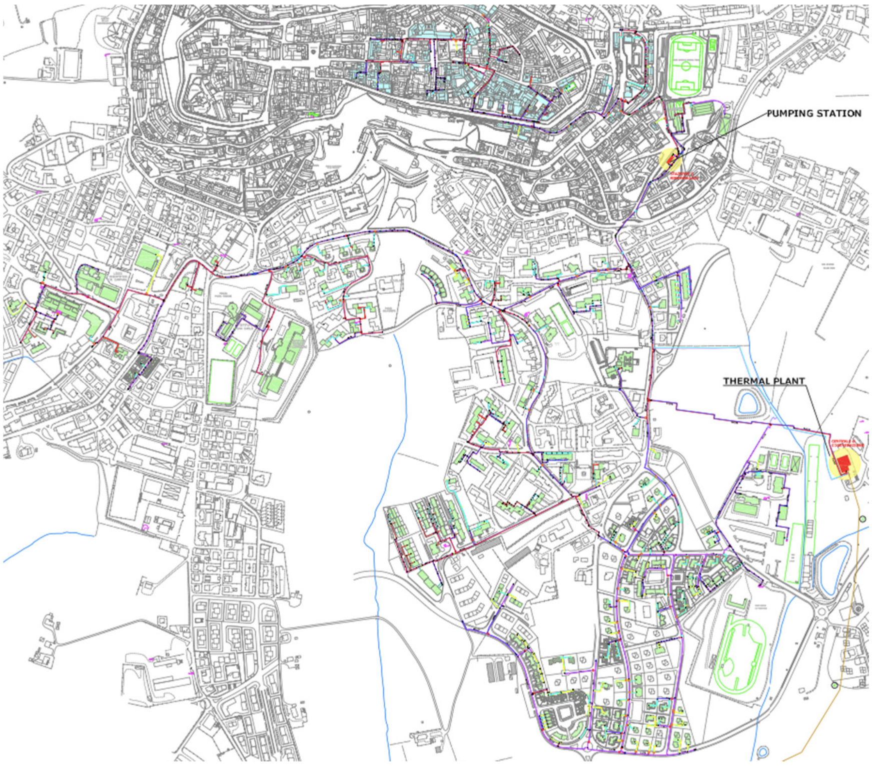


Figure 4. Overview of the DH network (both thermal power plant and pumping station are highlighted in yellow).

Table 2. Thermal losses in the DH network (year 2019).

Month	1	2	3	4	5	6	7	8	9	10	11	12
Heat losses [MWh]	643.7	575.8	564.6	497.0	487.6	406.4	353.0	345.1	369.2	432.5	496.2	563.7
Incidence of the heat losses [%]	16.6	20.2	27.0	34.0	39.8	60.6	61.3	62.1	56.3	50.2	28.8	20.5

The local heat demand is provided with a 15-min resolution for the whole year as shown in Figure 5. The peaks of the heat demand are close to 9.5 MWh in the winter season, namely in January, and drops down to 0.5 MWh in the summer one, namely between June and September.

The water supply temperature is regulated in the different seasons to compensate the thermal losses inside the DH network. Usually, the CHP unit has the priority on the energy production, while the boilers are switched on whenever the thermal demand exceeds the maximum available thermal power of the CHP unit. In the winter season (November–March), the supply temperature is 95 °C and the CHP unit is always operating coupled with the boilers, which provide additional thermal power to reach the maximum set temperature. In the mid-season (April–mid-June and mid-September–October), the supply temperature ranges between 78 °C and 85 °C: the ICE modulates its load in the night (from 20:00 to 7:00), while during the day it operates like in the winter season: the boilers are switched-on only if needed. In the summer season (mid-June–mid-September), the CHP unit usually does not operate, and the thermal power is entirely produced by the boilers reaching a maximum temperature of almost 75 °C. This happens because the heat demand required by the end-users falls below the maximum value that can be delivered by the CHP unit: in this case, the machine operates partially being limited below 60% of the CHP unit rated power. Whenever the value of the thermal power falls below the minimum threshold value of 780 kW, the CHP unit is switched off and the thermal power is entirely supplied by the boilers. Certainly, the repeated switching on/off makes the use of the CHP unit inconvenient, as well as dangerous; thus, several devices must be used to let the CHP unit operate properly and limit the risk of possible failures as well.

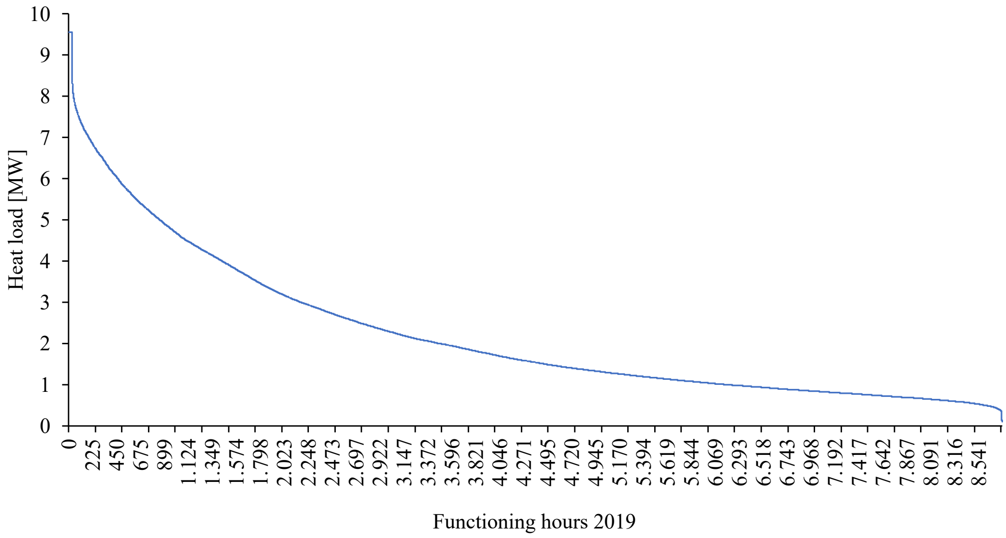


Figure 5. Heat load duration curve (year 2019) provided by the DH.

3. Methodology

The methodology used in this paper for evaluating energy, environmental, and economic aspects of the analyzed DH network, to evaluate the benefits with respect to residential/industrial boilers, is presented. In particular, Section 3.1 deals with both energy and the environmental analysis, while Section 3.2 presents the used economic one.

Figure 6 shows a flow chart that summarizes the methodology used and presented in this study, highlighting the correlation between the energy and environmental analyses in the thermal power plant with the one in the end-users' side.

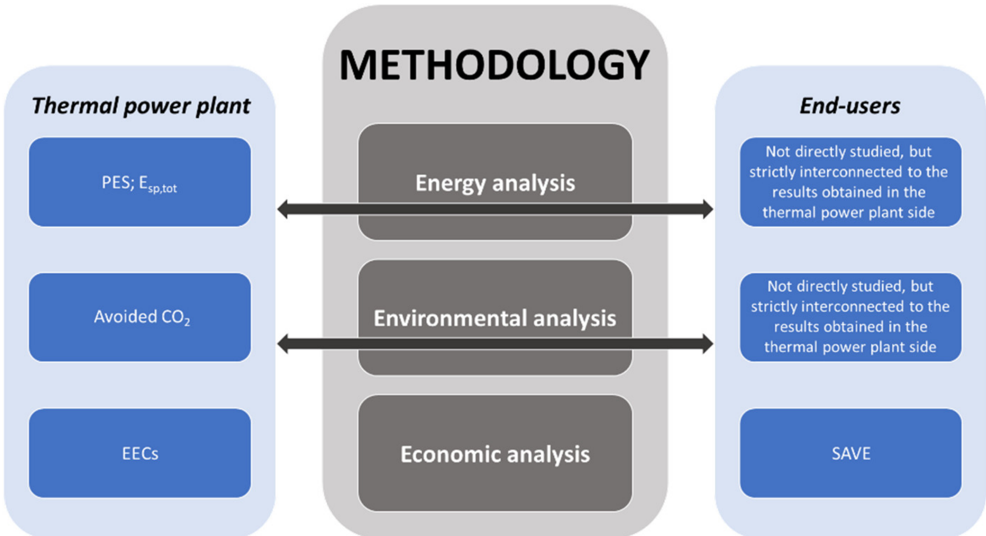


Figure 6. The flow chart of the methodology used in both thermal power plant and end-users' side.

