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Energy mapping and district heating as effective tools to decarbonize a city: Analysis of a case study in Northern Italy

Giulia Spirito[a,*], Alice Dénarié[a], Vincenzo F. Cirillo[a], Francesco Casella[b], Jacopo Famiglietti[a], Mario Motta[a]

[a] *Department of Energy, Politecnico di Milano, via Lambruschini 4, 20156 Milano, Italy*
[b] *Department of Electronics, Information and Bioengineering (DEIB), Politecnico di Milano, Via Ponzio 34/5, 20133 Milano, Italy*

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Abstract

The process of achieving decarbonization and greenhouse emissions' reduction goals is facilitated and accelerated by the implementation of renewable-based DH rather than multiple individual renewables systems. This work presents an application case that demonstrates how an energy system based on conventional and carbon-emitting heat supply sources can be converted in a fully renewable network.

In its current configuration, the city under study, located in Northern Italy, gets 40% of the total 160GWh of heat demand of the DH from a waste-to-energy plant, 9% from a biomass-fuelled ORC, 33% from natural gas cogeneration and 18% from natural gas boilers. In order to support the city's municipality in developing decarbonization measures through the modernization of the current district heating network, the aim of this work is to investigate in detail the possibility to integrate local renewable and excess heat sources, whose availability and synergy with the heat demand has been highlighted by a recent mapping-based project developed with the Italian DH Association, AIRU, on the whole Italian territory. The present work can be therefore seen as a validation case study of the methodology developed at large-scale level in the latter project. The results of that analysis show that there are the conditions to meet 90% of the heating needs of the DH with renewables and waste heat recovery from two already existing plants, namely a wastewater treatment plant (WWTP) and a steelwork. The approach used in this work, in which different scenarios of integration are simulated in energyPRO, brought to the definition of the energy mix which evidenced a favourable cost–benefits ratio: 59% of thermal energy from the steelwork, 31% from the WWTP, 5% from the natural gas CHP and 5% from the boilers.

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Keywords: Waste heat recovery; Renewables; Energy planning; DH potential; Decarbonization; Demo case

* Corresponding author.
E-mail address: giulia.spirito@polimi.it (G. Spirito).

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1. Introduction

1.1. Background and objectives

As member of the European Union, aimed at achieving carbon-neutrality in 2050 [1], Italy has been asked to develop national long-term strategies towards reduced greenhouse gases emissions, improved energy efficiency and energy security. In order to accelerate this process towards full decarbonization of the energy sector, 2030 has been set as an interim milestone and an Integrated National Energy and Climate Plan (INECP) has been established [2]. According to it, in 2030 Italy plans to pursue the target of generating 30% of gross final energy consumption from renewable sources, of which 45% is their contribution in the heating and cooling sector. As it is recognized in [3], district heating has the potential to play a major role in this task since it can enhance the large-scale integration of high-efficient heat pumps, through which it would be possible to recover heat from unconventional, low-temperature excess heat sources such as wastewater treatment plants (WWTPs) and industrial facilities, together with the more common combined heat and power (CHP) plants.

Within the illustrated framework, this work presents an application case in which, thanks to a mapping-based approach, district heating is proven to be an effective technology for complete decarbonization of an existing energy system based on conventional and carbon-emitting heat supply sources. By considering the available heat sources that can be potentially integrated in the district heating system of the city under study, four different scenarios have been simulated and analysed through the software energyPRO[1] [4]. A sensitivity analysis has been then conducted in order to assess the impact of changes in total costs and CO_{2eq} emissions and, based on the obtained outcome, the configuration the most convenient for the city has been selected.

The treated city has been chosen as demo case because of two main reasons that brought the attention to it:

- the local administration showed an interest in transitioning towards a greener and more sustainable energy mix to supply thermal energy in the existing DH network. Among other proposed business cases, the one defined in this work have been therefore submitted to the local authority.
- the results obtained in a recent study [5] funded by AIRU and conducted by Politecnico di Milano and Politecnico di Torino, concerning the assessment of the unexploited potential of waste and renewable heat in Italy through detailed mapping of these sources, showed that in the examined city there are the conditions to meet 95% of its heating needs through renewables and waste heat sources. This reference work not only supported the intention to perform the feasibility study, but it also proved to be its basis in terms of methodology and data. An overview of its main results, taken as starting point, is presented in Chapter 2.

