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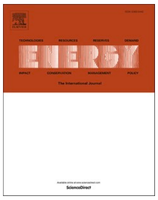

Environmental and economic assessment of industrial excess heat recovery collaborations through 4th generation district heating systems

D. Chinese [a,*], A. Meneghetti [a], G. Cortella [a], L. Giordano [b], E. Tomasinsig [c], M. Benedetti [b]

[a] DPIA, Polytechnic Department of Engineering and Architecture, University of Udine, Udine, Italy
[b] ENEA, Italian National Agency for New Technologies Energy and Sustainable Economic Development, Rome, Italy
[c] eFrame Srl, Parco Scientifico Tecnologico "Luigi Danieli", Udine, Italy

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ABSTRACT

The external use of excess heat from industrial processes is an important factor in the energy transition and 4th generation district heating is an enabling technology. This paper presents a calculation tool for assessing the economic feasibility and the environmental impact of collaborations between potential industrial sources and users. The tool supports the sizing of district heating pipe diameters, pumps, heat pumps, and heat storage systems. A distinctive feature of the model is the possibility of calculating carbon and blue water footprints, alongside economic indicators, for both existing stand-alone systems and potential collaborative configurations. Excess heat recovery from water-cooled condensers of refrigeration systems is evaluated for two case studies involving the space heating of offices in a food logistics hub and the heating of a greenhouse from a frozen pizza factory, respectively. Only the second collaboration is profitable with the baseline price of natural gas (0.04 €/kWh) and electricity (0.12 €/kWh), provided that the distance between the source and the user is less than 2 km. For higher gas prices, distances of approximately 8 km would be viable. However, for source-user distances above 5 km, the water footprint of the collaboration would be higher than that of stand-alone systems.

1. Introduction

Half of the European energy demand is due to heating and cooling uses, and a vast majority of this energy is still supplied by fossil fuels [1]. To achieve carbon-neutrality in the industrial sector, space and process heat will need to be supplied by renewable energy sources, and energy efficiency should be enhanced. Nevertheless, it is expected that many industrial processes will continue to produce excess heat that cannot be used on-site in the process or for other purposes. Several studies [2] have quantified such industrial excess heat in the EU, and potentials in the order of 300 TWh per year have been estimated [3] which could nevertheless be reduced by 6–30 times in the future as a consequence of decarbonisation policies in the industries with the highest energy intensity [4].

1.1. Background: external uses of excess heat and inter-firm cooperation

In most of the literature, municipal district heating systems are identified as the natural users of industrial excess heat [4], particularly in Sweden, where about 70 locations with operating cooperations can be found [5], and in Austria, where more than 93 % of external industrial excess heat utilisation involve municipal district heating systems [6]. Consequently, literature reports several feasibility studies on identifying and assessing synergistic collaboration areas between industry and cities where district heating exists [7] or where district heating is planned to exploit industrial excess heat to meet urban heating demand [8]. In some cases, industrial waste heat sources may be crucial for decarbonisation, and even long distances, up to some tens of kilometres, may be economically feasible to meet base loads [9].

On the other hand, in the absence of municipal district heating networks, sharing of excess heat in inter-firm collaborations has proven to be a viable option for decarbonisation [10], belonging to the domain of industrial symbiosis [11].

European industries have been estimated to require about 2300 TWh/year for space and process heating [12]. Almost half of this heat is required at low (<200 °C) temperatures [12] and manufacturing companies are normally located in industrial areas, potentially closer to each other than to urban areas. Hence, energy exchanges between companies may apparently be easier to implement than exchanges with urban energy systems. However, inter-firm energy supply concepts are still rare:

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* Corresponding author.
E-mail address: damiana.chinese@uniud.it (D. Chinese).

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the review by Butturi et al. [13] mentions examples from Korea [14], Finland [15], Belgium [16], and China [17]. Some strategic barriers to energy exchange between firms highlighted in the literature decades ago [18] are still present nowadays [19]: they include uncertainties about the quality, quantity and continuity of the flows to be connected, about the benefits and expenses of inter-company concepts, as well as fears about dependence on partners and loss of control over resources and related decisions. As observed in Ref. [20], these barriers are particularly pronounced for greenfield projects and in absence of general experience in district heating systems. Additionally, the decarbonisation of energy intensive industries is expected to introduce technical barriers as the amount and temperature levels of available excess heat will decrease in the future [4]. A proposed technical solution to overcome decarbonisation related barriers to the external exploitation of industrial excess heat is the so called fourth generation district heating (4DH) which allows better to exploit low grade waste heat by using low temperature (60–70 °C maximum) water as an energy carrier and by including centralized or decentralized heat pumps [21] if needed, i.e. when such temperatures do not match the temperature requirements of users. This may happen frequently in interfirm cooperation concepts, as industrial users often have higher temperature requirements than typical third or fourth generation temperatures, e.g. in the food industry for pasteurization and sterilization [10]. However, in the past the use of heat pumps has demonstrated to represent an additional risk for the stability of energy collaborations, due to the increased dependence on possibly volatile electricity prices [5].

1.2. State of research: calculation tools supporting energy inter-firm cooperation

The introduction of calculation tools to assess the costs and benefits of interfirm collaboration can increase transparency and thus support interfirm collaborations and is particularly necessary in view of the increased technical complexity of the 4DH infrastructure. Nevertheless, Karner et al. [22] pointed out that only few studies go beyond the estimate of technical potentials to match available heat sources with local sinks and economically assess the costs of utilizing this excess heat source. Municipal energy planning models that incorporate energy symbiosis between industry and cities can be valuable tools for this purpose. However, they are often complex enough to be useable only by specialists or with the help of facilitators. This may be the case with multi-criteria models [23] or with dynamic simulations, which focus on the evaluation of temperature profiles e.g. when a mix of industrial sources and renewable energy is used to feed novel networks [24]. Similarly complex are models based on optimisation algorithms, which according to a recent review [25] represent the state of the art, especially when combined with GIS models and global sensitivity analysis.

Few models offer a tool that is accessible, if not to the public, at least to specialist technicians, such as energy managers, for a straightforward, albeit approximate, evaluation of the feasibility of interconnecting multiple buildings. The Thermos platform [26] based on Openstreetmap is one such tool, yet its assessment on an annual scale—focused on peak loads and yearly consumption—fails to capture the time mismatch between energy demand and supply. The same limitation affects the model proposed by Ref. [27], an easily reproducible tool to compare DH with other technology options for recovering a constant predetermined flow of industrial excess heat: the input data consists in a discretized yearly duration curve, and it is assumed that demand is always met by the available heat recovery capacity, even at peak load.

However, in the context of industrial energy symbiosis and in nascent networks with few users, time mismatch [7] is a fundamental barrier that needs to be identified and solved by sizing appropriate energy storage systems. Furthermore, practically all the mentioned tools do not account for temperature mismatch between sources and sinks, and for heat pumps as a solution technology.

