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Stakeholder-centric model for efficient district heating: Networks interconnection and industrial waste heat in north-eastern Italy☆

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ABSTRACT

The study investigates the interconnection of district heating networks as a solution to enhance energy efficiency and accelerate the decarbonisation of thermal systems. The research focuses on analysing the environmental and economic performance resulting from the integration of two independent district heating networks located within the same urban area and supplied by industrial heat sources and cogeneration systems. To this aim a mathematical model describing the behaviour of the system representing the interconnection of the two district heating networks has been developed. Since different stakeholders are involved in the system, a multi-objective optimization approach is adopted, through a genetic algorithm (MOGA-II). The results of the model application to the case of Udine highlight that the proposed initiative improves system energy efficiency, reduces fossil energy consumption and energy dissipation compared to the current scenario, while ensuring excellent economic performance by lowering energy supply costs. Furthermore, a sensitivity analysis assesses the robustness of the results under variable network conditions.

Introduction

In 2021 the residential sector accounted for 27 % of the final energy consumption in the EU. The main utilization of energy within the households was for space heating, which represented more than 64 % with natural gas as the main source, accounting for almost 40 % of the total energy consumption [1]. Thus, curbing energy consumption related to the heating sector, coupled with the adoption of cleaner energy sources, is crucial for overall emission reduction [2].

An approach to improve energy efficiency in areas with high heating demand is the adoption of district heating (DH) systems [3]. DH systems involve the centralized production and distribution of heat to multiple customers within a specific area, allowing also for the integration of multiple energy sources [4]. Despite improvements, DH continues to have a significant environmental impact due to its reliance on fossil fuels [5]. To address this issue, the integration of renewable energy sources into district heating systems is a key solution to improve energy efficiency and reduce greenhouse gas emissions. In this context, the concept of efficient district heating network (EDHN), as outlined in the European Energy Efficiency Directive 2012/27/EU, is a fundamental regulatory reference point. A DHN is classified as EDHN if it uses at least 50 % of energy from renewable sources or recovers at least 50 % of industrial waste heat. It can also be considered efficient if it combines renewable energy and industrial waste heat, providing this combination accounts for at least 50 % of the total energy utilized.

The integration of different renewable energy sources in DH systems has been widely investigated in recent years. Specifically, researchers have explored the utilization of solar energy, geothermal power and biomass as well as waste heat to replace fossil fuels for heat generation [6,7].

Ushamah et al. evaluated different collectors investigating different solar hybrid DH system integrated with thermal storage [8], while Andersen et al. compared two different distribution systems aiming to determine the most cost efficient [9]. It has been found that solar energy could cover up to 50.2 % of heating demand in renewable-integrated DH systems [10,11], while Frison et al. demonstrated a 75 % reduction in thermal energy demand through bidirectional heat transfer and predictive control [12]. Other studies, however, emphasized the increased maintenance requirements, demonstrating notable heat losses from collectors and efficiency drops as a result of soiling [13].

Focusing on geothermal energy, Maione et al. demonstrated through a life cycle analysis that geothermal DH systems could reduce environmental impacts by 90 % [14]. Further research has evaluated the cost-

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Nomenclature

Acronyms

4GDH	4th generation district heating
CHP	Cogeneration heat and power
DH	District heating
DHN	District heating network
DOE	Design of Experiment
DSS	Decision support system
EDHN	Efficient district heating network
EAW	Equivalent annual worth
GHG	Green-house gases
HE	Heat Exchanger
HOB	Heat-only-boiler
MOGA	Multi-objective genetic algorithm
PB	PayBack time
PES	Primary energy saving
SES	Smart energy system

Symbols

c	Specific cost
h	Time step
H	Heat
L	Load
N	North
S	South

Subscripts/superscripts

exc	Exchanged
exp	Exported
in	Entering
IND	Industrial
int	Integrated
imp	Imported
out	Exiting
rec	Recovered
red	Reduction
TES	Thermal energy storage
waste	Dissipated

effectiveness of geothermal networks in different climates [15], the technical and economic aspects of systems integrated with geothermal wells [16], and the efficiency of thermal storage in wells [17]. Arslan et al. optimized the operational parameters of geothermal systems using a multi-criteria approach based on neural networks [18].

Regarding biomass utilization, Sartor et al. developed a methodology to assess the economic, environmental, and energy performance of biomass-based DH systems [19], that showed a 17 % emission reduction in a university campus application [20]. Other studies have proposed decision-making models to optimize biomass DH networks, introducing new profitability indices [21,22]. Perea-Moreno et al. demonstrated that integrating biomass in an urban area can significantly reduce energy demand [23].