1.2. Literature survey

The opportunity to integrate renewable and excess heat in DH has been highlighted for the first time in the European project Ecoheatcool [6], in which it has been recognized that the net heat demand in Europe essentially equals the amount of heat released during primary to final energy conversion. Henceforth, many studies related to excess heat recovery and renewables' integration in DH systems have been performed, aimed at quantifying the technical realistic potential at small and large-scale applications. Among these studies, mainly conducted in Scandinavian countries with a mature DH market, we can find the study [7] in which Bühler et al. analysed excess heat sources from the industrial sector in Denmark, determining how to integrate them in DH and quantifying the heat potentially recoverable directly or through heat pumps. Similar analysis, but related to the Swedish framework, can be found in [8] and [9]. The viability of large heat pumps in existing district heating systems has been examined also in Finland, in the study at Ref. [10], where the feasible share of heat pump production has been quantified by simulating different sized DH systems with energyPRO. This software has been used in a variety of other European case studies aimed at transitioning towards more sustainable and less-emissive energy systems, as in [11] where the replacement of coal boilers with natural gas boilers has been validated, and in several studies finalized in promoting the integration in existing district heating networks of renewable sources, such as biomass and solar

[1] EnergyPRO, developed by EMD International, is the leading software for modelling complex energy systems from a technical and economic point of view. Given input data such as energy needs, weather data and market prices, it allows to combine a variety of energy technologies and to simulate different configurations and operating strategies aimed to a common target (i.e. amount of thermal energy to be annually supplied).

thermal technologies in combination with large scale heat pumps [12–15], and of excess heat sources, such a local refinery [16], datacentres [17], waste-to-energy plants [18]. In this latter paper, also the integration of heat storages is considered, which allows the peak shaving effect: the required installed capacity is reduced, together with the related needs for investment in peaking capacities.

2. Current framework

With the aim to explore the challenges and the opportunities of deploying a higher share of renewables and excess heat sources in the DH system of the city under study, different supply options have been investigated and modelled by means of the energy system model energyPRO [4], which performs an hourly simulation of heat supply technology dispatch under the condition that demand is always met.

As said before, thanks to the analysis performed within the project developed with AIRU [5], the starting context in terms of heat demand, available heat sources and their synergy in the analysed city was clear. An annual heat demand of about 580 GWh has been estimated for both residential and service sector buildings and for both space heating and domestic hot water preparation. Of this, 160 GWh is the estimated quota of heat demand that can be technically connected to DH system without further interventions at building level and that is competitive with respect to the individual heating solutions taken as reference. According to what is declared by the district heating operator in the city, this estimated value matches the thermal energy effectively distributed annually through the current DH configuration. Indeed, 162 GWh of thermal energy are supplied annually to more than 600 buildings (of both residential and service sectors) by means of a network of 95 km, with a supply temperature of 90 °C and a return temperature of 60 °C on average. As illustrated in Fig. 1, currently this amount of heat supplied to the city is generated by three main sources that are: a waste-to-energy plant that covers 40% of the overall heating needs, a cogeneration plant fed by natural gas which covers 33% of the heat demand and a biomass-fuelled Organic Rankine Cycle (ORC) which supplies a share equal to 9%. Natural gas boilers, which accounts for 18% of the total, are used as back-up in order to ensure the coverage of the heating needs in case of peak demand.

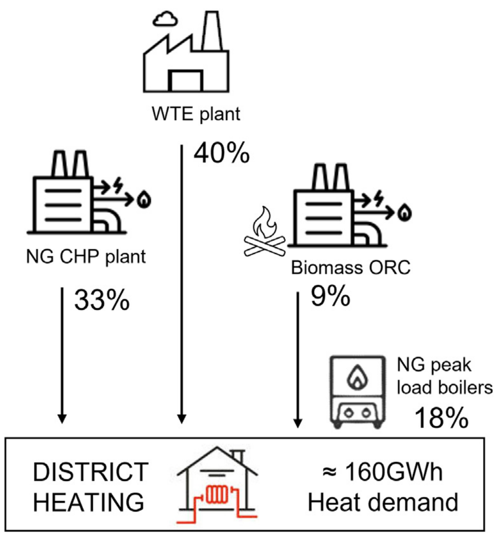

Fig. 1. Current heat generation mix in the city under study.