Simple techno-economic models, such as those proposed in Ref. [28] to compare several industrial surplus heat utilisation technologies, including heat storage and district heating, or as the one proposed in Ref. [29] to evaluate industrial heat upgrading with heat pumps, can be more easily reproduced and used by energy managers because the reported cost functions and energy balances can be implemented in any calculation tool, including Excel. Based on the present literature review and to the best of the authors' knowledge, the only model for a quick economic assessment of connecting a potential industrial excess heat source and a potential industrial user with a 4DH network, without performing a detailed technical evaluation of component sizes, is the one described in Ref. [30]. Only economic parameters are assessed and environmental considerations are only qualitative.

One platform that attempts to provide an accessible interface and at the same time the necessary sizing options for 4DH networks in an industrial environment is EMB3RS [31] a generator of inter-industry heat sharing optimisation models in which the time domain, time resolution and technology options are completely flexible and chosen by the user. The types of technologies that can be modelled include heat exchangers, heat pumps, boilers, etc. Thus, EMB3RS considers the possibility of evaluating both heat generation and heat upgrading systems as well as seasonal storage systems. The EMB3RS platform provides a GIS-based, user-friendly interface to its core optimisation engine. However, its high flexibility requires the input of a substantial dataset, with over fifty parameters for both sources and sinks. This results in a non-negligible training effort, even for expert users. While the platform provides a range of economic performance indices, the only environmental index it calculates is the CO2 emissions associated with the operation of various inter-company heat exchange collaborations available for user selection.

In this respect, previous work [27] demonstrated that, while waste heat recovery generally improves the energy efficiency and carbon performance of industrial energy systems, it can have different impacts on the overall blue water footprint, depending on the intended use of the recovered waste heat and on the systems originally used for heat dissipation prior to the introduction of heat recovery. In other words, the water-energy-carbon nexus [32] does not only occur in regional or global energy systems, but also emerges at the level of individual industrial systems [33], particularly when changes in energy supply or waste heat management strategies are introduced.

Unlike EMB3RS [31] and the techno-economic models, the techno-economic model proposed in Ref. [27] offers tools for calculating the carbon footprint and water footprint of different collaborative configurations.

1.3. Goals and structure of the research

The objective of this work is to provide an immediate and easily replicable model that, with a small number of inputs, allows the dimensioning and evaluation of an energy collaboration between two companies through a 4DH network. This involves the integration of heat pumps and heat storage systems to resolve temperature and time mismatches between source and sink. Unlike existing tools in the literature, this model should allow immediate calculation of not only economic results and CO2 emissions, but also indirect and embodied CO2 and water footprints of different proposed configurations. We also intend to explore the potential and limitations of the developed tool and to study the driving factors behind the economic and environmental performance of such collaborations, with reference to the Italian context, by applying the model to two case studies.

The model developed builds on the study presented in Ref. [27]. As in that paper, current configurations (AS IS) and potential collaborative configurations (TO BE) are simulated separately, assuming an external point of view i.e., considering the full capital costs of purchasing and installing systems (e.g., boilers) for existing systems as well, in order to compare systems with the same service life.

The methodology and parameters discussed in Section 2 are used in the decision support tool to calculate the direct and indirect carbon emissions as well as the blue water footprint of the potential producer and the potential user, and this both in the perspective of inter-firm cooperation (“’TO BE” configuration) and in the existing situation of independent operation (“AS IS” configuration) so that a comparison can be made. Economic performance indicators are also calculated for TO BE and AS IS configurations as discussed in section 2. In section 3, two applications of the model to two case studies are presented: the renovation of office heating systems in a food logistics centre (case study 1) and the design of the heating system for a new basil greenhouse serving a frozen pizza factory (case study 2). The discussion of the case studies, provided in Section 4, allows for the exploration of the potential and limitations of the calculation tool developed, as well as for the identification of the driving factors underlying the economic and environmental performance of such collaborations.

2. Methods

A parametric static energy balance model, presented in section 2.1, was developed to enable the rapid dimensioning of components and the evaluation of fuel, electricity, and water consumption for existing systems, on the one hand, and for planned collaborations, on the other. The calculation of economic, energy, and environmental performance indicators required the construction of parametric cost and impact functions, obtained from the data presented in section 2.2.

The model takes as inputs the hourly heat load of the potential user and the hourly excess heat flow from the potential source during two reference days (usually one in winter and one in summer) chosen to represent the system behaviour for all days in the corresponding season. Other inputs include the temperature levels of the hot water supplied from the source, the desired return temperature, and the inlet and outlet temperatures of the water to be heated at the user’s site. The model was implemented in Excel VBA.

2.1. System model

To compare the performance of existing (AS IS) individual systems with that of the collaboration (TO BE) the components illustrated in Fig. 1 (AS IS) and 2 (TO BE) have been modelled.

2.1.1. “AS IS” configurations

Fig. 1 illustrates a potential source system in its AS IS state, utilizing an excess heat dissipation system such either a water-based cooling or condensation system (e.g. cooling tower), or a forced air cooling (FAC) system, or an open loop heat exchanger that transfers heat to a body of water (lakes, rivers, sea). The comprehensive decision support system also accommodates AS IS configurations where the existing heat dissipation does not necessitate extra equipment, water, or energy for dissipation, for example when hot combustion gases are freely dispersed into the atmosphere.

The energy consumption, costs and environmental impacts of potential users are also evaluated. Compared with previous work [27], in the current computation model the decision maker can model either a heating system based on natural gas (NG) boilers, which according to the literature is the most common fuel in process heat production in Europe, or a system based on air-water heat pumps, for required water temperatures of 55 °C or less (as in most commercially available machines – [34]).

As daily heat loads are represented as discretized profiles of hourly useful heat demand $Q_{u,h}$ for two reference days *r1* and *r2*, the annual useful heating demand E_u is expressed by equation (1), where $N_{h,r}$ is the number of hours of operation per year at the load conditions of reference day *r1* or *r2* in the *h*-hour interval.

$$E_u = \sum_{h=1}^{24} Q_{u,h,r1} N_{h,r1} + \sum_{h=1}^{24} Q_{u,h,r2} N_{h,r2} \tag{1}$$

If the demand is met by NG boilers, the chemical energy of the fuel E_{fuel} is determined by dividing E_u by the average seasonal efficiency of the boilers reported in Table 1.