The integration of renewable energy sources in DH systems often requires structural and operational adjustments, necessitating a transition to fourth-generation district heating (4GDH) [24]. Volkova highlighted the challenges of upgrading from high-temperature to low-temperature systems [25], hindered by the reluctance of providers [26] and the need for consumer-side interventions [27]. In this context, the concept of Smart Energy Systems (SES) plays a crucial role emphasizing the interconnection and integration of various energy networks, including electricity, heating, and cooling, to optimize the overall energy system efficiency and flexibility [28,29]. This approach is akin to the advancements in electrical grids, where interconnections between different grid systems have enhanced reliability, facilitated the integration of renewable energy sources, and improved load balancing [30–32]. Similarly, interconnecting district heating networks can provide significant benefits, such as sharing thermal loads, optimizing resource use, and increasing system resilience. For this reason, solutions like industrial waste heat recovery and interconnection between neighbouring DHNs could represent viable solutions to increase the efficiency and profitability of DH systems, thus emerging as a remarkable example of urban-industrial symbiosis.

To this concern, several studies have demonstrated the effectiveness of integrating waste heat into DH systems. Simeoni et al. developed a multi-objective optimization model to evaluate the sustainability of an urban DHN powered by industrial waste heat, providing design and operational guidelines [33]. Moser et al. analyzed the share of industrial waste heat in DH systems in Austria [34], while other studies explored waste heat recovery from data centers and its economic, energy, and environmental implications [35,36]. Another study investigated the use of waste heat through heat-to-power technologies and DH systems, showcasing economic and environmental benefits [37]. Fitò et al. optimised the design of an industrial waste heat recovery system, demonstrating that it can meet a significant portion of residential demand [38]. Lastly other studies concluded that industrial waste heat is a promising solution for enhancing the sustainability of DH systems and improved informational support could help overcome barriers to its integration [39,40].

Regarding independent networks interconnections, although some attempts have been made to investigate this alternative, the topic has received limited attention in the literature. Karlsson introduced the concept of DHNs interconnection investigating the economic potential of connecting industrial plants and DH systems to a heat market, showing encouraging results [41]. Dominkovic et al. investigated the effect of multiple interconnections of different DHNs minimizing total annual cost, showing a reduction of energy supply and CO_2 emissions [42]. The same authors assessed the economic and environmental impacts of DHNs interconnection of the city of Zagreb, aiming at socio-economic cost minimization, confirming profit increase and lower environmental impact following increased cogeneration utilization [43]. Kaisermayer et al. presented a decentralized energy management system that can handle multi-owner interconnected DHNs [44], based on a cost function, highlighting how different DHNs are often operated by different owners, with competing objectives. They also proposed control strategies to reduce CO_2 emissions, successfully testing them in simulations and real applications [45]. Karner et al. proposed networks interconnection as a measure to enable thermal flexibility with waste heat recovery from steel industry, proving improvements in both environmental and economic global performances. However, these referred to the whole intervention and costs for waste heat have been neglected [46].

From the above-exposed literature, it emerges that some issues for DHNs interconnection, like managing the competing objectives of the different stakeholders involved in such projects or the possibility of switching from a DHN to an EDHN by interconnection, have not yet been fully addressed. A research gap therefore emerged due to the lack of suitable tools to define clear and stable collaboration conditions over time, considering sustainability and profitability of DHNs interconnection. This manuscript addresses this research gap by proposing a novel multi-objective optimization model designed to act as a decision support system for interconnection projects between DHNs. The model aims to facilitate fair and balanced negotiations among stakeholders, optimize the technical and economic configuration of the system, including heat exchanger sizing and energy exchange pricing, and assess both environmental sustainability and economic profitability. In doing so, it promotes urban-industrial symbiosis and supports the transition to EDHNs. The model has been subsequently applied to a local case study to unveil its practicality and utility.

The remainder of this paper is organized as follows: in Section 2 the developed model is described. In Section 3 the investigated case study is presented. In Section 4 the results are disclosed and discussed, while the conclusions are derived in Section 5.

The multi objective optimization model

The multi-objective optimization model has been developed to allow the estimation of benefits for the different stakeholders involved in a waste heat-based DH networks interconnection project, highlighting the compromise solutions to be exploited.

The selected decision variables of the multi-objective optimization problem are the size of the heat exchanger (H_{HE}) to be installed for the networks connection, the specific cost of the thermal energy exchanged between the networks (c_{exc}) and the specific cost of the thermal energy recovered from the industrial waste heat source (c_{rec}). The two costs represent the main economic parameters on which to act to fulfil the objectives of the various stakeholders involved in such a waste heat recovery project.

An iterative, evolutionary multi-objective optimization model has been developed to address the problem. DHN and energy balances have been modelled in Matlab®, further integrated with the modeFRONTIER® software. The initial step involves the design of experiment (DOE), where the starting population of values assignable to decision variables is generated. At each iteration, simulation of the investigated system is then conducted to evaluate the objective functions for the given candidate solutions. From these, by the implementation of genetic operators, ranking on the objective function values, a new set of candidate solutions is generated for the next iteration. A multi objective genetic algorithm (MOGA-II) has been adopted. Subsequently, Pareto fronts constituted by non-dominated solutions based on the considered objectives are obtained. The flow chart of the optimization process is represented in Fig. 1.