Together with the heat demand, in the study taken as Ref. [5] also the renewable and excess heat sources existing in proximity of the city were identified and mapped and the amount of excess heat recoverable from them was estimated. Their location, the potentially recoverable heat and their synergy with the heat demand served as starting point for the definition of the simulated scenarios. The mapping-based analysis conducted for the Italian territory within the reference project funded by AIRU [5] highlighted, for the demo city, the existence of two main unconventional heat sources from which a great amount of thermal energy can be potentially integrated in DH: they are a wastewater treatment plant (WWTP) and a steelwork plant, both in combination with one or more heat pumps able to exploit the heat embedded in the water flux released in the environment. These sources are mapped in Fig. 2, where the polygons represent the clusters of heat demand. They are linked one to the other and/or to the available heat sources with the red arrows that represent the energy fluxes. For further details on the methodology developed and used to obtain this map, please refer to the report of Ref. [5].

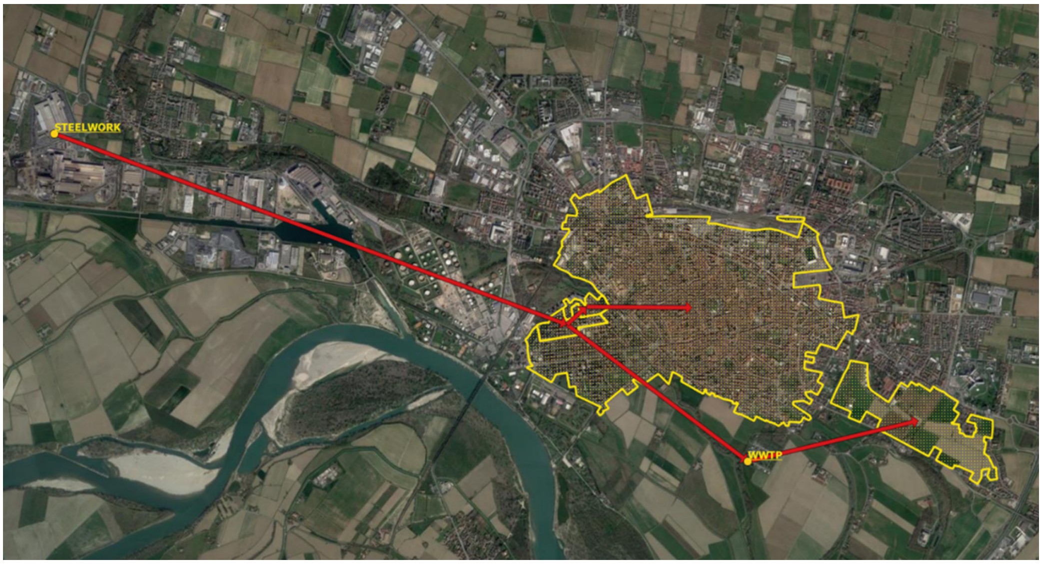

Fig. 2. Map of the city under study as a result of the analysis performed in [5]. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

The four scenarios modelled with energyPRO consist in energy systems in which these two sources are combined with a NG-fuelled cogeneration plant, used to supply electricity to the heat pumps, and with natural gas boilers. Both are also used as backup. In each scenario, each source account for the required heating needs in different proportions.

Before the description of the modelled scenarios, a glimpse on the available excess heat from the two available unconventional sources is reported in the following.

2.1. Available excess heat from the wastewater treatment plant

The heat recovery potential from the existing wastewater treatment plant has been evaluated through the methodology illustrated in [5], based on the data retrieved from the *Hotmaps Toolbox* [19] and from the plant's website, from where also the geographical coordinates have been derived. Considering that the flow rate annually treated ranges from 300 to 600 kg/s and assuming the heating value of wastewater c_{ww} equal to 1.16 kWh/m^3 K and ΔT equal to 5 K, the thermal recovery from the wastewater treatment plant has been computed as in Eq. (1).

$$P = c_{ww} \cdot V \cdot \Delta T \quad [\text{kW}] \tag{1}$$

Then, by assuming that the wastewater temperature is equal to 18 °C on average (as it can be retrieved from studies conducted in other cities of Northern Italy [20,21]) and by considering a DH supply temperature of 90 °C, the coefficient of performance of the required heat pump equals 3 and, starting from the thermal potential of the plant estimated equal to 12.5 MW, the technically recoverable energy from this source is assessed equal to about 120 GWh/year.

2.2. Available excess heat from the steelwork plant

Concerning the steelwork plant, the recoverable heat estimated with the methodology and the input data used in [5] is about 356 GWh/year. This value is supported by the analysis based on more detailed provided data, according to which, from the water flow rate released in the environment at low temperature (30–50 °C), about 360 GWh/year is the recoverable thermal energy. In this case a heat pump with COP = 4.6 is required.