3.1. Energy and Environmental Analysis

The energy analysis has been carried out by analyzing two parameters, namely the Primary Energy Saving (PES) and the specific energy (E_{sp}), while the environmental one takes into account the avoided CO_2.

Considering the European countries, the PES formula and its correction factors have been determined by the EU regulation [33]. The PES expresses the relative saving of the primary energy achievable by a CHP unit compared to the separate production of both thermal energy and electricity. It is calculated as indicated by Equation (1):

$$PES = (1 - 1/((\eta_{e,CHP}/\eta_{e,ref}) + (\eta_{th,CHP}/\eta_{th,ref}))) * 100\ [\%] \quad (1)$$

where:

- $\eta_{e,CHP}$ is the electrical efficiency of the CHP unit, defined as the ratio between the yearly electricity produced by the cogeneration unit and the energy of the entire fuel supply used to produce both useful heat and electricity by the CHP unit;
- $\eta_{e,ref}$ is equal to 49.81% [33] and it is the reference efficiency value for the separate electricity production;
- $\eta_{th,CHP}$ is the thermal efficiency of the CHP unit, defined as the ratio between the yearly useful heat produced by the cogeneration unit and the energy of the entire fuel supply used to produce both useful heat and electricity by the CHP unit;
- $\eta_{th,ref}$ is equal to 92% [33] and it is the reference efficiency value for the separate heat production.

The PES calculation allows to determine whether a CHP unit is highly efficient or not: this qualification can be obtained from plants smaller than 1 MWel if they do not consume more primary energy than the most efficient thermal power plants that produce the same amounts of heat and electricity separately. Similarly, the qualification of high-efficiency cogeneration can be obtained if they guarantee a primary energy saving higher or equal than 10% [33] for plants having a power capacity higher than or equal to 1 MWel.

Another parameter that is worth investigating is the specific energy, which expresses the highest potential energy exploitation from a cubic meter of fuel, such as NG in this case. Considering the overall thermal power plant, the specific energy is calculated through Equation (2):

$$E_{sp,tot} = TE_{sp,CHP} + TE_{sp,boil} + EE_{sp,CHP}\ [kWh/Sm^3] \quad (2)$$

where $TE_{sp,CHP}$ and $TE_{sp,boil}$ are the specific thermal energy of the CHP unit and boilers, respectively, while $EE_{sp,CHP}$ is the specific electric energy of the CHP unit. Equations (3)–(5) show how to evaluate $TE_{sp,CHP}$, $TE_{sp,boil}$, and $EE_{sp,CHP}$ respectively.

$$TE_{sp,CHP} = \text{Net thermal energy produced by the CHP unit (losses included)/fuel consumed by the CHP unit}\ [kWh/Sm^3] \quad (3)$$

$$TE_{sp,boil} = \text{Net thermal energy produced by the boilers (losses included)/fuel consumed by the boilers}\ [kWh/Sm^3] \quad (4)$$

$$EE_{sp,CHP} = \text{Net electric energy produced by the CHP unit (losses included)/fuel consumed by the CHP unit}\ [kWh/Sm^3] \quad (5)$$

Once the total specific energy of the thermal power plant ($E_{sp,tot}$) is calculated, including both thermal and electrical ones, the difference (ΔE_{sp}) of the specific energy obtained through the thermal plant ($E_{sp,tot}$) and the residential/industrial boilers (Low Heating Value LHV_{CH4}), which is equal to 9.339 kWh/Sm^3 in the case of NG at standard condition (T = 25 °C, P = 1 bar), is obtained through Equation (6) considering the reference thermal efficiency [33]. The overall energy saving ($Es_{th,el}$), both thermal and electrical included, has been calculated per each month of the year 2019 in which $\Delta E_{sp} > 0$ according to Equation (7), namely by multiplying ΔE_{sp} with the cubic meters of NG that would have been consumed by residential/industrial boilers. The latter has been calculated by dividing the thermal energy effectively consumed to the LHV_{CH4}, thus ignoring the boilers' thermal efficiency that has been already considered in the ΔE_{sp} calculation (see Equation (6)). Finally, the tonnes of avoided CO_2 are calculated through Equation (8):

$$\Delta E_{sp} = E_{sp,tot} - (LHV_{CH4} * \eta_{th,ref}) \ [kWh/Sm^3] \quad (6)$$

$$Es_{th,el} = \Delta E_{sp} * (Sm^3 \text{ of NG consumed by residential/industrial boilers}) \ [kWh] \quad (7)$$

$$\text{Avoided } CO_2 = (Es_{th,el} * Fc_{CO2})/1000 \ [tCO_2] \quad (8)$$

where:

- Fc_{CO2} is the conversion factor, which is used to evaluate the avoided CO_2 by knowing the energy that would have produced that amount of CO_2, equal to 0.1936 $kgCO_2/kWh$ [34].

3.2. Economic Analysis

After both energy and environmental analyses, the economic one must be performed to assess the advantages of using a DH network from both thermal power plant and end-users' perspective.

3.2.1. Thermal Power Plant Side

In Italy, the economic advantages due to the use of high-efficiency cogeneration plants are assessed through the so-called Energy Efficiency Certificates (EEC) that remunerate energy producers that have performed energy efficiency interventions on a system, thus achieving primary energy saving over time.

The PES, which has been defined in Section 3.1, indicates whether the high-efficiency cogeneration requirements have been fulfilled or not according to the size of the thermal power plant, and it is a quantifier of the Italian EEC to be provided to an energy producer as described by Equation (9) [35]:

$$EEC = (RISP * 0.086) * K \ [-] \quad (9)$$

where:

- (RISP * 0086) is the saving, if positive, expressed in Tonnes of Oil Equivalent (TOE) and calculated according to Equation (10):

$$RISP = E_{CHP}/\eta_{e,ref} + H_{CHP}/\eta_{th,ref} - F_{CHP} \ [kWh] \quad (10)$$

where:

- RISP is the primary energy savings, expressed in kWh, achieved by the CHP unit in the solar year in which access to the support scheme is requested;
- E_{CHP} is the electricity produced by the CHP unit in the same solar year expressed in MWh;
- H_{CHP} is the thermal energy produced by the CHP unit in the same solar year expressed in MWh;
- F_{CHP} is the energy consumed by the CHP unit in the same solar year expressed in MWh;
- $\eta_{e,ref}$ is the reference electric efficiency, which is equal to 0.53, and it must be adjusted according to the connection voltage, the amount of both consumed and supplied energies to the grid as well as the climatic zone;
- $\eta_{th,ref}$ is the reference thermal efficiency equal to 0.90;
- K is a harmonized coefficient, equal to 1.386, and calculated as shown in [34].

The values previously reported, considering the case study under investigation, are listed in Table 3: it is worth noting that these values change whether considering the EU legislation [33] or the Italian one [35].

Table 3. Different correction factors values and electric and thermal reference efficiencies.