The objective functions of the problem have been selected according to the stakeholders' different conflicting objectives. The model has been consequently set to pursue 4 main objectives, as presented in Table 1. The optimized performances are: the Equivalent Annual Worth (EAW) of the two different DH providers involved, the Payback time (PB) for the industrial waste heat source to cover the heat recovery system investment cost, and green-house gas (GHG) emission reduction (CO_{2red}) for local Institutions and the citizenship.

CO_{2red} accounts for the global CO_2 emission reduction deriving from substitution of energy integration with energy recovery. EAW has been calculated, for each DHN, as the sum of annualized investment costs, costs related to boilers energy integration, maintenance of utilized units (HE and boilers), energy supply, and revenues associated with energy exchange, and incentives rewarding primary energy saving (PES, white certificates) and GHG emission reduction (carbon tax). Since the model considers the interconnection of different DHNs, only the HE investment has been considered, neglecting costs for the DH system installation. The avoided GHG emissions and PES are calculated through the proper emission and conversion factors of the reference fuel. Performance indicators have been evaluated as difference compared with the case of independent networks.

DH system modelling

Since the scope of the work is the investigation of the feasibility of DHNs interconnection projects and not a detailed simulation of the networks physical behaviour, the model is based on some hypothesis such as: constant supply and return temperature, steady state conditions of the network. As a consequence, equipment efficiency drops at partial load operations are neglected in this analysis [47,48].

The overall heat demand for each DHN was estimated by the

Table 1
Goals of the multi-objective optimization model.

Stakeholder	Objective function	Optimization
DH service provider 1	EAW	Maximization
DH service provider 2	EAW	Maximization
Industrial waste heat provider	PB	Minimization
Institutions / citizenship	CO_{2red}	Maximization

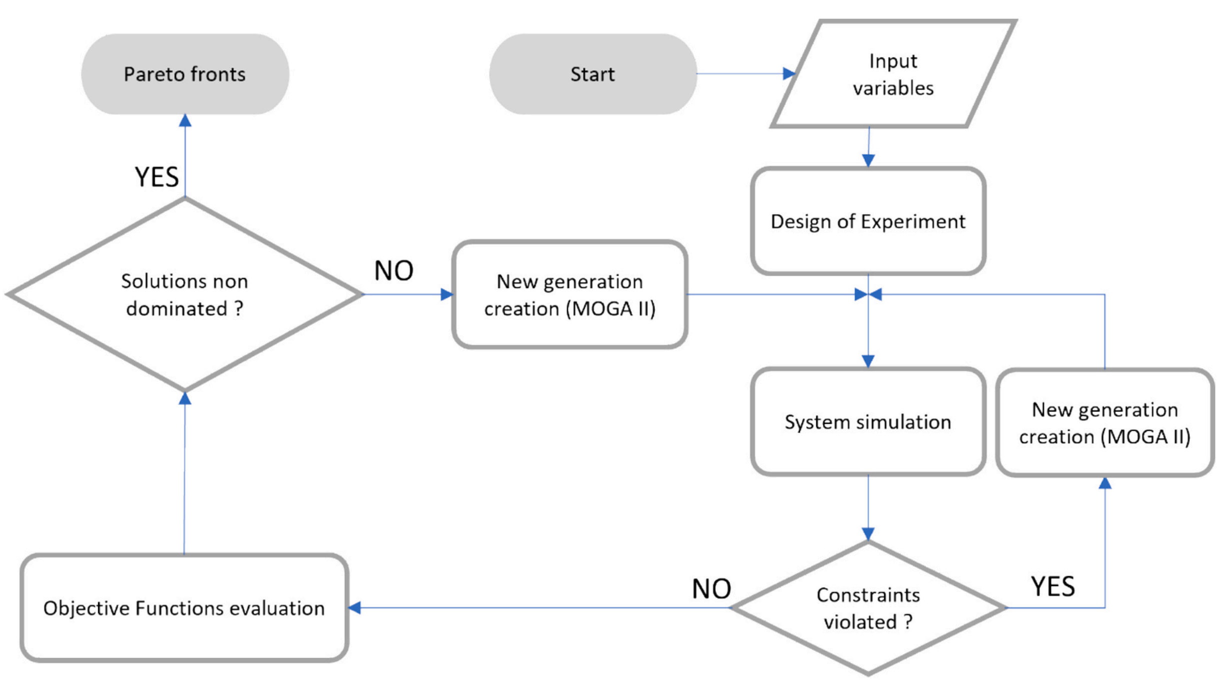

Fig. 1. Optimization process flow chart.

correlation between the required thermal power and the outdoor temperature, considering the thermal power installed at end users [33]. The simulation was conducted with an hourly time step, capturing the dynamic variations in heat demand throughout the day. The total thermal load computation is based on the nominal capacity installed in the thermal plants of buildings. The demand is determined as a function of the difference between the indoor design temperature and the hourly average outdoor temperature. This value is then related to the difference between the indoor and the outdoor design temperature, which is location-specific and defined by national regulations.