3. Methodology

The studied scenarios are modelled based on the local possibilities evidenced for the demo city, based on previous analysis and based on the earlier described aim towards complete decarbonization. Operation of the considered technologies is allowed during their technical lifetime, no emission limitation is used, the costs associated to each technology are retrieved from the Danish Energy Agency (DEA) [22] catalogue and then adapted to the Italian context through the consultancy of Italian DH operators and other experts. Regarding the economic aspect of the analysis, it should be clarified that the electricity required for the heat pumps' operations is assumed to be generated from the considered biomass-fuelled CHP plant, whose generated heat is also integrated in the district heating system and therefore exploited to meet the heating needs of the city.

Regarding the heat storage, its integration is simulated in three scenarios and its dimensioning, together with its cost, is assessed again based on the DEA catalogue [23] on large-scale hot water tanks. Based on this catalogue, the energy storage capacity C of the water tank is correlated to the tank volume V according to Eq. (2), where ΔT, assumed equal to 55 K, indicates the typical temperature difference (hot/cold) in storage and k indicates the heat availability: generally, only 90% of the heat stored can be utilized. Regarding the costs, the equation reported in Fig. 3 is applied.

$$C = V \cdot \Delta T \cdot k \quad \text{[kW]} \tag{2}$$

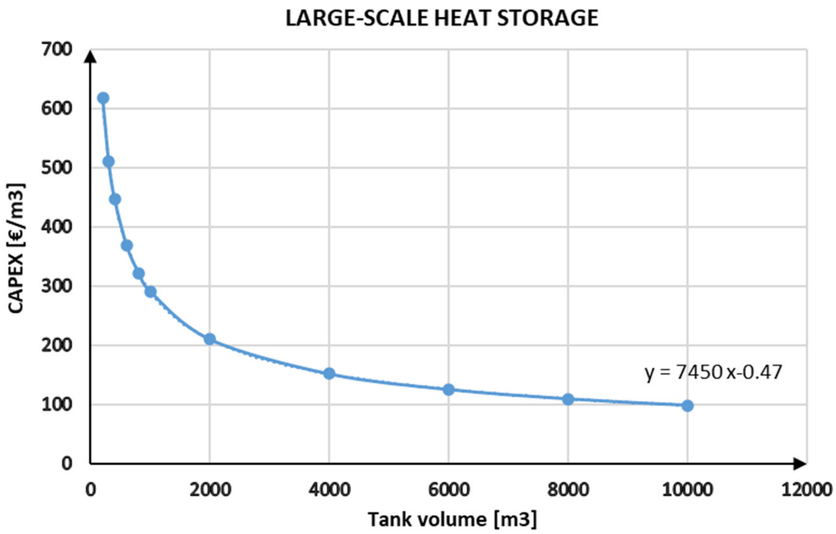

Fig. 3. Specific cost per m^3 of stored heat by total size of tank. Figure based on Rif. [23].

The proposed scenarios are listed in the following and a schematic overview is shown in Table 1:

- **Scenario 1**: here the main difference with the current energy system is the exploitation of the available heat embedded in the wastewater treated in the WWTP through a heat pump of 6 MW. Moreover, the electric power required by the HP is not supplied by the electric grid but by the NG-fuelled CHP plant, whose generated thermal energy is also recovered in district heating. The share of fossil fuels is however still predominant since more than half of the heating needs of the city is still met through natural gas boilers.
- **Scenario 2**: in this case more than half of the heat demand (70% circa) is met by the excess thermal energy recovered through large-scale heat pumps from the WWTP and from the steelwork plant. The natural gas boilers and the CHP are used mainly as backup, in order to cope with peak demand, but a 200 m^3 hot water storage is also considered with the aim to reduce their utilization and therefore their associated costs.
- **Scenario 3**: this scenario is similar to the previous one, since the same heat sources are considered, but a larger storage tank and an additional heat pump integrated in the steelwork facility allow to reduce the share of heat supplied by the two more conventional typologies of sources: the peak load boilers and the CHP plant. The latter, anyway, is always considered in the overall energy mix for heat pumps' supply.

Table 1. Overview of the considered scenarios simulated with energyPRO.