Parameters	EEC Calculation (Italian Legislation [35])	PES Calculation (EU Legislation [33])
$\eta_{e,ref}$ (a) [-]	0.46	0.53
Correction factor 1: climatic zone (b) [-]	0.00369	0.00369
Correction factor 2: off-site (c) [-]	0.945 [1]	0.935 [2]
Correction factor 3: on-site (d) [-]	0.925 [1]	0.914 [2]
$\eta_{e,tot} = (a + b)*(c * EE_{del}{}^{3} + d * EE_{self\text{-}cons}{}^{3})$ [-]	0.4374	0.4981
$\eta_{th,ref}$ [-]	0.90	0.92

[1] These values are related to a connection voltage level between 0.4 and 50 kV. [2] These values are related to a connection voltage level between 12 and 50 kV. [3] These values for the case study under investigation are 92% and 8%, respectively.

3.2.2. End-Users' Side

To make the DH network economically competitive, the management of the DH network under investigation brought the cost of the connection closer to that of a 25 kW condensing boiler. In particular, the cost of a 25-kW condensing boiler varies from 2000 to 2500€: that said, the cost of the connection to the DH network is about 1800€. From the end-users' point of view, the economic analysis is carried out by multiplying the effective thermal energy consumed by the end-users (residential/industrial) using the DH network [36] and gas [37] tariffs considering the consumption ranges; thus, the overall yearly costs in 2019 for both DH (DH_{tot}) and Individual Heating (IH_{tot}) have been obtained. In addition, an average cost for maintenance, repairing, mandatory periodic boiler controls, cleaning, and check of the flue gases are added to the individual yearly heating cost as well as the cost of the electricity used to the boiler switch-on and functioning ($IH_{tot + extra\ costs}$). It is worth noting that all these extra costs have been made available by the company that manages the DH network of this case study, quantified as 170€/year. For clarity, Table 4 lists in detail the cost items previously mentioned.

Table 4. List of yearly average costs for a residential/industrial boiler.

Parameters	Values
Average cost of maintenance, periodic boiler control, cleaning, and check of the flue gases [€/year]	100
Average cost for repairing [€/year]	50
Average cost of electricity to switch-on the boiler [€/year]	20
Total [€/year]	170

Once the overall yearly costs per user, whether connected to the DH or to individual boilers, have been calculated, the present economic analysis related to the end-users' side considers only the residential one. This choice allows to work with reliable and quantifiable data, which can be reproduced on a large scale, and to not fail in the quantification of extra costs that non-residential users would have incurred by using boilers. Furthermore, in this analysis it has been also assumed extra costs for non-residential IH are higher than residential ones because the higher the power of the installed boilers, the higher the operating, maintenance, and spare parts costs.

Hence, residential users have been divided into four groups according to the thermal consumption: (i) yearly energy consumption less than or equal to 5000 kWh/y (Group 1), (ii) yearly energy consumption between 5001 and 10,000 kWh/y (Group 2), (iii) yearly consumption between 10,001 and 15,000 kWh (Group 3), and (iv) yearly energy consumption greater than 15,001 kWh/y (Group 4). Then, the difference between the overall yearly costs of end-users connected to the DH and those who have the IH has been calculated by Equation (11), thus obtaining the cost difference between the first technology and the second one:

$$\Delta Cost = DH_{tot} - IH_{tot + extra\ costs}\ [€/year] \quad (11)$$

Finally, by dividing the cost difference obtained with Equation (11) with the overall yearly cost for each residential user connected to the DH, Equation (12) evaluates the percentage of the previous difference to assess the saving (SAVE): negative SAVE values ($SAVE_{<0}$) imply that IH is cheaper than DH; conversely, positive SAVE values ($SAVE_{>0}$) imply that the DH is cheaper than IH.

In the latter case, the percentages of SAVE have been divided in three categories: (i) residential users with a SAVE lower or equal than 10% ($SAVE_{10}$), (ii) between 10% and 50% ($SAVE_{10,50}$), and (iii) greater than 50% ($SAVE_{50}$). Certainly, SAVE values equal to zero imply that there is no economic difference whether the DH or the IH is used.

$$SAVE = (\Delta Cost/DH_{tot}) * 100\ [\%] \tag{12}$$

4. Results and Comments

This section deals with the performance of the thermal power plant focusing on the CHP unit in the year 2019, moving then to both energy and environmental results from the thermal power plant point of view in Section 4.1. In addition, Section 4.2 deals with the economic results from both thermal power plant and end-users' side.

Figure 7 shows the share of the NG used by the CHP unit and boilers, while Table 5 reports the CHP plant energy performance in the year 2019. It can be observed that, yearly, the CHP and the boilers consumed almost the same amount of primary energy, namely 1,553,871 Sm^3 by the CHP unit and 1,456,713 Sm^3 by the boilers. Furthermore, only the gas boilers operate in the summer season, while in the mid-season the CHP unit has the priority over the boilers: this is also clear in Table 5 when comparing the columns related to the "CHP unit Thermal Energy production" and to the "Boiler Thermal Energy production", respectively.

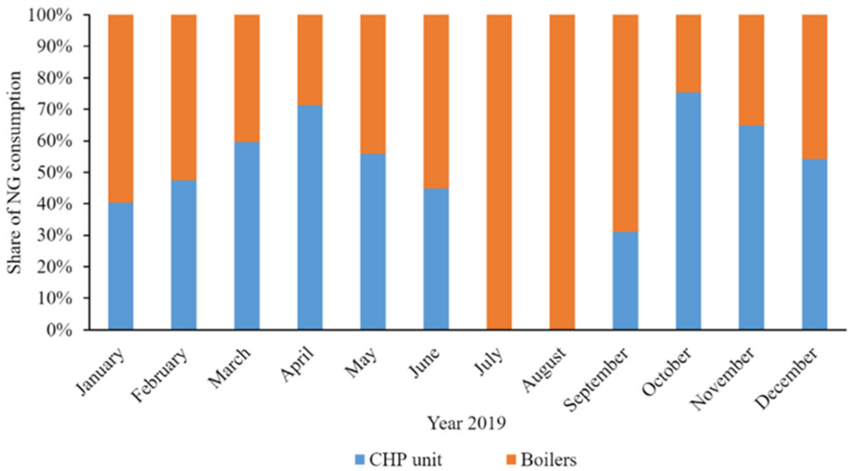


Figure 7. Share of the NG consumption by the CHP unit and boilers (year 2019).

4.1. Energy and Environmental Results

According to Equation (1), Table 6 shows the monthly trend of the PES related to the CHP unit recorded in the year 2019. It can be stated that the CHP unit, not considering the summer months of July and August since it does not operate, is more competitive than the separate production, providing a yearly reduction of the primary energy consumption of 21.3%. The maximum PES achievable is 22.4% in December (with $\eta_{th,CHP}$ = 43.1% and $\eta_{e,CHP}$ = 40.8%), while the minimum one is 18.8% in September (with $\eta_{th,CHP}$ = 39.5% and $\eta_{e,CHP}$ = 39.9%). Since the PES is greater than 10%, the Osimo CHP unit falls within the definition of high-efficiency cogeneration (electric power production higher than 1 MWel). Among the energy saving, EEC can be issued by the Italian Government for 10 years long.

Table 5. Monthly operational data/performance parameters of the CHP unit (year 2019).