The network load pattern is determined by the activities performed inside the buildings. Thus, the users constituting the basin have been categorized in: residential, public institutions, health and social services, commercial, and industrial. Each category has been associated with a specific load pattern, based on the activities taking place in the building: continuous, night set back and time clock operation, as identified by [49]. In order to take into account the contemporaneity effect given the high number of users, a simultaneity factor has been embedded in the model [50]. Fig. 2 illustrates the investigated interconnected DH system.

The idea behind this study is to exchange energy from a network characterized by a surplus to the other, in order to reduce both energy integration and dissipation. Thus, each network should balance its heat demand through energy production or transfer to the other network. As energy sources heat-only-boilers (HOB) for energy integration, heat produced through cogeneration heat and power (CHP) and industrial waste heat recovery have been implemented.

The model evaluates the amounts of all the considered energy shares needed to ensure energy balance for each time interval of the simulation. Waste heat recovery, both industrial ($H_{rec,IND}$) and from CHP ($H_{rec,CHP}$), is prioritized over energy integration for load (L_{th}) covering. Any energy surplus could be then exchanged (H_{exp}) to the other network, whenever integration is needed, or stored for future utilization ($H_{TES,in}$), considering dissipation (H_{waste}) as the last option. As a utilization strategy, priority is given to load coverage of both the networks over energy storage. Energy integration (H_{int}) occurs when inputs from energy recovery ($H_{rec,IND} + H_{rec,CHP}$), supply from the other network (H_{imp}), and stored energy extraction ($H_{TES,out}$) aren't sufficient to cover the network heat demand. The energy balance driving the model is reported in equation (1).

Case study

The decision support system (DSS) developed was implemented in the city of Udine, located in North-Eastern Italy. The city operates a district heating network covering the Northern basin (N-DH). This network, initiated in 2014 and completed in 2023, originates from a CHP plant located at the city's main hospital. The CHP plant is equipped with three cogeneration engines (2 operational and 1 reserved for backup purposes), that generate the energy required to meet the hospital's electricity demand and the thermal load of both the hospital and the district heating network for 3.5 MW thermal power. Auxiliary boilers (HOBs) are installed to provide additional thermal integration when needed. No waste heat recovered from industrial facilities is currently integrated in this network. Nominal installed power served by the N-DH is 45 MW. In 2023, the district heating system supplied a total heated volume of 1,186,379 m^3, which included 398,337 m^3 of residential buildings and 788,042 m^3 of tertiary sector buildings such as schools, swimming pools, and public offices. The total energy delivered in 2023 amounted to 23,652 MWh. The average energy consumption was 27.78 kWh/m^3 for the residential sector and 15.97 kWh/m^3 for the tertiary sector.

The municipality is evaluating the development of a district heating network covering the Southern part of the basin (S-DH). The basin load has been estimated at 107 MW and includes buildings from both the residential and tertiary sectors (schools, public institutions, administrative offices, a healthcare facility), as well as some industrial consumers. The S-DH is planned to be supplied by waste heat recovered from a nearby steel casting facility. In addition, HOBs, fed by natural gas from the national grid, have been considered for energy integration. Thermal power made available from the waste heat recovery system has been estimated by [33] equal to 25 MW, with a cost for recovered heat, expected by the project, of 30 €/MWh. Constant supply has been assumed, given the steel plant is continuously operating 24 h per day along the whole week. However, an availability factor of 80 % has been adopted to account for steel plant maintenance downtime.

An overview of the served area and the proposed DHNs

$$L_{th,h} + H_{exp,h} + H_{TES,in,h} + H_{waste,h} - H_{rec,IND,h} - H_{rec,CHP,h} - H_{imp,h} - H_{TES,out,h} - H_{int,h} = 0 \quad (1)$$

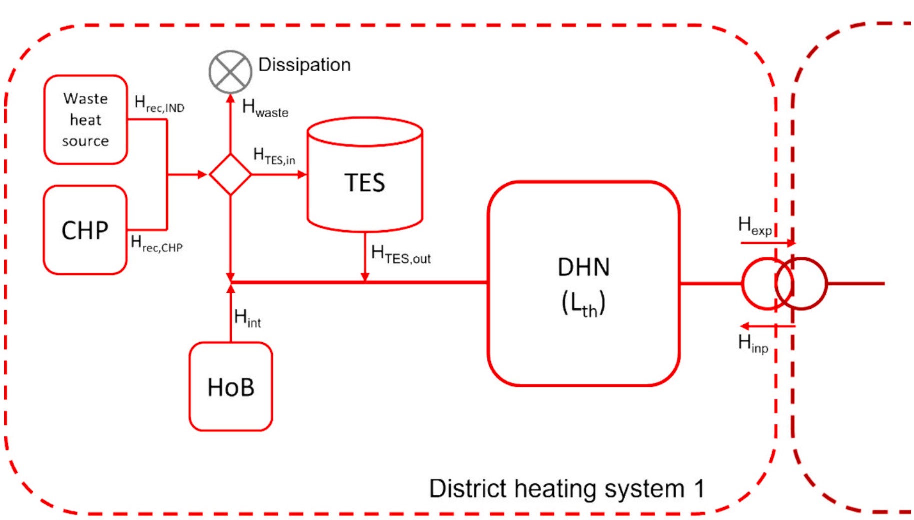

Fig. 2. Block diagram of the investigated DH interconnected system.