On the other hand, to evaluate the electrical energy absorbed if heat is generated with air source heat pumps, reference was made to the European standards EN14511 and UNI/TS 11300-4, evaluating, from data provided by manufacturers [35] and reported in Table 2, the second-law efficiency as per equation (2).

$$\eta_{II} = \frac{COP}{COP_{th}} \tag{2}$$

Using local climatic data as input (average temperatures on the two reference days, winter and summer), the COP for partial loads (COP_{CR}) is evaluated according to Equation (3), where *CR* is the capacity ratio, C_c is a correction coefficient equalling 0.9 and COP_x is the recalculated coefficient of performance for different values t_x of outdoor air temperature.

$$COP_{CR} = COP_x \frac{CR}{1 - C_C + CR \bullet C_c} \tag{3}$$

Having divided the reference period into *n* intervals in which the outside air temperature falls within the *i-th* range and having correspondingly determined the COP_{CR} for the two reference days, the electrical energy E_{e_PdCair} absorbed annually by air-water heat pumps used in

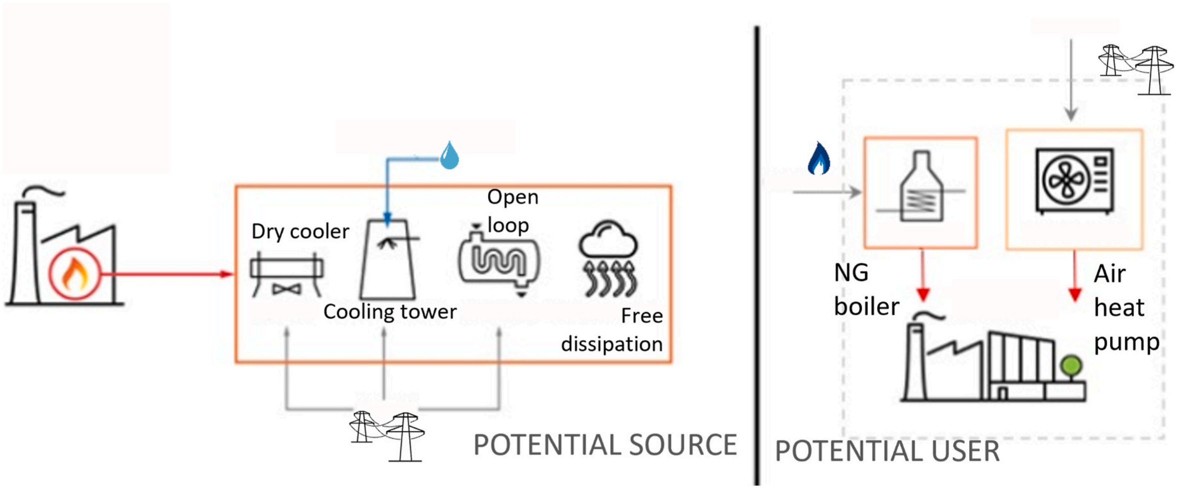

Fig. 1. System model of AS IS configuration – without collaboration.

Table 1
Technical, economic, and environmental data for components.

Technology	Efficiency or energy consumption rate	Equipment carbon footprint [$kgCO_2eq/u$]	Equipment water footprint [m^3H_2O/u]	Size independent cost component C_0 or b [€]	Reference size u_0 [u]	Scale factor m or slope a
Natural gas boiler [$u = kWth$]	$\eta = 85$ %	26.0	0.05	$C_0 = 31795$	460	$m = 0.76$
Heat exchange substation [$u = kWth$]	$\eta = 99$ %	21.9	0.07	$b = 6275$	–	$a = 14$
Water pump [$u = kWel$]	$\eta_{el} = 75$ %	28.3	0.21	$C_0 = 8136$	29	$m = 0.35$
Dry cooler [$u = kWth$]	$P = 4 + 0.03 \bullet u$	44.5	0.36	$C_0 = 8000$	200	$m = 0.7$
Cooling tower [$u = kWth$]	$P = u \bullet 1.46 \bullet 10^{-3}$	5.6	0.06	$C_0 = 60000$	8000	$m = 0.7$
Open loop System [$u = kWth$]	$P = u \bullet 6.3 \bullet 10^{-3}$	21.9	0.07	$b = 6275$	–	$a = 14$
Water to water heat pump (R410A) [$u = kWth$]	$\eta_{LOR} = 45$ %	107.9	1.05	$b = 9242$ ($u \leq 120$) $b = 32320$ ($u \leq 10000$)	–	$a = 543.4$ ($u \leq 120$) $a = 345.9$ ($u \leq 10000$)
Hot water storage [$u = m^3$]	$\eta = 100$ %	408.5	1.17	$C_0 = 57600$	84	$m = 0.64$

Table 2
COP and second law efficiencies of air-to-water heat pumps.

d.b. Air temperature	P_h [kW]	P_e [kW]	COP	COP_{th}	η_{II}
0	287.3	146.7	1.96	5.97	0.328
5	349.2	149.3	2.34	6.56	0.356
7	388.7	150.7	2.58	6.83	0.376
10	417.1	152.1	2.74	7.29	0.368
15	462	153.1	3.02	8.2	0.35
20	501.3	152.6	3.28	9.37	0.322
25	532.6	151.1	3.52	10.93	0.282
30	553.3	149	3.71	13.13	0.233
35	560.6	149.6	3.82	16.41	0.174
40	552.2	144.3	3.83	21.88	0.15

AS IS configurations is estimated according to equation (4).

$$E_{e\_PdCair} = \frac{\sum_{h=1}^{24} N_{h,r1} Q_{u,h,r1}}{COP_{CR,r1}} + \frac{\sum_{h=1}^{24} N_{h,r2} Q_{u,h,r2}}{COP_{CR,r2}} \tag{4}$$

2.1.2. *"TO BE" configurations*

The basic elements of the collaborative system with external heat recovery, depicted in Fig. 2, include.

- A heat exchanger at the industrial site;
- The flow and return pipes of district heating;
- The pumping system associated with piping;
- A substation of the district heating network at the end user, consisting of a heat exchanger and optionally a heat pump, which the calculation model integrates into the system when the temperature level required at the user is higher than the flow temperature of the hot fluid from the source (4th generation district heating). The model assumes that the heat pump is located at the user, as shown in Fig. 2, so that hot water is transported in the pipes at the lowest possible temperature, thus reducing heat losses.
- An integration boiler. This is assumed to be at the end user, so that in the event of insufficient or no excess heat exchange, the user can use it autonomously for backup or integration.
- A thermal hot water storage tank, also normally located at the utility.

Regarding the sizing of the district heating exchangers and pipelines, as well as the estimation of the associated heat losses and pressure drops, the consequent dimensioning of the network circulation pumps and estimation of the electrical energy requirements, the equations reported in Ref. [27] were used. To speed up calculations in the present Excel based implementation, it was assumed that the district heating diameters can take any multiple value of 1 mm starting from a minimum diameter of 15 mm, rather than linking the sizing to look-up tables that query a database of actual commercial diameters.