Month	CHP NG Consumption [Sm^3]	Boiler NG Consumption [Sm^3]	CHP TE Production [MWh]	Boiler TE Production [MWh]	DH Load [MWh]	CHP Unit EE Production [MWh]	CHP Unit EE Delivered [MWh]
1	230,266	342,387	915.0	2971.7	3243.0	878.4	804.21
2	207,910	230,301	822.8	2025.5	2272.5	793.5	733.83
3	211,114	143,278	832.7	1254.7	1522.8	804.9	753.00
4	187,692	76,050	733.8	725.8	962.6	713.9	661.53
5	108,686	86,382	424.8	800.5	737.7	411.6	376.85
6	43,548	53,861	165.7	505.2	264.5	162.5	146.44
7	0	65,468	0.0	576.2	223.2	0.0	0.0
8	0	62,047	0.0	556.0	210.9	0.0	0.0
9	27,280	60,587	101.3	554.3	286.4	102.4	92.87
10	120,848	39,490	460.8	400.8	429.1	458.0	420.26
11	185,260	100,635	749.2	971.2	1224.2	708.5	647.42
12	231,267	196,227	937.0	1818.0	2191.3	887.5	798.47
Total	1,553,871	1,456,713	6143.1	13,159.9	13,568.2	5921.2	5434.9

Table 6. Monthly specific energy parameters and the avoided CO_2 (year 2019).

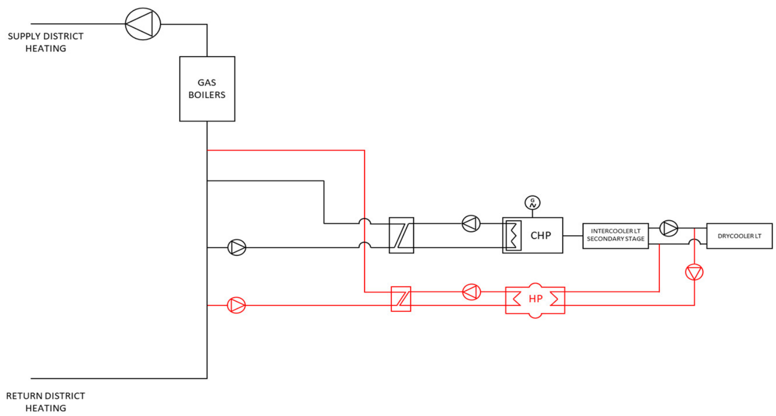
Month	PES [%]	$TE_{sp,CHP}$ [kWh/Sm^3]	$TE_{sp,boil}$ [kWh/Sm^3]	$EE_{sp,CHP}$ [kWh/Sm^3]	$E_{sp,tot}$ [kWh/Sm^3]	ΔE_{sp} [kWh/Sm^3]	$E_{th,el}$ [kWh]	Avoided CO_2 [Tonnes]
1	21.5	3.32	7.24	3.81	14.37	4.97	1,906,550	369
2	21.4	3.16	7.02	3.82	13.99	4.59	1,233,595	239
3	21.3	2.88	6.39	3.81	13.08	3.68	662,448	128
4	20.9	2.58	6.29	3.80	12.68	3.28	372,941	72
5	20.7	2.35	5.58	3.79	11.72	2.32	202,329	39
6	19.2	1.50	3.70	3.73	8.93	−0.47	-	-
7	0.0	-	3.41	-	3.41	−5.99	-	-
8	0.0	-	3.40	-	3.40	−6.00	-	-
9	18.8	1.62	4.00	3.75	9.37	−0.02	-	-
10	20.0	1.90	5.05	3.79	10.74	1.34	68,168	13
11	22.2	2.88	6.87	3.82	13.57	4.17	603,501	117
12	22.4	3.22	7.37	3.84	14.43	5.03	1,302,964	252
Average	21.3	2.78	6.35	3.81	12.94	3.54	5,678,900	1099

Another parameter that is fundamental for investigating the energy results of the CHP unit and, indirectly, for analyzing the environmental results is the specific energy. Table 6 lists the monthly results related to the specific energy; in particular, there are no advantages in terms of energy exploitation when $\Delta Esp < 0$ (summer period). The same considerations can be done for the boilers, while the electrical specific energy from the CHP unit is constant throughout the year. It is worth noting that the heat losses recorded during the year, being equal to 5734.8 MWh, have been considered in the energy assessment of the thermal power plant, leading to lower exploitation of the primary energy and thus to lower values of specific energies. Indeed, the heat losses increase from 16.6% in January to 62.1% in August when the DH network achieves its minimum production, thus leading to a significant decrease in the specific thermal energy, considering both CHP and boilers, that ranges from 3.32 kWh/Sm^3 in January to 1.50 kWh/Sm^3 in June, and from 7.37 kWh/Sm^3 in December to 3.40 kWh/Sm^3 in August, respectively. On the other hand, the specific electric energy does not suffer grid losses and remains constant: this is essentially due to the need of keeping the heat transfer fluid temperature constant, even when end-users do not need it. It would be unthinkable to interrupt the heat supply when there is the minimum demand because the reaction times to increase the thermal load would be too long to adequately satisfy end-users' needs.

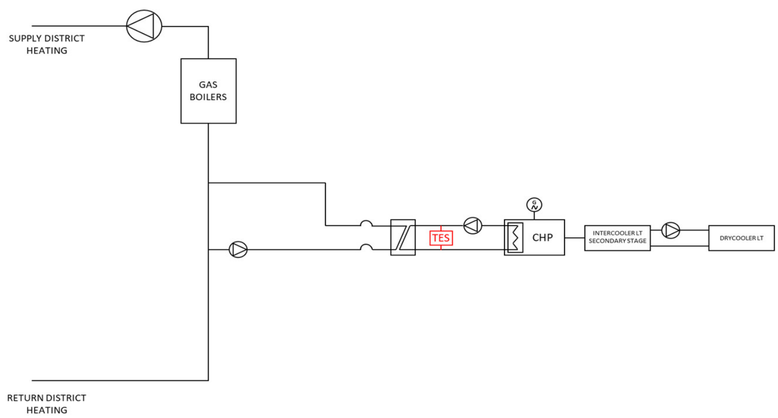
To deepen the Osimo DH network analysis and to sum up the outcomes obtained so far, it is interesting to notice that the thermal power plant performance varies between summer/mid-seasons and winter season. Indeed, the formers harm the entire energetic, environmental, and economic points of view from the thermal power plant side, as already discussed in Section 4.2.1, while in the latter there is a considerable improvement due to the higher end-users' demand that leads the thermal power plant to operate most of the time at rated condition.

At first glance, a possible solution for improving the performance of any DH network throughout the year can be the supply temperature reduction. However, this solution cannot be adopted in the Osimo case due to the presence of a hospital among the users served, which involves the need to maintain a supply temperature always higher than 70 °C in the summer season due to the continuous anti-legionella sanitization treatments.

Nevertheless, possible further advantages can be achieved by performing important interventions on the thermal power plant, namely to install a Heat Pump (HP), as shown in Figure 8a, and a Thermal Energy Storage (TES), as shown in Figure 8b, where both increase the flexibility of the CHP unit, thus further improving the operation of the CHP unit itself and increasing the amount of CO_2 avoided. It is worth noting that this part is only intended to provide useful information, and numerically quantify possible obtainable results, in case of the implementations of HP and TES technologies. Figure 9 shows the results obtained with the two configurations, previously mentioned, compared to the baseline layout, highlighting how both thermal and electrical efficiencies, the PES, the avoided CO_2, and the EECs vary in different seasons and in the entire year as well.



(**a**)



(**b**)

Figure 8. Schematics of the CHP-DH plant configurations and in red, the new technologies: (**a**) configuration with the heat pump (CHP + HP); (**b**) configuration with thermal energy storage (CHP + TES).