Scenarios	Components	Heat power [MW]	Thermal energy [GWh]	Heat demand coverage [%]
Scenario 1	NG Boiler	75	110,1	68%
	HP — WWTP	6	50,9	31%
	NG CHP	2	1,7	1%
	TOTAL = Heat demand		*162,7*	
Scenario 2	NG Boiler	75	36,2	22%
	HP — WWTP	6	50,8	31%
	HP — steelworks	20	61,6	38%
	NG CHP	6,4	14,1	9%
	Storage	200 [m^3]		
	TOTAL = Heat demand		*162,7*	
Scenario 3	NG Boiler	75	7,4	5%
	HP — WWTP	6	50,8	31%
	HP1 — steelworks	20	66,9	41%
	HP2 — steelworks	10	29,8	18%
	NG CHP	8,7	7,8	5%
	Storage	300 [m^3]		
	TOTAL = Heat demand		*162,7*	
Scenario 4	NG Boiler	75	1,6	1%
	HP — WWTP	6	50,9	31%
	HP1 — steelworks	20	71,6	44%
	HP2 — steelworks	10	24,4	15%
	HP3 — steelworks	10	9,1	6%
	NG CHP	12,2	5,1	3%
	Storage	400 [m^3]		
	TOTAL = Heat demand		*162,7*	

- **Scenario 4**: here the contribution of large-scale heat pumps, which became four (three combined with the steelwork plant and one with the WWTP), is about 96% of the total. The remaining fraction (4%) is covered by the peak load boilers and the CHP plant. A larger heat storage tank, of 400 m^3, is considered.

By looking at the table is evident that there are the conditions to reduce the share of fossil-based heat supply technologies to satisfy the heating needs of the city. Indeed, by exploiting already existing sources, it is technically possible to satisfy 31% of the heat demand with the energy mix simulated in scenario 1, almost 70% in scenario 2 and 90% and 96% in scenario 3 and 4 respectively. In the following chapter, the scenarios are compared in terms of costs and CO_{2eq} emissions and the scenario with the best cost–benefit ratio is selected.

4. Results

The outcome of the economic analysis is reported in Fig. 4, where it is possible to see the resulting investment cost [M€] for each modelled scenario, composed by the costs associated to each component. It equals 7.2 M€ in the first scenario, 15.7 M€ in the second one and 25.9 M€ and 33 M€ in the third and in the fourth scenarios respectively.

Concerning the environmental impact in terms of amount of CO_{2eq} emitted, the results allow to state that an increasing renewable share in the energy mix corresponds to a decrease in emissions of $CO_{2eq.}$ Indeed, we have that the first scenario accounts for 0.29 tCO_{2eq}/MWh_{th} and second one for 0.19 tCO_{2eq}/MWh_{th}, while scenarios number 3 and 4 are almost equivalent from this point of view with 0.14 and 0.13 tCO_{2eq}/MWh_{th} respectively. Eventually, by considering a climate change avoidance cost of 100 €/tCO_{2eq} as defined in [24], in Fig. 5 the climate change cost is reported in terms of [€/MWh_{th}] and compared with the total annualized specific cost of each scenario.[2]

[2] Climate change costs are formulated as CO_2 avoidance costs based on the target agreed in the Paris Agreement. They are actual or imputed costs for preventing environmental deterioration by alternative production and consumption processes. Therefore, a low value of climate change cost means that reduced interventions and or substitutions of energy systems are required to prevent the global temperature rise above 1.5–2 °C.

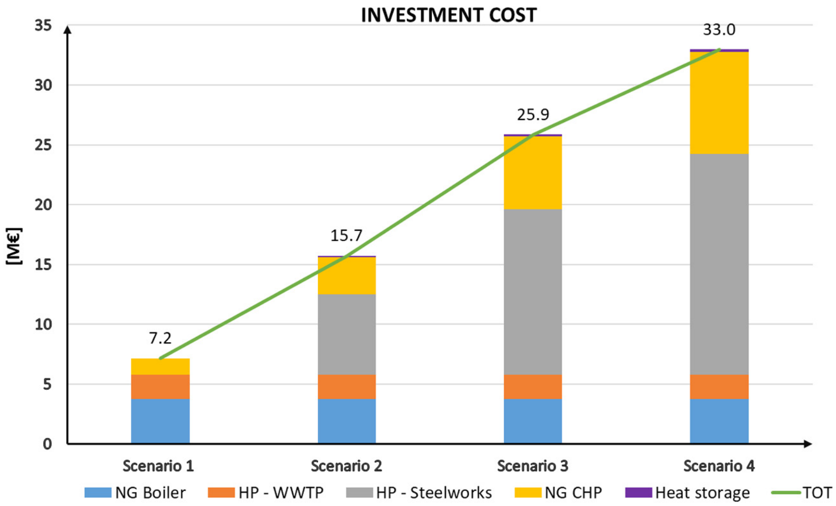

Fig. 4. Estimated investment cost [M€] required for each modelled scenario. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