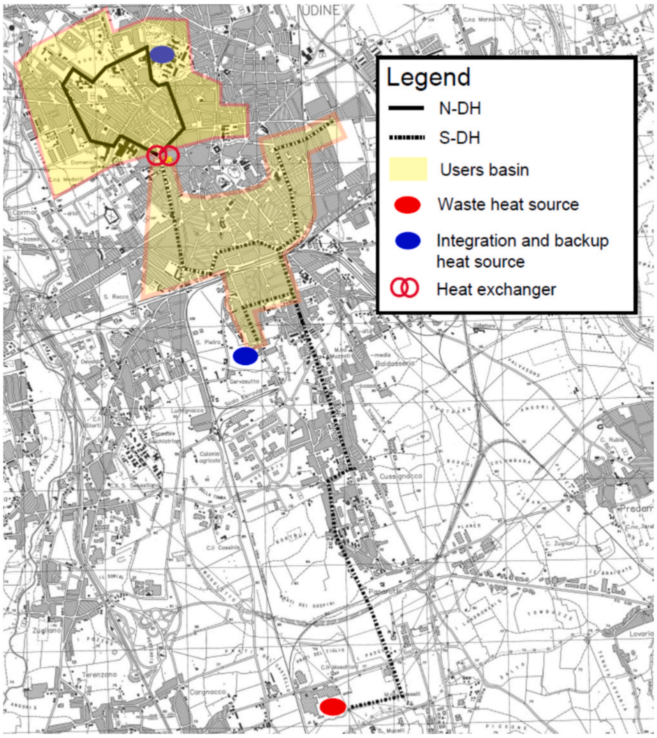

Fig. 3. Layout of the case study DHNs.

Table 2
Main parameters used in the model.

Parameter	Value	Reference
Storage volume [m^3]	7,000	[33]
Industrial waste heat availability [MW]	25	[33]
DH final user energy price [€/MWh]	70	[33]
CH_4 grid cost [€/Sm^3]	0.46	[51]
White certificate [€/toe]	250	[52]
Carbon tax [€/tCO_2]	80	[53]
H_{CHP} [MW]	3.5	Real plant data
Electric energy grid cost [€/MWh]	120	[54]
Cooler energy efficiency ratio	8	[55]
CH_4 emission factor [tCO_{2eq}/Sm^3]	$1.94 \cdot 10^{-3}$	[56]
CH_4 primary energy conversion factor [toe/Sm^3]	$8.20 \cdot 10^{-3}$	[56]
η_{HE} [%]	98	[37]
Maintenance cost [% of investment]	2	[57]

interconnection layout is represented in Fig. 3. A bi-directional connection between the two networks is planned to integrate waste heat as a source of supply for the N-DH network and ensure an EDHN. While the load characterization of the basin served by the N-DH network was based on real data from the existing system, the behaviour of the S-DH network was simulated using the main project data.

The main parameters considered in the optimization process are reported in Table 2. For the decision variable ranges, the H_{HE} parameter is between 0.5 MW and 25 MW, with an incremental step of 0.5 MW. The c_{exc} and c_{rec} variables change between 0 and 100 €/MWh, increasing by 1 €/MWh.

Simulations were run along the whole heating period (i.e. from 15 October to 15 April, according to the Italian regulation). Hourly average external temperature have been gathered from the regional observatory [58].

The application of the proposed multi-objective optimisation model to the case study has been investigated by developing two different scenarios:

- Scenario 0: the current urban context consisting of two separated DHNs serving different shares of the whole city basin (reference scenario);
- Scenario 1: energy connection through a heat exchanger between N-DH and S-DH is proposed, in order to investigate the potential of a symbiotic integration of the two municipal networks.

The hourly operation profiles of the considered DHNs, in terms of share of energy source (i.e. waste heat and integrated one) and surplus energy management (i.e. stored and dissipated), for scenario 0 along the simulation period are shown in Fig. A1. Specifically, Fig. A1a shows how the N-DH thermal load is satisfied for the most part by energy integration, since energy recovery from CHP accounts for around 30 % of the load, providing approximately 14,000 kWh. Natural gas supply to boilers leads to 7,400 tCO_{2eq} emissions, with a cost of 0.87 M€.

Regarding the planned S-DH (Fig. A1b), the thermal load during the considered heating period has been estimated in almost 91,000 MWh. Heat recovery from the steel casting facility provides around 78,000 MWh, accounting for roughly 86 % of the load. Cost for energy integration accounts for 0.36 M€ and leads to 2,800 tCO_{2eq} of GHG emissions.