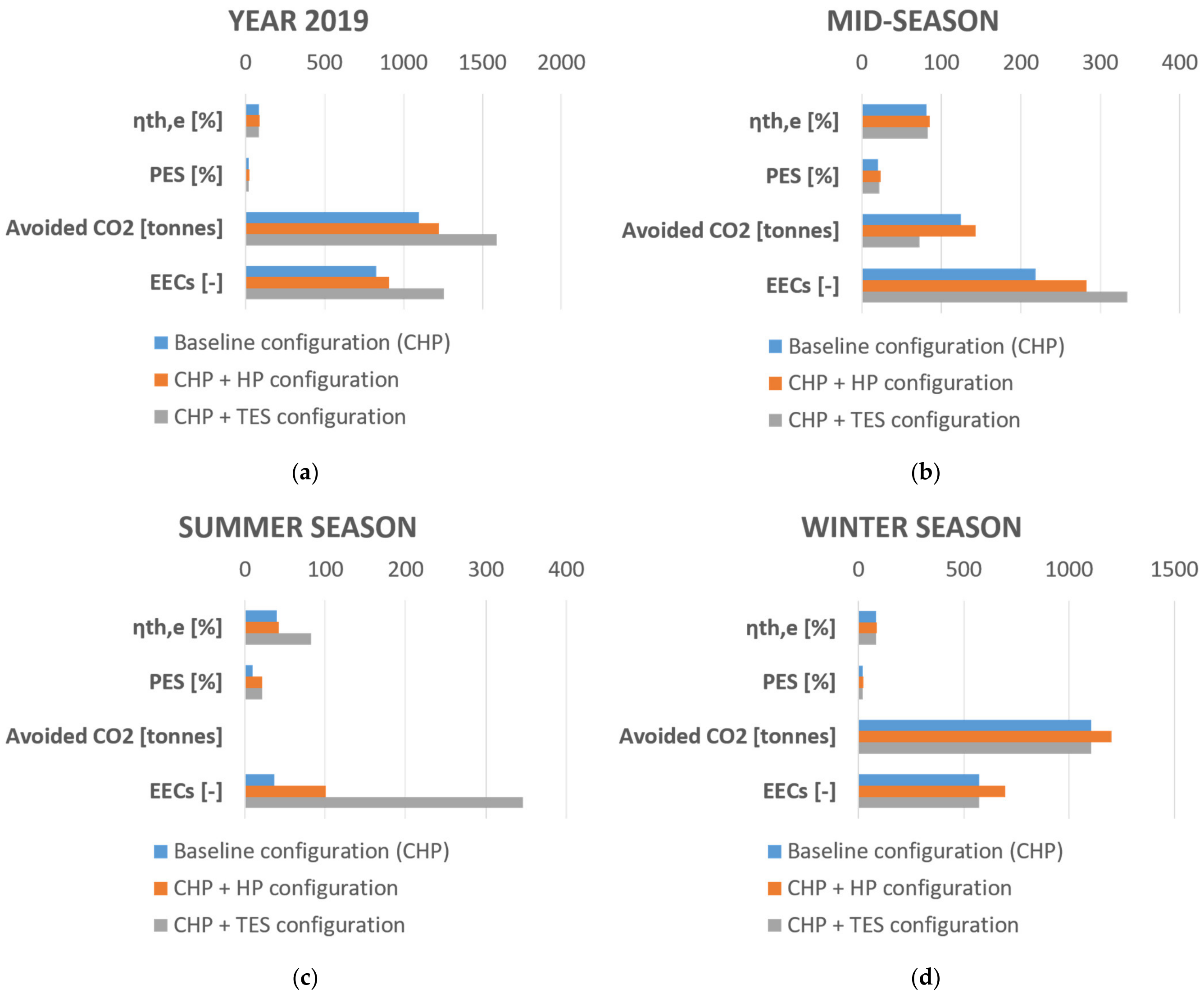


Figure 9. $\eta_{th,e}$, PES, Avoided CO_2 and EECs of the total 2019 year (**a**), mid-season (**b**), summer season (**c**), and winter season (**d**) for the CHP-DH plant baseline configuration, configuration with the heat pump (CHP + HP) and configuration with thermal energy storage (CHP + TES).

4.1.1. CHP + HP Configuration

The installation of the HP in parallel with the CHP unit (CHP + HP configuration) can allow recovering waste heat from the low-temperature ICE cooling system, and then use it to integrate the thermal energy production for the DH network. In particular, a HP having a rated thermal capacity of about 150 kW and an average COP of about 4, can be selected based on the amount of thermal energy dissipated by the CHP unit, which remains constant over time, and it is equal to about 130 kW.

This new installation can let the HP operate without negatively affecting the CHP unit performance, while it is driven by the electricity produced by the CHP unit itself. Based on the working hours of the CHP in the 2019 year, and the technical specification of the HP, this new installation can reach an annual thermal energy production of about 618 MWh, leading to an increase of the yearly thermal efficiency of 4.2% and total yearly efficiency of 86.8%. In addition, the yearly PES would increase up to 24% allowing to avoid about 120 tonnes of CO_2 more than it can be achieved by the configuration without HP. On the other hand, considering the specific energy in the summer period where a negative ΔE_{sp} is obtained, it has been forecasted that the installation of this new heat pump does not bring significant improvements in the summer period when the CHP unit operates less than in the other periods of the year. Figure 9 shows the possible energy, environmental, and economic benefits of the CHP + HP configuration in all the periods of the year, especially highlighting this solution that would perform better in winter season and the mid-seasons as well.

4.1.2. CHP + TES Configuration

Based on the current layout constraints of the existing thermal plant, it has been also assumed the installation of a TES (CHP + TES configuration, Figure 8b) having the following dimensions: a length of 12.6 m, which represents the maximum height within the plant; a diameter of 3.35 m, which is the best compromise between having a height-to-diameter ratio as high as possible and not having small dimensions that would lead to turbulent water flows within the TES. Indeed, the TES has the aim to obtain a proper water stratification (mixing between hot and cold water), and this can be achieved by, rather than optimally sizing the TES, inserting iron plates with decentralized holes that further slowdown the mixing process to have the flow as laminar as possible.

To simulate the CHP + TES configuration, the white-box approach is used: not having experimental data available, a mathematical model has been constructed using the mathematical equations dealing with the phenomenon under investigation. The TES has been schematized as a stratified hot water tank (multi-node 1Dmodel category): it is a fluid-filled sensible energy storage tank, subject to thermal stratification, assuming that the tank consists of 16 fully mixed equal volume segments [38]. Flow streams enter the tank at fixed positions. The water flow from the DH network side enters at the bottom of the tank and the hot source stream from the CHP enters at the top of the tank. Further details related to the model are explained and discussed in [39].

Data from the year 2019 shows that the CHP unit operates at full capacity in the winter season and some months of the mid-season; thus, it has been decided to investigate the new configuration (CHP + TES) in the months between May and October (mid- and summer season). The TES installation allows to increase the CHP unit operating hours up to 2344 h in the period May-October, thus allowing to lengthen its functioning in the summer season and especially in July and August when it is currently switched off.

As shown in Table 7, the thermal and electric efficiencies are 42.3% and 40.8%, respectively, and the overall efficiency increases up to 83.2% in August with respect to the configuration without TES. On yearly basis, instead, there is not an evident increase in efficiency: the thermal one increases by 0.3%, while the electric one increases by 0.2%, achieving an overall efficiency increase of 0.5% with respect to the current configuration without TES. In addition, considering the minimum value of PES obtained in August for the current configuration (12.4%), it increases up to 21.8%. The yearly PES, instead, could increase up to 0.4%.