To resolve temporal mismatches in heat supply and demand a heuristic approach was used to size a combination of heat storage and integration boilers. The balance between the total energy offered by the source and the total energy demanded by the potential user is evaluated as a first conditional step. If the total excess heat available at the source $Q_{s,h}$ is higher than the user demand in the same time step $Q_{u,h}$, the storage is sized to complement the heat flow from the source during the few periods when this is lower than demand. The storage size is evaluated separately for each reference day *r1* and *r2*, and the maximum is selected as expressed in Equation (5).

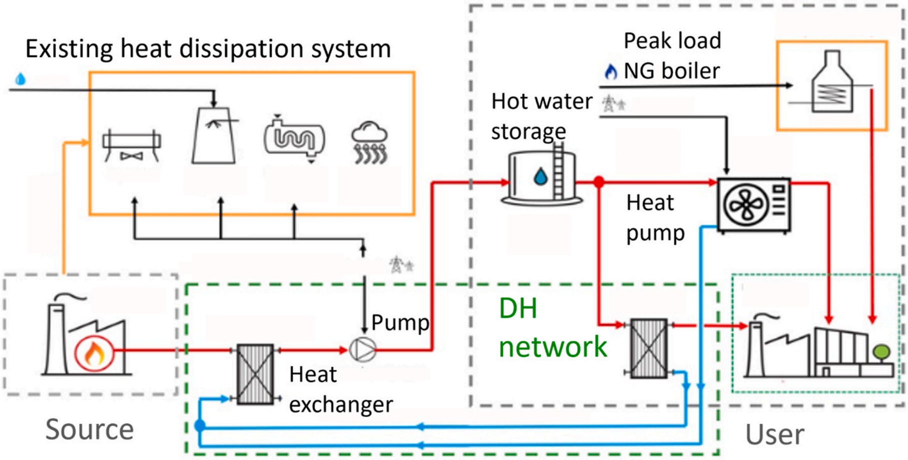

Fig. 2. System model of TO BE configuration – with collaboration.

$$Cap_{storage} = max\left\{\begin{array}{l}\sum_{h\in[1,24],h:\left(Q_{u,h,r1}-Q_{s,h,r1}\right)>0}\frac{\left(Q_{u,h,r1}-Q_{s,h,r1}\right)N_{h,r1}\bullet 3600}{\rho\bullet c_p\Delta t},\\ \sum_{h\in[1,24],h:\left(Q_{u,h,r2}-Q_{f,h,r2}\right)>0}\frac{\left(Q_{u,h,r2}-Q_{s,h,r2}\right)N_{h,r2}\bullet 3600}{\rho\bullet c_p\Delta t}\end{array}\right\} \tag{5}$$

If the total excess heat supply is lower than the heating demand in at least one of the seasons represented by reference days, an integration boiler is required. It is assumed that heat integration is achieved with a single NG boiler, whatever the starting AS IS situation. The heat storage is sized according to Equation (6) so that all the surplus energy available in any time slot can be stored.

$$Cap_{storage} = max\left\{\begin{array}{l}\sum_{h\in[1,24],h:\left(Q_{s,h,r1}-Q_{u,h,r1}\right)>0}\frac{\left(Q_{s,h,r1}-Q_{u,h,r1}\right)N_{h,r1}3600}{\rho\bullet c_p\Delta t}\\ \sum_{h\in[1,24],h:\left(Q_{s,h,r2}-Q_{u,h,r2}\right)>0}\frac{\left(Q_{s,h,r2}-Q_{u,h,r2}\right)N_{h,r2}3600}{\rho\bullet c_p\Delta t}\end{array}\right\} \tag{6}$$

To define the boiler capacity, two auxiliary binary variables $aux_{h,r1}$ and $aux_{h,r2}$ are defined for each time step h of each reference day $r1$ and $r2$, respectively, that equal 1 when the boiler is potentially active because demand is greater than supply, 0 otherwise. For each reference period r_i, the total energy to be supplied by the integration boiler will be equal to the sum over h time steps of the excess heating demand by the user, minus the total heat that can be stored when the transferred excess heat is higher than the user's demand, as shown in equation (7).

$$E_{boiler,r_i} = \sum_{h\in[1,24],h:\left(Q_{u,h,r_i}-Q_{s,h,r_i}\right)>0}\left(Q_{u,h,r_i}-Q_{s,h,r_i}\right) - \sum_{h\in[1,24],h:\left(Q_{s,h,r_i}-Q_{u,h,r_i}\right)>0}\left(Q_{s,h,r_i}-Q_{u,h,r_i}\right) \tag{7}$$

The capacity of the integration boiler in kW Q_{int_boiler} is calculated according to equation (8) based on the average output, so that during its operation hours, as counted by the auxiliary variables, the boiler is able to deliver all the energy calculated as per equation (7).

$$Q_{int\_boiler} = max\left\{\begin{array}{c}\frac{E_{boiler,r1}}{\sum_{h\in[1,24],h:\left(Q_{u,h,r1}-Q_{s,h,r1}\right)>0}aux_{h,r1}},\\ \frac{E_{boiler,r2}}{\sum_{h\in[1,24],h:\left(Q_{u,h,r2}-Q_{s,h,r2}\right)>0}aux_{h,r2}}\end{array}\right\} \tag{8}$$

Water heat pumps are modelled as in Ref. [36] using the Lorenz's COP calculated as a function of logarithmic mean temperatures T_{ml} according to equation (9), where $T_{ml,h}$ is the logarithmic mean temperature between the inlet and outlet of the source *(h)* and $T_{ml,l}$ is the logarithmic mean temperature between the inlet and outlet of the sink *(l)*, respectively.

$$COP_H = \eta_{Lor}\bullet\frac{T_{ml,h}}{T_{ml,h}-T_{ml,l}} \tag{9}$$

In line with [36], a minimum temperature difference ΔT_{pp} of 5 K was applied between both the condensation and the heat sink and between the evaporation and heat source, and the Lorenz efficiency η_{Lor} reported in Table 1 was assumed. A maximum temperature lift of 60 K and a maximum outlet temperature of 110 °C have been imposed to guide the decision maker in selecting equipment actually available on the market at costs consistent with the cost functions built into the calculation model.

Using the resulting estimates of COP_H, the electrical energy absorbed by water-to-water heat pumps is determined. The waste heat flow required as input to the water-to-water heat pump Q_{in,WHP,h,r_i} is calculated according to the first-law balance equation (10).

$$Q_{in,WHP,h,r_i} = Q_{u,h,r_i}\left(1-\frac{1}{COP_H}\right) \tag{10}$$

The waste heat input to the heat pump Q_{in,WHP,h,r_i} is then subtracted from the excess heat at the source within the same time step to calculate the residual heat flows that need to be dissipated by the existing systems in collaborative configurations involving water-to-water heat pumps.