Given the limited basin available for waste heat recovery in this scenario, around 12.8 MWh of thermal energy made available by the steel casting facility remains unused and is thus dissipated for a total cost of 51 k€.

Results and discussion

The multi-objective optimization for the interconnection scenario 1 has been carried out as explained in Fig. 1. For the considered case study, Fig. 4 reports the Pareto front of the optimal solutions obtained by pursuing the four different objectives reported in Table 1.

Analyzing the solution constituting the Pareto front, it can be seen how the optimization pushes towards emission reduction near to the maximum value. Indeed, the size of the bubbles, representing the emission reduction, is almost the same for the majority of the solutions.

The PB of the industrial waste heat source, represented by the color of the bubbles, is mainly dependent on the price of recovered energy. Since the energy recovered from the steel plant is purchased by the Southern network, an inverse relationship between the objectives of these two stakeholders is evident. Specifically, as the price of the recovered energy decreases, the economic benefits exhibited by S-DH improve, while on the contrary an increased PB for the industrial facility can be noticed.

Furthermore, the bubbles form bands of similar color that indicate similar PB values for the facility, reflecting constant prices of the recovered energy. This makes the color bands indicative of the relationship between the objectives of N-DH and S-DH. Being characterized by a negative slope, they show, as expected, an inverse relationship between the economic performances of the two DH providers.

Looking at the spread of solutions that are generated, it can be noticed that there are optimal solutions which could satisfy the objectives of the DHN providers, as well as of the industrial facility, together with the environmental one. Pushing towards DHN interests, disregarding the industrial facility's objective, economic gains over 500 k€/year and even 2.1 M€/year are possible. On the contrary, when prioritizing the industrial facility's benefits, payback periods as low as 1.6 years would be possible. In this regard, the selection of the best recovered and exchanged energy prices should be driven by a compromise among the involved stakeholders' different objectives. In particular, it would be possible to keep PB for the industrial waste heat source below 4 years, while assuring remarkable benefits for the DHNs managers above 500 k€/year and reach a share of load covered by recovered energy of 59 %, as required by an EDHN.

Fig. 5 describes the behaviour of the objective functions with H_{HE}. In order to accurately represent the dependence of the objectives on H_{HE}

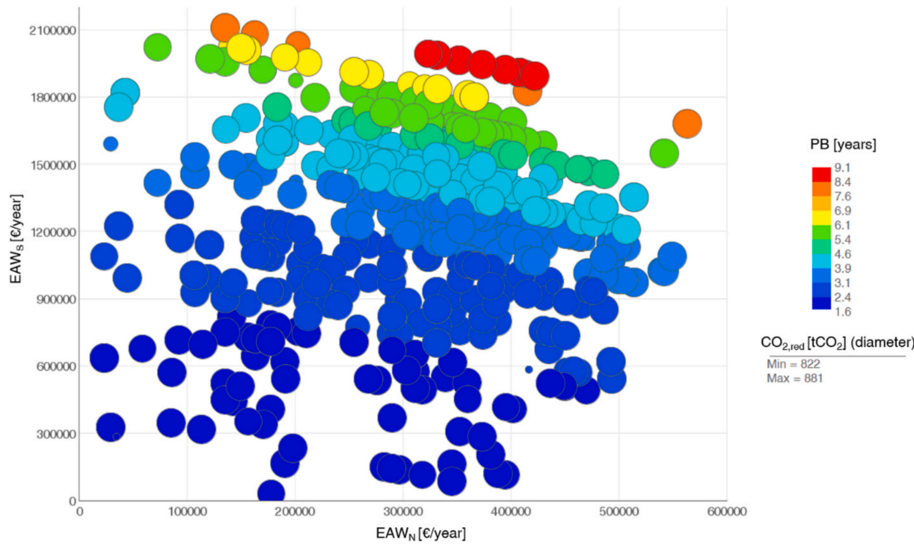

Fig. 4. Pareto fronts: economic performance for S-DH (y-axis), N-DH (x-axis), the waste heat provider (coloured scale), and emission reduction (size).