Finally, considering the specific energy in the summer season, the specific thermal and electrical energies of the CHP unit achieve values of 1.54 and 3.83 in the month of July, and 1.51 and 3.84 in the month of August, respectively. These results lead to a negative ΔE_{sp} in the months when the TES operates, namely from May to October. Nevertheless, the ΔE_{sp} would reach a value of −4.03 in the month of July and −4.05 in the month of August, these values being less negative than the ones obtained with the current configuration.

These worsening results from the ΔE_{sp} point of view are due to lower exploitation of NG with the CHP unit than boilers due to the lower overall efficiency of the CHP unit (adding both thermal and electrical efficiencies and considering the same percentage of the heat losses in May-October period). For this reason, ΔE_{sp} is negative when the boiler operates less or not at all. However, on a yearly basis, the configuration with TES allows avoiding about 490 tCO_2 more than the configuration without TES. Finally, it should therefore be pointed out that the installation of the TES leads to environmental and economic advantages (the latter discussed in Section 4.2.1) instead of energy ones, displayed in Figure 9.

Table 7. Monthly parameters of CHP + TES configuration (year 2019).

CHP + TES Configuration											
Month	$\eta_{th,CHP+TES}$ [%]	$\eta_{e,CHP+TES}$ [%]	$\eta_{th+e,CHP+TES}$ [%]	**PES** [%]	[1] $TE_{sp,CHP+TES}$ [kWh/Sm^3]	[1] $TE_{sp,boil}$ [kWh/Sm^3]	[1] $EE_{sp,CHP+TES}$ [kWh/Sm^3]	[1] $E_{sp,tot}$ [kWh/Sm^3]	[1] ΔE_{sp} [kWh/Sm^3]	$E_{th,el}$ [kWh]	**Avoided CO_2** [tonnes]
1	42.3	40.6	82.9	21.5	3.32	7.24	3.81	14.37	4.97	1,906,550	369
2	42.1	40.6	82.7	21.4	3.16	7.02	3.82	13.99	4.59	1,233,595	239
3	42.0	40.6	82.6	21.3	2.88	6.39	3.81	13.08	3.68	662,448	128
4	41.6	40.5	82.1	20.9	2.58	6.29	3.80	12.68	3.28	372,941	72
5	42.8	41.2	84.0	22.6	2.42	2.11	3.87	8.41	−0.99	-	-
6	40.9	39.4	80.3	19.1	1.52	0.41	3.70	5.63	−3.77	-	-
7	42.3	40.7	83.0	21.7	1.54	-	3.83	5.37	−4.03	-	-
8	42.3	40.8	83.2	21.8	1.51	-	3.84	5.35	−4.05	-	-
9	42.6	41.0	83.6	22.3	1.75	0.75	3.86	6.36	−3.04	-	-
10	42.8	41.2	83.9	22.6	2.00	2.80	3.87	8.67	−0.73	-	-
11	43.0	40.7	83.7	22.2	2.88	6.87	3.82	13.57	4.17	603,501	117
12	43.1	40.8	83.9	22.4	3.22	7.37	3.84	14.43	5.03	1,302,964	252
Average (5–10)	42.3	40.8	83.1	21.8	1.83	1.93	3.83	7.60	−1.80	-	-
Average (yearly)	42.3	40.7	83.0	21.7	3.17	6.95	10.12	13.94	4.54	8,217,808	1591

[1] It has been assumed that the heat losses are the same as in the current configuration.

4.2. Economic Calculation

In the following subsections, the economic analyses related to the thermal power plant and the end-users' side are presented, respectively. In this Subsection, dedicated to the thermal power plant, the advantages due to the use of possible new configurations, namely CHP + HP and CHP + TES are reported.

4.2.1. Thermal Power Plant Side

According to Equation (9), Figure 9 shows the primary energy saved, expressed in MWh, monthly and the economic value of EECs, while Table 8 shows the number of EECs that the CHP unit has reached. Overall, 829 EECs were obtained in the year 2019, reaching the corresponding economic income of 207,222€. Furthermore, by analyzing the new configurations such as CHP + HP and CHP + TES, the following results would be obtained: an increase of 81 EECs with a further 20,325€ in the first case, and an increase of 425 EECs with further 106,358€ in the latter.

Table 8. EEC results of the thermal power plant (year 2019).

Month	1	2	3	4	5	6	7	8	9	10	11	12	Total
RISP [MWh]	1036.0	931.5	942.5	830.8	481.1	187.7	-	-	114.8	522.0	848.1	1061.0	6955.6
Italian EECs [-]	123	111	112	99	57	23	-	-	14	63	101	126	829
Income [€]	30,845	27,719	28,028	24,736	14,315	5682	-	-	3455	15,616	25,230	31,566	207,222

It is worth noting that EECs have a strong influence on the CHP unit operation profitability. At present, the CHP unit of Osimo case operates primarily in the energy production over boilers: in the winter season, the CHP unit operates at full load, in the mid-seasons it operates at partial load, and in July and August it is switched off as already widely discussed in Section 2. The CHP unit partial load operation in the mid-seasons, as well as the shutdown in the summer months, leads to a decrease of the energy production and sale of both heat and electricity as well, thus leading to a significant loss of EECs and therefore to lower economic revenue.

As depicted from this analysis, the TES installation allows an early CHP unit switch-on, which increases its operating hours and therefore it leads to a substantial increase of EECs as well.

In addition, it is important to implement optimization strategies in the planning of the CHP unit switch-on without the need to make substantial changes in the thermal power plant. The thermal demand of Osimo varies during the day and the months as well: this behavior cannot be exactly predicted, and therefore it cannot be planned a priori. However, based on the parameters recorded in the past, it is possible to estimate the trend. According to the season, the heat load provided by the DH network varies depending on the temperature as shown in Figure 10, which highlights a large difference between winter and summer thermal powers when considering only the domestic hot water. Analyzing the values of the thermal demand in 2019, it is clear that, during the day, the load curve takes the form of a "camel hump", which becomes more marked in the winter season.

Considering the thermal power of the CHP unit (Figure 10, dotted line), it can be easily figured out that there is a greater thermal demand than the one offered in the mid-seasons up to 22. By updating the CHP unit programming in the face of this possibility, it leads to a daily increase of two hours of the CHP unit operation itself. The current planning (07:00–20:00 in the mid-seasons), which was created before 2017 and maintained until now, took into account that, in that period, the value of EECs was around 100.00€ and that the sale of electricity in those additional hours fell (and still falls) in the low-cost range, and therefore is unprofitable. Thus, it was not convenient, even if there was the possibility, to run the CHP unit. At present, the value of an EEC is much higher, accounting to 250.00€, and thus implying a considerable convenience and the justification of such discussion. It is necessary to add, for the sake of clarity, that Figure 10, and in particular the graph concerning the mid-seasons, can be misleading as it does not reflect the veracity of the daily load curve, but the average of four months.

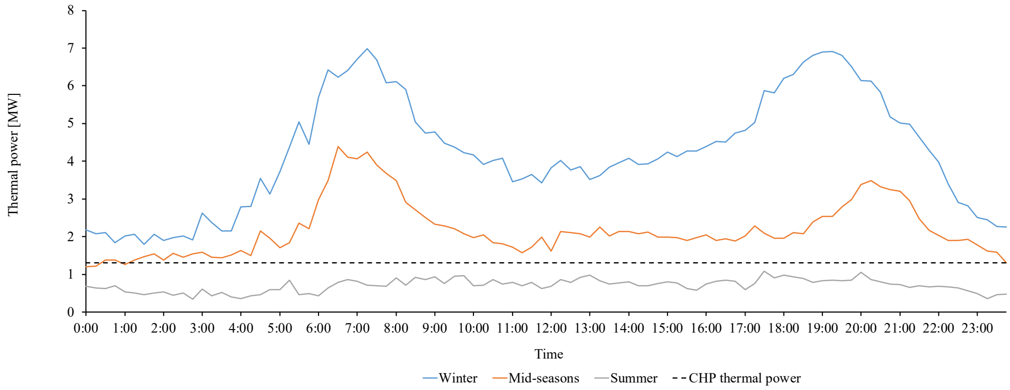


Figure 10. The trend of typical daily heat demand in winter, mid-, and summer seasons.