2.2. Calculated indicators and required data

The model output includes.

- the size of equipment (heat rate of boilers, heat pumps, heat exchangers, volume of the hot water storage, and diameter of pipes)
- the estimated life cycle costs of AS IS and TO BE configurations and simple payback times of TO BE on AS IS configurations, as economic performance indicators.
- the estimated blue water footprint and carbon footprint of AS IS and TO BE configurations, calculated with the parametric approach introduced in Ref. [27] that accounts for embedded, indirect and direct contributions.

For cost calculations, the model includes component cost functions expressed in the form of a linear function (equation (11)) or power function (equation (12)) respectively using the parameters shown in Table 1, which have been obtained from the literature ([29,37–39]) and from communications by manufacturers.

$$C(u) = a\bullet u + b \quad [€] \tag{11}$$

$$C(u) = C_0\left(\frac{u}{u_0}\right)^m \quad [€] \tag{12}$$

The costs of rigid pre-insulated twin pipes have been calculated based on [27] according to equation (4) as:

$$c(d) = 2.48\bullet d + 191.1 \quad [€/m] \tag{13}$$

Where d is the pipe nominal diameter expressed in mm. Since the model deals with point-to-point collaborations in industrial areas, it is assumed that the networks are built on green fields, i.e. they normally run under unpaved soil, and minimal work is required for excavation and restoration.

The contribution of plant and operating costs to the life cycle cost was assessed over a time horizon of 30 years, corresponding to the service life assumed for the piping. For the remaining machinery, a useful life of 15 years was assumed and the resulting replacement cost - at constant amounts - at year 15 was accounted for. An interest rate of 6 % was assumed for the calculations.

Table 1 also reports the efficiencies used for component modelling. The electricity and water consumption rates are evaluated as functions of unit [kW] of dissipated heat according to equations reported in Ref. [40].

The parametric coefficients for the embedded water footprint and carbon footprint of equipment reported in Table 1 are estimated based on the inventories shown in Table 3 and obtained from literature or manufacturers' catalogues, using Probas [41] or Ecoinvent 3.5 [42] to account for the impact of individual materials as needed.

The footprints for district heat pipes are calculated as function of diameters d according to equations (14) and (15) by interpolating the values reported in Ref. [27].

$$co_2eq(d) = 0.0017\bullet d^2 + 0.705\bullet d + 61.3 \quad \left[kgCO_{2eq}/m\right] \tag{14}$$

$$m^3_{H_2O}eq(d) = 4\bullet 10^{-6}\bullet d^2 + 0.032\bullet d + 0.391 \quad \left[m^3_{H_2O}/m\right] \tag{15}$$

To evaluate the indirect consumption associated with electricity

Table 3
Inventories of equipment materials used for parametric modelling of footprints.

Component	Materials	Mass [kg]	Power	References
Pump	Stainless Steel	1.51E+01	18.5 kWe	[43]
	Cast Iron	1.36E+02		
Heat Exchange station	Galvanized steel	2.27E+01	25 kWth	[43]
	Stainless steel	2.70E+00		
	Copper	2.16E+01		
	Foamed polyurethane	2.70E+00		
NG boiler	Cast Iron	1.45E+01	25 kWth	[43]
	Steel	1.26E+01		
	Aluminium	3.18E+00		
	Brass	2.40E+01		
Forced air heat dissipation system	Stainless steel	8.60E+01	24 kWth	[44]
	Aluminium	5.80E+01		
	Copper	3.50E+01		
Water cooled heat dissipation system	Galvanized Steel	1.97E+01	48 kWth	[44,45]
	Fibreglass - reinforced	1.94E+01		
	Polypropylene	1.15E+01		
	PVC	2.40E+00		
Hot water storage	Stainless Steel	4.91E+03	560 kWc	[46,47]
	PVC	2.19E+03		
	PUR foam	1.38E+02		
	Coating	2.44E+00		
Air-to-water heat pump for standalone heating	Steel, unalloyed	1.29E+02	10 kWth	[48]
	Aluminum	4.72E+01		
	Copper	3.92E+01		
	Refrigerant (R410a)	6.4E+00		
	Lubricant oil	1.6E+00		
Water-to-water heat pump for district heating	Steel, unalloyed	5.85E+03	800 kWth	[49,50]
	Aluminum	1.05E+03		
	Copper	6.5E+01		
	Refrigerant (NH3)	1.5E+02		
	Lubricant oil			

usage in Italy, the study referred to the values published in Ref. [40], which had been derived by fitting a wide range of literature data on indirect blue water consumption for electricity production from various energy sources, and weighing the obtained coefficients by the national energy mix as of 2017. In this study, we have updated the values for Italy to the values reported in Table 4 with reference to the 2020 national electricity mix as per ISPRA elaborations of Terna data [51], from which the greenhouse gas emission coefficients for electricity and NG consumption in Italy reported in Table 4 were also derived.

The coefficients used for the calculation of primary energy are taken from the MISE (Italian Ministry for Economic Development) most recent Circular, which dates back to December 18, 2014. Electricity and NG prices have been derived from Eurostat [52] non-household prices as of June 2023.

3. Case studies and scenarios

To validate the model and to test the feasibility of inter-firm energy collaboration, two case studies were analysed that differ significantly in size and time profile of the required heat loads, although they both belong to the food industry sector.

Table 4
Prices and coefficients used in the *baseline* model.

Utility	Carbon equivalent emission factor	Blue water consumption factor	Primary Energy Consumption coefficient	Price
Electricity	0.33 tCO_{2eq}/MWh	0.0064 m^3/kWh	1.87 E−04 TOE/kWh	0.157 €/kWh
Natural gas	0.27 tCO_{2eq}/MWh	1.19E-05 m^3/kWh	8.90E-04 TOE/Nm^3	0.042 €/kWh

3.1. *Case study 1: logistics HUB*

The first case study concerns a logistics hub, located in North-eastern Italy, that supports the storage and distribution of frozen, fresh, and perishable food products. The logistics hub, represented in Fig. 3, has a total indoor surface of 43000 m^2 and includes office buildings (denoted as A, B, D), warehouses at room temperature (E and F) and a refrigerated warehouse (C) partly used for fresh food and mostly for frozen food preservation. The refrigeration system of warehouse C is based on a water condensed ammonia cycle with a maximum condensation temperature of 43 °C, an average water inlet temperature of 38 °C and outlet temperature of 35 °C. The explored collaboration is internal to the logistics hub and would consist in recovering heat from condensers to heat the office buildings in the winter season, which lasts for about 7 months (2288 heating degree days with 20 °C base temperature).

This is a case of energy-efficient refurbishment: renovation of heating systems in office buildings is being evaluated, considering the option of recovering heat from water cooled condensers in the refrigeration plant to heat buildings currently supplied by boilers with the characteristics shown in Table 5.