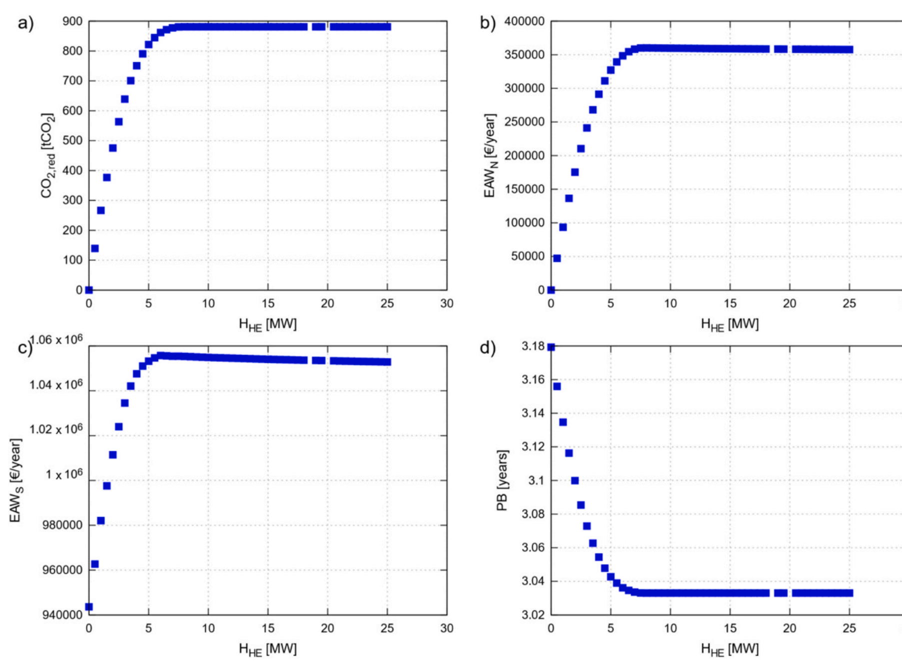

Fig. 5. CO_2 emission reduction (a), differential cash flow for N-DH (b) differential cash flow for S-DH (c) and PB of the industrial waste heat source (d) for different HE sizes.

and eliminate the influence of the other two decision variables, the latter have been fixed. To this purpose, the values leading to a compromise solution among the different objectives, considering them to have equivalent weights, have been chosen. Thus, the exchanged energy price and the recovered energy price have been set equal to 43 €/MWh and 18 €/MWh, respectively. Despite emission reduction increases as H_{HE} increases, it can be noted how, above a specific value of around 8 MW, the graph doesn't display any further visible increment in the GHG emission reduction for higher sizes. Regarding the DHNs, as the energy recovery increases with $H_{HE,}$ the economic benefits increase with a similar behaviour till a maximum. After that value, a plateau is reached, related to the halted rise in energy recovery despite the increase in H_{HE}. Specific values of benefits experienced by the networks depends on the adopted values of exchanged and recovered energy. Concerning the objective of the industrial waste heat source, a slight reduction in PB with H_{HE} can be noted, due to the increased energy recovery deriving from the incremented basin load.

The results presented above highlight how an adequate negotiation between the different providers can lead to a win–win situation from a sustainability and economic perspective for each stakeholder involved in the intervention. During specific settings, stakeholders should find a trade-off solution between the optimal ones proposed by the developed system (Fig. 4) by weighing the different objectives in order to balance and satisfy their different interests.

Sensitivity analysis

When developing a decision support model for a DHNs interconnection project, it is crucial to evaluate the impacts of future variations of various parameters of the involved systems. Specifically, nominal installed power of both N-DH and S-DH can influence performances from the economic, environmental and energy point of view. Therefore,

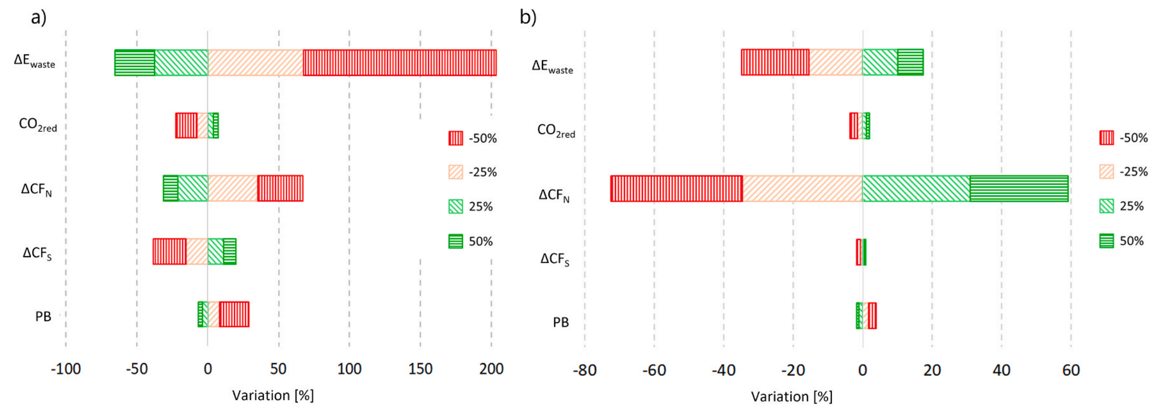

Fig. 6. Sensitivity analysis of the impact on different variables of: a) S-DH basin load and b) N-DH basin load.

two sensitivity analysis are performed to investigate the effects that different basin loads exert on key performance indicators. To this concern ± 50 % and ± 25 % variations of the parameters have been adopted. Variations are computed considering the compromise configuration as reference. As performance indicators, the four objectives of the optimization have been considered. In addition to these, due to the relevant variations exhibited, also energy waste has been included. Fig. 6 depicts the results of the sensitivity analysis.