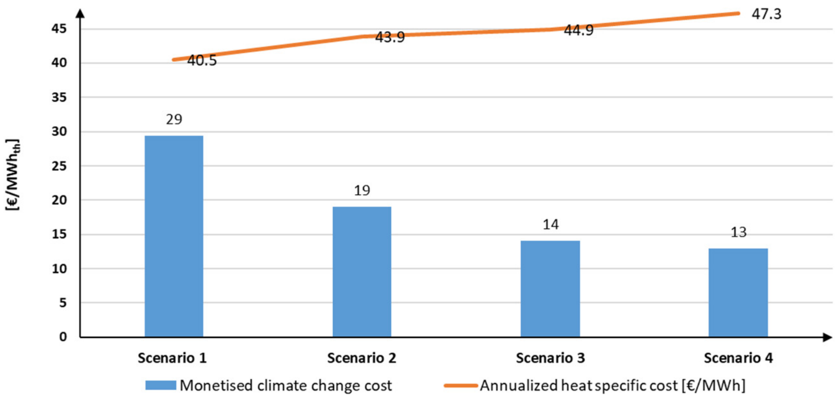

Fig. 5. Comparison between the modelled scenarios in terms of monetized climate change cost [€/MWh$_{th}$].

Based on the results reported in Fig. 4 and in Fig. 5, the optimal energy configuration in terms of cost–benefit ratio for the city under study would be potentially selected among the second and the third one. Indeed, while the first and the fourth scenarios tend to be excluded because of too high climate change costs and too high investment cost respectively, the second and the third scenarios appear as the most interesting. The third scenario could be eventually seen as the optimal one since a lower environmental impact is obtained in the face of a slightly higher annualized heat specific cost. Indeed, if compared with the second scenario, it is possible to state that with an increment of only 2% of the annualized specific cost, a reduction of 26% of the climate change cost is obtained.

The hourly consumption profile, together with the production profiles from the different sources composing the supply mix, is reported in Fig. 6. As expected, the heat consumption in DH network is much higher in winter than in summertime, when heat is mainly provided for domestic hot water. The required heat is mainly met by the heat pumps (exploiting the excess heat from the WWTP and the steelwork), with the CHP and the gas boilers entering the production mix to cover the heat demand peaks.

5. Conclusion

This paper presented a techno-economic analysis aimed at investigating the possibility to integrate local renewable and excess heat sources in the existing DH network of a city located in Northern Italy. Through the software

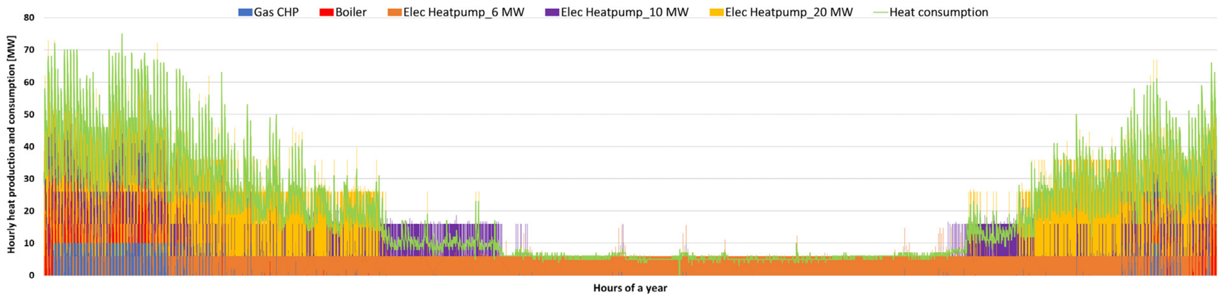

Fig. 6. Hourly heat consumption (in green) and hourly heat production in the DH system of the city under study during a typical year. Figure obtained in EnergyPRO when simulating scenario 3. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

energyPRO, four different scenarios have been modelled and, among them, the optimal energy configuration has been identified. It is composed as follows: 59% of thermal energy is supplied by the heat pumps integrated with the steelwork and 31% with the WWTP; 5% is the quota covered by the natural gas CHP and 5% by the boilers. 90% of the heating needs of the DH system in the city under study could be therefore met with renewables and waste heat recovery from two already existing plants.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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