The available waste heat profiles, represented in Fig. 4 left, were obtained from measurements at the refrigeration plant by choosing a reference day in January and one in August. Each of these days was assumed to be representative of the heat availability profile for the 7 months of the winter season (in this case accepting a probable error in estimation by default) and for the 5 months of the summer season (in this case accepting a probable error by excess), respectively.

As the office buildings have a low thermal inertia, the user demand profiles (Fig. 4 right) were estimated by assuming that heat loads profiles only depend on external temperatures using equation 16

$$Q_{u,h} = CF_u \bullet CAP\_BOIL_u \bullet \frac{t_{id} - t_{env,h}}{t_{id} - t_{env,d}} \tag{16}$$

Where t_{id} represents the indoor design temperature, set at 19 °C, $t_{env,h}$ is the hourly average value of the outdoor temperature derived from local meteorological station recordings over the last four years, $t_{env,h}$ is the outdoor design temperature, which according to national standards equals −5 °C at the location of the hub.

CAP_BOIL denotes the capacity of installed boilers, and *CF* stands for a calibration factor. This factor is determined to align the estimated winter gas demand, derived from these profiles and the efficiency outlined in Table 1, with the average NG usage recorded in the buildings over the previous four years. The *CF* accounts for the buildings' partial usage and the oversizing of aged boilers, which might result from obsolete design standards or building upgrades. As a result, the estimated peak loads are significantly lower than the capacity of the boilers installed earlier, as reported in Table 5. The water inlet and outlet temperatures of the district heating system are in line with the requirements of heat distribution systems at existing users.

3.2. *Case study 2: frozen pizza factory and basil greenhouse*

The second case study involves a potential new building as user, with the heat recovery from water-cooled condensers in an existing refrigeration plant as the source.

The potential source industry is a frozen pizza factory located in Northeastern Italy and covering an area of 60000 m^2. The water-cooled condenser system is serving three refrigeration systems having a total cooling capacity of about 11 MW, intended for 4 °C cold rooms for the storage of some raw materials (mozzarella, ham, etc.) and −20 °C cold rooms for freezing, storage of frozen raw materials, and of finished products. Significant amounts of fresh vegetables are used for pizza topping. The opportunity of building greenhouses to help produce leaf

Fig. 3. Layout of the buildings and proposed DH network branches – Case study 1.

Table 5

Technical parameters of the existing installations at the potential source and the potential users of the collaboration – Case study 1.

Case study 1 Logistics hub	**AS IS**	**Identifier**	**Type of building and energy system**	**Rated output of energy system**	**Actual peak load or peak waste heat flow**
		Building A	Office building, independent NG boiler	270 kW_{th}	100 kW_{th}
		Building B	Office building, independent NG boiler	350 kW_{th}	128 kW_{th}
		Building C	Refrigerated warehouse, water condensed (WCC) chillers	818 kW_{ref}	344 kW_{th} (winter)
		Building D	Office building, independent NG boiler	686 kW_{th}	252 kW_{th}
	TO BE	**Configuration identifier**	**Source**	**Users**	**Length of connection**
		A	Waste heat recovery from WCC in C Water temperatures: $T_{s,o} = 38$ °C $T_{s,i} = 35$ °C	As per configuration identifier Water temperatures: $T_{u,i} = 70$ °C $T_{u,o} = 50$ °C	230 m
		B			45 m
		D			400 m
		A + B			232 m
		A + B + D			480 m

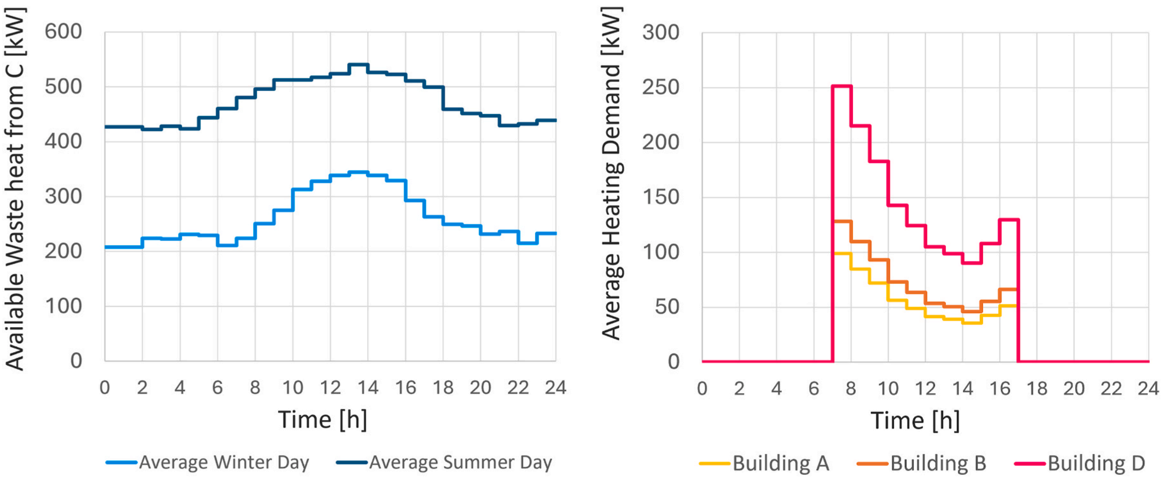

Fig. 4. Input data for case study 1: waste heat from refrigeration system, in typical winter and summer days respectively, and reference heat load profile of office buildings in winter days.

basil locally has been considered, vegetables whose shelf life is very low and for which km 0 production would therefore be crucial. The company currently purchases about 4 t/year of basil (*Ocimum Basilicum* L.) and 15 t/year of spinach (*Spinacia Oleracea*). Based on the area yield values reported by Ref. [53] for basil and by Ref. [54] for spinach leaves, ranging from 2 kg/m^2 to 3.6 kg/m^2 per year, the covered surface of a greenhouse able to meet the vegetable demand was estimated at 10200 m^2, as reported in Table 6. A possible site for the greenhouse building G was identified at about 350 m from the potential waste heat recovery site at the food industry I, as shown in Fig. 5.

The available waste heat profiles, represented in Fig. 6 left, were calculated based on the monitoring of the refrigeration system data for one reference day in January and one in August, as in case study 1.

The heating requirements for the greenhouse (Fig. 6 right) were estimated using the model described in Ref. [55], thereby maintaining a constant internal temperature of 22 °C, as recommended for basil in

Table 6
Technical parameters for the design and assessment of installations at the potential source and the potential users of the collaboration – Case study 2.