When considering the sensitivity of the selected variables towards the S-DH basin load, the energy dissipation is the most impacted, with a significant increase for lower basin load. In this case, the reduced basin for S-DH limits its energy recovery, leaving a greater availability of waste heat that can be recovered by N-DH. However, due to the different basin size of the two networks, N-DH cannot compensate for the reduction in energy recovered by S-DH, leading to a significant increase of energy dissipation. Consequently, S-DH experiences a decline in economic performance. Meanwhile, N-DH's economic performance exhibits an increase. Due to the reduction in energy recovery, the industrial waste heat source experiences an increase in the PB time for the investment. The reduction in energy recovery leads also to lower emission reduction, reaching −19 % for a basin 50 % lower.

On the contrary, with a larger Southern basin it is possible to better exploit the availability of waste heat, thereby allowing for the recovery and allocation of a greater amount of energy to users, leading to higher revenues and reducing dissipation. On the other hand, increased waste heat recovery by S-DH reduces the amount of heat transferable to the other network, making the heat exchanger oversized and consequently reducing the savings achievable by the N-DH through energy recovery, thus worsening its economic performances.

Concerning the sensitivity towards N-DH basin load, all the considered variables vary directly with the basin load, apart from the economic performances of S-DH. Higher N-DH basin loads lead to increased energy recovery from the industrial waste heat source, and, consequently, lower need for energy dissipation. In turn, this allows for greater recovered energy exchange between the networks, translating in good performances for both networks. N-DH economic performances exhibit the biggest variations. Also in this case, the global increase in energy recovery allows good performances also for the industrial waste heat source, reaching a PB reduction of 2 % and, as well as a 2 % increase in the emission reduction.

With lower N-DH basin loads, the benefits deriving from an increased energy recovery are lost, leading to a decrease in economic performances of both networks, as well as the industrial waste source, together with a reduction in emission reduction.

Scenario comparison

Fig. A2 in Appendix represents the different energy shares for load coverage and surplus management of the two networks for scenario 1. These graphs refer to an installed HE size of 7.5 MW since, as shown by the Pareto solutions reported in Fig. 5a, such size represents a good compromise solution between all the considered objectives. Fig. A2a shows a reduction in energy integration for the coverage of thermal load by the N-DH, since more than 14 % (over 7,000 MWh) is covered by waste heat from the industrial facility and exchanged by S-DH.

When considering S-DH (Fig. A2b) a slight decrease in load share covered by waste heat (around 3,000 MWh) can be noticed. This is basically due to the hypothesis of prioritizing load coverage of the conjoint networks over heat storage by S-DH. However, a sensible reduction in energy dissipation (more than 3,900 MWh) is reached.

Finally, global energy efficiency and environmental benefits are achieved, since the increase in energy recovery exhibited by N-DH outreaches the decrease experienced by the S-DH. The connection intervention leads to increase energy recovery of almost 5 %, that translates in quite 900 tCO_{2eq}/year emission reduction, comprehensively.

Conclusions

This study focused on the modelling and optimization of energy interconnection, through a HE, between different DHNs for industrial waste heat recovery. The objective was to identify the optimal system configuration and operation, including the installed HE size and the pricing of exchanged energy shares, from both economic and environmental perspectives, reflecting the different stakeholders' interests. To this purpose, maximization of GHG emission reduction, equivalent annual worth for the DHNs and minimization of PB for the industrial waste heat provider have been adopted as objective functions.

The model was applied to a real-world case study in the city of Udine, in North-Eastern Italy. Results demonstrate the potential for symbiotic integration between the two networks, yielding both economic and environmental benefits. Specifically, the optimal HE size was found to be 7.5 MW. The integration led to a GHG emission reduction of up to 8 % (equivalent to 900 tCO_2eq/year), while ensuring robust economic performance for the DHNs (between 500,000 € and 2.1 M€/year) and for the industrial provider (PB below 10 years, down to 1.6 years).

Moreover, the model supported the definition of optimal cost and price ranges for the exchanged energy shares, proving the intervention to be economically viable compared to the baseline scenario of independent DHNs. A sensitivity analysis further investigated the impact of basin load variations on economic, environmental, and energy performance, offering valuable insights into the resilience and adaptability of the interconnection strategy. The analysis emphasizes the importance of considering load dynamics when planning future modifications, to preserve the benefits achieved. Overall, the proposed model emerges as a flexible and practical decision-support tool for facility managers, aiding both the design and negotiation phases of DHN interconnection projects. It also supports alignment with sustainable energy policies and promotes industrial symbiosis initiatives for waste heat recovery and urban integration. Public institutions may also leverage this tool to create collaborative frameworks that foster more efficient, resilient, and sustainable district heating systems, while accounting for the diversity of stakeholder strategies.

CRediT authorship contribution statement

Mattia Cottes: Methodology, Software, Data curation, Writing – original draft, Investigation, Conceptualization. **Antonella Meneghetti:** Conceptualization, Writing – review & editing, Supervision. **Patrizia Simeoni:** Methodology, Writing – review & editing, Writing – original draft, Conceptualization, Supervision.

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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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.seta.2025.104431.

Data availability

Data are available at the link: https://doi.org/10.5281/zenodo.14721805

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