4.2.2. End-Users' Side

Data related to 1154 residential users (50 residential users with annual consumption below 1000 kWh have been excluded from this analysis. It has been assumed that these residential users use alternative technology for domestic heating while remaining connected to the DH network) have been used in this analysis (see Figure 10). Group 1, whose consumption does not exceed 5000 kWh/y, represents 46.2% (533 users) of the test sample. Group 2, whose consumption ranges from a minimum of 5001 kWh/y to a maximum of 10,000 kWh/y, represents 45.8% (528 users) of the sample. Group 3, whose consumption is between 10,001 and 15,000 kWh/y, represents 7% (76 users) of the sample. Finally, Group 4, composed by residential users with a yearly consumption higher than 15,001 kWh, represents 1% (17 users) of the sample.

Figure 11 shows that, yearly, DH is cheaper than IH in 84.7% of the cases. In particular, residential users have obtained a maximum saving of 10% in 55.2% of the cases, and from a minimum of 10% to a maximum of 50% in 27.3% of the cases. Only in 2.2% of the cases, a saving greater than 50% has been obtained only from residential users belonging to Group 1. In 3.3% of the cases, there was no difference between the two technologies. Finally, a negative SAVE has been achieved in 12% of the cases, meaning that DH is less convenient than IH. Nevertheless, it is worth noting that in the latter case, and only for one residential user, the maximum percentage of negative SAVE reached in Group 2 is 15%: in the other cases in Group 2, the negative SAVE is always below 10%. In Group 1 there is a maximum of 10% of $SAVE_{<0}$ and in Group 3 a maximum of 7% of $SAVE_{<0}$: this means that the economic advantage of IH does not reach significant percentages such as it occurs in DH.

It is interesting to note that, if the extra costs related to boilers were not taken into account, a higher bill would have been obtained for all the DH end-users in each group. In particular, regarding Group 1, 41.1% of the end-users would pay more than 30%; 0.8% of the end-users would pay more than 10%, and the remaining 58.1% of end-users would pay between 10 and 29% extra. Regarding Group 2, 3.8% of the end-users would pay more than 30%, 1.9% of the end-users would pay more than 10%, and the remaining 94.3% end-users would pay between 10 and 29% extra. Regarding Group 3, 55.3% of the end-users would pay more than 10%, and the remaining 44.7% end-users would pay between 11% and 21% extra. Finally, regarding Group 4, 100% of the end-users would pay 10% more. The cost difference in the DH bill compared to IH fades a consumption increase (from Group 1 with lower consumption, which recorded a greater increase, to Group 4 with higher consumption and lower increases). This detail is in line with the sentiment of a part of DH users of the Osimo network, who complain about the high cost in the bill, preferring therefore a lower monthly payment and then paying the extra annual costs of the boiler separately. These extra costs are not wrongly taken into account as attributable to IH users, so they are not counted in their household budget. Another important aspect that should not be underestimated regards the facilities that IH users can access, compared to those of DH—such as preferential taxes and social bonuses—which, unfortunately, affect the choice of one technology rather than another one.

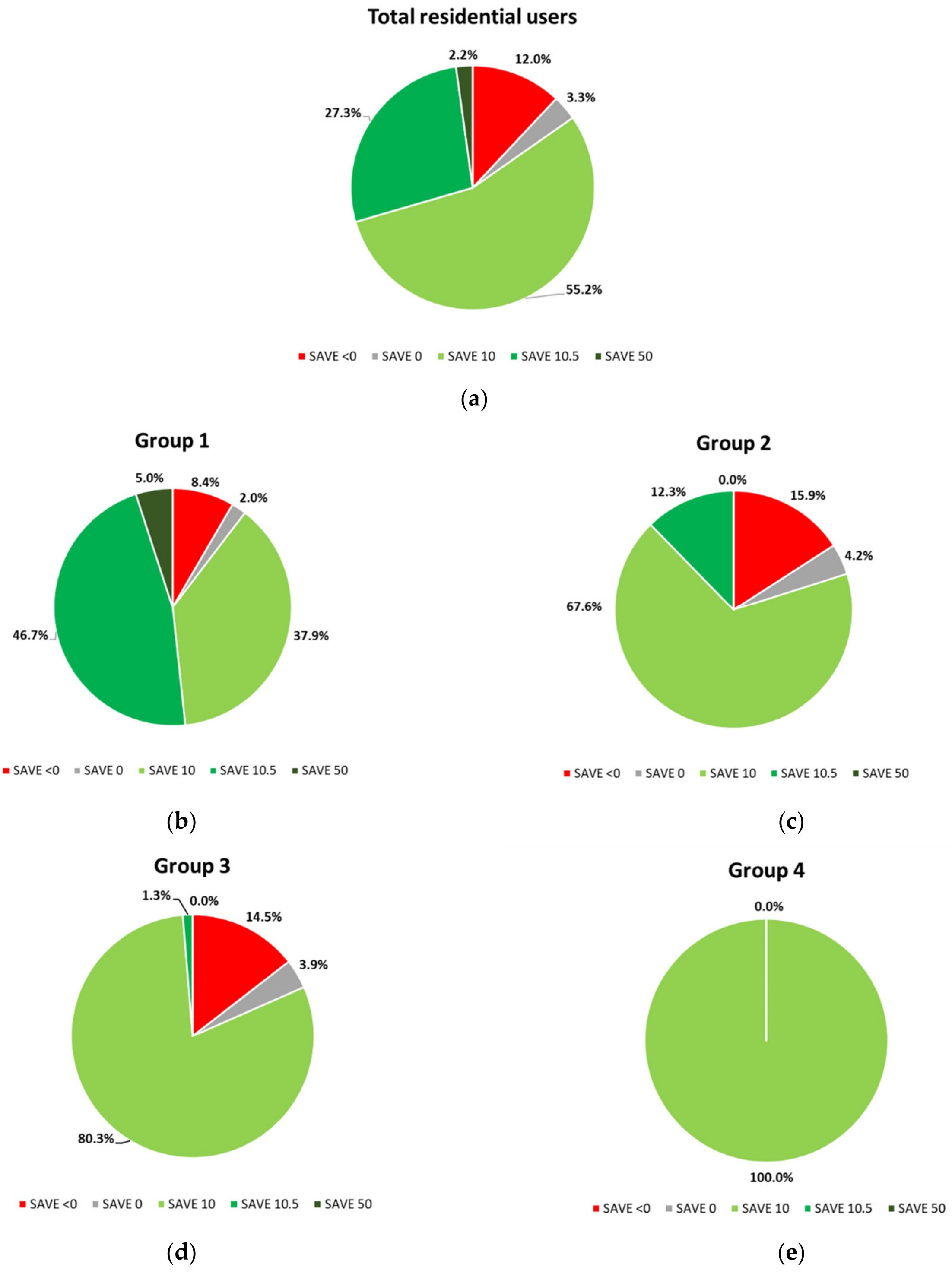


Figure 11. Economic results of the total residential users (**a**), Group 1 (**b**), Group 2 (**c**), Group 3 (**d**), Group 4 (**e**) for the year 2019. The red slice means IH is more convenient than DH; the green graduations, from light to dark green, mean DH is more convenient than IH; the grey slice means the economic results of IH and DH are the same.