Case study 2	AS IS	Identifier	Type of building and energy system	Rated output of energy system	Actual peak load or peak waste heat flow
Pizza factory		Building I	Water cooled refrigeration system from deep-freezing system and cold storage rooms	3180 kW_{ref}	3071 kW_{th} (winter) 5449 kW_{th} (summer)
		Building G	Basil greenhouse, 10200 m^2 NG boiler	2874 kW_{th}	2874 kW_{th}
	TO BE	**Configuration identifier**	**Source**	**User**	**Length of connection**
		Baseline	Waste heat recovery from WCC in I Water temperatures: $T_{s,o} = 35$ °C $T_{s,i} = 30$ °C	Building G Water temperatures: $T_{u,i} = 55$ °C $T_{u,o} = 40$ °C	350 m

Fig. 5. Layout of the buildings and proposed DH network branches – Case study 2.

Ref. [56], and replicating 30 modules with identical construction characteristics. The assessment utilized local climate data from the past four years, obtained from the nearest meteorological station, factoring in a heating season of about 8 months, 2597 heating degree-days with a baseline temperature of 20 °C, and an average annual global solar radiation of 4730 MJ/m^2.

In this second case study, the hourly heat load values derived from the model in Ref. [55] for two typical days in January and August were also adjusted using a correction coefficient. This leads to an underestimation of winter peak loads but ensures that the annual heat demand estimate is consistent with the estimate obtained by using full year climate data. A flow temperature of 55 °C and a return temperature of 40 °C (see Table 6) are assumed to be appropriate for the heat distribution system at the user's site, based on information reported in Ref. [55] for newly constructed greenhouses.

3.3. Scenario analysis

For each case study, the AS IS independent configuration and the TO BE collaborative configuration described in sections 3.1 and 3.2 have been identified and evaluated as *baseline* scenarios. In both cases, NG boilers are used in the AS IS *baseline* configuration to meet user heating demand and excess heat recovery from water cooled condensers takes place in the TO BE configuration. Both the heating load and the available excess heat in the second case study are about an order of magnitude higher than in the first.

For case study 1, collaborations were explored separately with each user building - A, B, D, respectively - as well as with the combination of the two buildings -A and B - closest to the source and with the three buildings as a whole: in this case, requirements are evaluated as sum of individual requirements and the pipe length is based on an equivalent distance considering the total length of the required connections.

To explore the different impact of excess heat collaboration opportunities on economic, energy and environmental performance indicators, a what-if analysis was developed on further scenarios defined for each case study as summarised in Table 7.

As the existing heat dissipation systems (water cooled condensers) result in significant direct water consumption due to evaporation, we wanted to understand how the collaboration could have a different impact on the water footprint in the case of FAC. This what-if scenario was explored for the first case study comparing blue water footprint

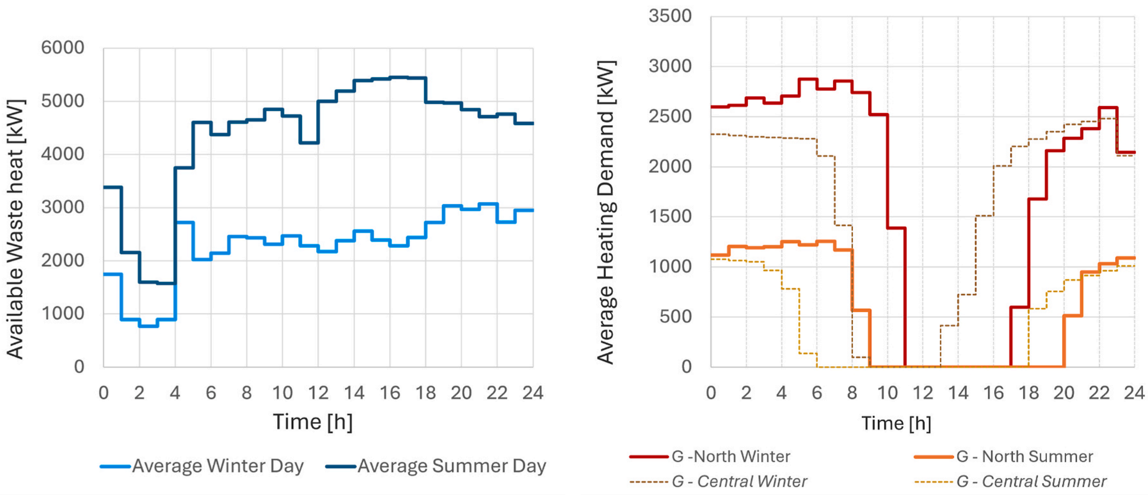

Fig. 6. Input data for case study 2: waste heat from refrigeration system in building I and estimated heating demand from the greenhouse G (at its real and its what-if location) in typical winter and summer days, respectively.

Table 7
Summary of what if scenarios analysed for case study 1 and case study 2.

Case study	What-if scenario	Configurations considered	Indicators
Case study 1	Forced air condensed (FAC) chillers instead of water condensed	A, B, A + B, A + B + D as individual independent systems and as collaborations	Water footprint
	$T_{u,i}$ = 60 °C $T_{u,o}$ = 40 °C Instead of $T_{u,i}$ = 70° C$T_{u,o}$ = 50 °C	Collaborations B and A + B + D	Carbon emissions Life cycle cost
Case study 2	AHP: Air-to-water heat pump instead of NG boiler at prospective user G	*Baseline* with air-to-water heat pump against collaboration with integration boiler	Water footprint Carbon emissions Life cycle cost
	Central Italy: Lower heating demand by user G due to varied climatic conditions (an alternative location in Central Italy is taken as reference)	*Baseline* with NG boiler, *baseline* with air-to-water heat pump against collaboration with integration boiler	Water footprint Carbon emissions Life cycle cost

indicators. As the water temperatures required by the user in case study 1 are relatively high, typical of traditional heating systems, we wanted to explore what would happen in terms of economic performance and impact on total carbon emissions if the required temperature level were reduced by 10 °C, while keeping the temperature drop unchanged, as could be the case with moderate renovations of the heat distribution systems to the user. This analysis is only carried out for the two configurations with the highest expected economic viability.

For case study 2, the water temperatures required at the utility are compatible with the use of commercially available air-to-water heat pumps at the user site in the independent operation mode. This alternative scenario was therefore explored to compare an economic performance indicator (life cycle cost) and two environmental performance indicators (life cycle cost and water footprint) with the results of the AS IS and TO BE configurations in the *baseline* scenario.

Finally, given the progressive reduction in heating degree days recorded in recent years as a result of climate change, we wanted to explore how the performance of the independent and collaborative configurations would change in the event of further reductions in heating requirements. Therefore, using the heat load simulation model developed for the case study 2 based on [55], the heating demand was recalculated for a climatic zone in central Italy with 1834 heating degree days, resulting in the values shown in Fig. 6. The available excess heat profiles, derived from actual measurements at the real site climatic conditions, were not adjusted for possible variations in temperature and humidity. In neglecting this effect, however, we are erring on the side of caution as to the feasibility of collaborations, as the heat to be dissipated by the condensers of a refrigeration system will increase in the presence of an increase in outside temperature.