5. Lessons Learned

Thanks to the analysis of a real case study as presented in this article, it was possible to learn the following lessons: (i) in a small DH network, localized in medium climate zone, the coupling of CHP and DH is more advantageous in terms of energetic, environmental, and economic points of view for both thermal plant and end users' side; (ii) the EEC markets are fundamental to sustain the cost of the investment, as well as being a source of income from the production perspective. For this reason, it is important to study the new possible installation of technologies able to increase system flexibility, such as heat pumps and/or thermal energy storage; (iii) The CHP + HP configuration allows to obtain major benefits in the winter season when the CHP unit is fully operational and therefore also the heat pump, (iv) the installation of TES in a CHP plant instead, where the CHP unit cannot increase its working hours in the winter season, does not affect in the winter season, but in the summer one. This is because the TES allows the CHP unit to work even in the summer season when the baseline configuration is off. These results can be considered a good indication for generally improving other DH networks located in the north of Europe with a forecast for obtaining better results than those reported in this work due to the colder temperatures throughout the year. (v) The installation of possible further technologies, such as the HP and TES considered in this study, can guarantee system flexibility if they are coupled with the CHP unit. These solutions can lead to important advantages from energetic, environmental, and economic points of view. Obtained outcomes can be useful to improve other DH networks and push forward the use of these technologies in those countries where the use of DH networks can be favorable. (vi) Although the European Union promotes the use of DH network, highlighting its convenience, comfort, and safety compared to IH, there are still too many bureaucratic obstacles that do not allow the reduction of construction costs, thus increasing the number of served end-users. (vii) The common feeling of consumers of DH networks is that the cost of DH is higher than that of IH: this aspect is mainly linked to the geographical position of the DH network, as well as the degree of development in a specific area.

6. Conclusions

In this study, a comparison between the current and the previous (with Individual Heating (IH)) configurations of a District Heating (DH) network located in the center of Italy has been carried out from energy, environmental, and economic points of view. In particular, both thermal power plant and end users' sides have been analyzed, as well as possible technical improvements. Since, a comprehensive study with real data, comprising energy, an environmental, and an economic analysis of both thermal plant and end-user sides, has not been investigated in detail so far, real data of both cogeneration plant and end-users' sides have been used in this analysis.

Precisely, two parameters have been used to assess the performance of the overall DH network under investigation: the Primary Energy Saving (PES) and the specific energy (E_{sp}). It is worth noting that the specific energy difference (ΔE_{sp}) obtained considering the actual thermal power plant layout, constituted by two boilers and a Combined Heat and Power (CHP) unit, and the IH has been studied, where positive values mean that the Natural Gas (NG) exploitation is better exploited and vice versa.

The current configuration of the plant records a ΔE_{sp} less than zero in the summer season (June-September): in particular, the month of August is the one in which the lowest ΔE_{sp} value has been obtained, equal to -6.00 kWh/Sm^3. Regarding the PES, a yearly value of 21.3% has been reached. From the environmental point of view, 1099 tCO_2 are avoided. As for the economic analysis on the thermal plant side, thanks to the achievement of 829 EECs, it is possible to obtain an economic income of 207,222€, while on the user side the DH was found to be, yearly, cheaper than individual heating in 84.7% of the cases considering that the management of the cogeneration plant lowered the connection cost till the one referred to a 25 kW condensing boiler installation.

However, the performance of the DH network can be further improved by implementing possible configurations, namely coupling the CHP unit with a Heat Pump (HP) or a Thermal Energy Storage (TES). In the first case, there was no significant improvement in the ΔE_{sp} in the summer season. From the environmental point of view, the yearly PES has reached the value of 24% with an increase in the avoided CO_2 value of about 120 tons compared to the current configuration. From the economic point of view, the installation of the HP allows increasing the EECs number of 81 by additional 20,325€ compared to the current configuration. In the latter, the installation of a TES increases the number of months in which the ΔE_{sp} turns out to be negative (May-October), but August showed a less negative ΔE_{sp} value of -4.05 kWh/Sm$^{3.}$ The yearly PES reaches the value of 21.7% with a further 490 tCO_2 avoided compared to the current configuration. From the thermal power plant side, the installation of the TES leads to a further 425 EECs with an additional income of 106,358€ compared to the current configuration.

As it can be seen, the configurations CHP + HP and CHP + TES do not bring improvements from an energy point of view, but they can lead to both environmental and economic points of view due to the higher tCO_2 avoided and thus to their remuneration through EECs.

Furthermore, other methods for improving the performance of the overall DH network have been discussed, such as the possibility to manage the CHP unit operation based on the EECs mechanisms. These do not necessarily imply important changes in the thermal plant and/or new installations: it is possible to obtain a greater number of ECCs with only the analysis of the thermal load curve monthly, combined with the updated cost of certificates, to target the best program solution to increase the CHP unit working hours.

The last aspect discussed in this paper is the economic analysis on the end-users' side, which highlighted how the extra cost related to the IH boilers influences the final bill of the end-users: considering the extra cost, the DH is more convenient than IH and vice versa.

Future research should focus on the use of flexibility technologies coupled with DH networks, comparing their initial investment cost, the energy, environmental, and economic benefits of their use, as well as depreciation time. Furthermore, the investigation of these ante and post intervention aspects with real data would be of great interest for current DH network to further enhance their performance and deployment as well.

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Abbreviations

Nomenclature

ΔCost	difference between the overall yearly costs of end-users connected to the DH and those who have the IH
ΔE_{sp}	delta specific energy
DH_{tot}	overall yearly costs in 2019 for district heating
ECHP	electricity produced by the CHP unit in the same solar year

$EE_{sp,CHP}$	specific electric energy of the CHP unit
E_{sp}	specific energy
$E_{sp,tot}$	total (thermal + electric) specific energy
$Es_{th,el}$	thermal and electrical energy saving
Fc_{CO2}	conversion factor to evaluate the avoided CO_2, equal to 0.1936 $kgCO_2/kWh$
F_{CHP}	energy consumed by the CHP unit in the same solar year
H_{CHP}	thermal energy produced by the CHP unit in the same solar year
IH_{tot}	overall yearly costs in 2019 for individual heating
$IH_{tot+extra\ costs}$	overall yearly costs in 2019 for individual heating + extra costs for maintenance, repairing, mandatory periodic boiler controls, cleaning, and check of the flue gases
K	harmonized coefficient, equal to 1.386
LHV_{CH4}	Low Heating Value of methane gas
RISP	primary energy savings achieved by the CHP unit in the solar year
SAVE	the ratio between ΔCost and DH_{tot}, expressed in percentage
$TE_{sp,boil}$	specific thermal energy of the boilers
$TE_{sp,CHP}$	specific thermal energy of the CHP unit
$\eta_{e,CHP}$	electrical efficiency of the CHP unit
$\eta_{th,boil}$	thermal efficiency of the boilers
$\eta_{th,CHP}$	thermal efficiency of the CHP unit
$\eta_{e,ref}$	reference efficiency value for the separate electricity production
$\eta_{th,ref}$	reference efficiency value for the separate heat production

Acronyms

CHP	Combined Heat & Power
DH	District Heating
DHC	District Heating and Cooling
EEC	Energy Efficiency Certificate
EU	European Union
EVs	Electric Vehicles
HP	Heat Pump
ICE	Internal Combustion Engine
iGDH	Generation of District Heating, where i = 1 to 5 represents the first to fifth generation
IH	Individual Heating
LHV	Low Heating Value
NG	Natural Gas
PBP	Payback Period
PES	Primary Energy Saving
PV	PhotoVoltaic
RES	Renewable Energy Sources
TES	Thermal Energy Storage
V2G	Vehicle-To-Grid

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