4. Results and discussion

For each AS IS and TO BE configuration, the main technical design parameters, the primary energy demand in TOE, the life cycle costs and the footprints in the *baseline* scenario were determined.

4.1. *Case study 1 – results of baseline scenario*

Table 8 reports the component size calculated by the model and the yearly primary energy consumption estimated for independent and collaborative configurations for each of the connections explored.

In every instance, the collaboration results in primary energy savings of 22 %–51 % when compared to the existing AS IS configurations, primarily through the elimination of NG consumption required to meet the same heating demand.

For the collaborations with individual buildings A, B, D, or with the combination of A and B, the excess heat available from the source is higher than the demand at any given time of the typical winter day, therefore peak load boilers are not required in any case, and only in the last collaboration scenario, where all office buildings are served, is a hot water storage tank required.

The life cycle cost comparison reported in Table 9 shows that collaborations never pay off compared to the AS IS configurations in which each office building is heated by a NG boiler. In spite of seemingly short distances and of the small diameters calculated for the pipes, capital costs of 4DH are too high to be paid back with an exclusively winter and daytime heating demand.

In the configurations considered for case study 1, the ratio of capital costs of water-source heat pumps to those of district heating pipes and storage varies between 40 % and 65 %, with the only exception of the configuration serving building B, where the cost of the heat pump is higher than that of the very short district heating connection.

The least costly collaborative configuration entails the connection of office building B to the source C, and it results in a 30 % increase in life-cycle costs compared to the use of stand-alone heating systems.

On the other hand, collaboration invariably leads to a significant reduction in total life-cycle greenhouse gas emissions. The increase in carbon-equivalent emissions for the equipment production in the collaborative scenarios is negligible compared to the reduction in operation-related emissions, even when accounting for higher indirect emissions from the electricity needed to run district heating and heat pumps in the collaborative scenarios. For case study 1, emission savings ranging between 30 % (building A) and 60 % (building B) can be

Table 8
Design parameters and primary energy consumption for *baseline* configurations – case study 1. (The subtotal and net balance figures are highlighted in bold.)

Case study 1	Pipe diameter [mm]	Pump rated power [kW]	Heat exchanger at source [kW_{th}]	Heat storage capacity [m^3]	Heat pump capacity [kW_{th}]	Yearly heating demand [kWh/year]	AS IS Primary energy consumption [TOE/year]	TO BE Primary energy consumption [TOE/year]
A	24	4	112	0	22	**72905**	**7.7**	**6.0**
B	28	1	153	0	28	**94500**	**9.7**	**6.4**
D	39	10	295	0	55	**185238**	**18.3**	**12.3**
A + B	37	6	266	0	50	**167405**	**16.4**	**10.4**
A + B + D	51	15	505	10	105	**352643**	**35.7**	**17.2**

Table 9
Comparison of costs and GHG emissions in independent and collaborative configurations of case study 1.(The subtotals and net balance figures are highlighted in bold.)

Case study 1	Capital costs	Natural gas	Electricity and water	Life cycle cost	Embedded CO$_{2eq}$ emissions	Direct CO$_{2eq}$ emissions	Indirect CO$_{2eq}$ emissions	Net CO$_{2eq}$ balance	Cost of CO2eq emission savings
	[€]	[€/year]	[€/year]	[€]	[tCO$_{2eq}$]	[tCO$_{2eq}$]	[tCO$_{2eq}$]	[tCO$_{2eq}$]	[€/tCO$_{2eq}$]
A AS IS	26959	3062	6625	**160248**	11.6	600	35	**−211**	**646**
A TO BE	127306	0	12298	**296522**	33.8	0	402		
B AS IS	30017	3969	6625	**175789**	13.3	777	35	**−520**	**105**
B TO BE	87442	0	10373	**230176**	22.1	0	283		
D AS IS	41410	7780	6625	**239614**	20.3	1524	35	**−622**	**401**
D TO BE	216309	0	19822	**489059**	66.8	0	891		
A + B AS IS	39305	7031	6625	**231986**	18.9	1377	35	**−669**	**215**
A + B TO BE	162081	0	16254	**375743**	48.7	0	713		
A + B + D AS IS	59348	14811	6625	**367549**	33.1	2901	35	**−1632**	**172**
A + B + D TO BE	315673	0	24119	**647549**	106.5	0	1231		

achieved with collaboration, which, in the most favourable scenarios, results in an average carbon reduction cost in the order of 100–200 €/tCO$_2$eq, based on the comprehensive net CO$_{2eq}$ balance up to the Scope 3 level reported in Table 9.

Table 10 reports interesting results from a water-energy nexus perspective. Compared to the AS IS *baseline* configurations, excess heat recovery results in a substantial reduction in direct water consumption, ranging between 7 thousand and 30 thousand cubic meters over the thirty-year life cycle. However, the water footprint balance, which takes into account the embedded water used in equipment manufacture and the indirect water used in electricity demand, is not always favourable.

Only in scenarios B, A + B and A + B + D does the collaboration result in an overall net reduction in blue water consumption, while in configurations A and D the impact of electricity consumption for heat pumps and pumping is so high that the overall footprint increases.

4.2. Case study 1 – results of what-if scenarios

The last columns of Table 10 report the results of the first what-if analysis for case study 1: if the condensers were forced-air cooled rather than water cooled, overall water consumption in the AS IS configuration would obviously be reduced. Based on the inventories reported in section 2.2, the embedded water consumption for the manufacturing of metal parts in a FAC system is slightly higher than in the case of water-cooled condensation system, but this increase is negligible. On the other hand, in the forced-air dissipation what-if scenarios all the inter-firm collaborations would result in a higher water footprint than the standalone configurations, due to the indirect water consumption resulting from a net increase in electricity demand.

The impact on electricity consumption of heat pumps needed to overcome the temperature mismatch between the source and the user is significant. As shown in Table 11 for the what-if scenario with lower temperature requirements at users, with a reduction of 10 °C in the average temperature required at the consumers, heat pumps with a capacity about 30 % lower than in *baseline* configurations are sufficient, and improvements in carbon emissions savings in the order of 10 % are achieved.

However, even in this what-if scenario of case study 1, the total life cycle costs, although decreasing due to the lower use of heat pumps, remain higher in the TO BE configurations than in the AS IS configurations. It can be concluded that the main obstacle to the economic viability of the collaborations in case study 1 remains the high investment in district heating networks combined with low heat demand, rather than the operating costs.

4.3. Case study 2 – results of baseline scenario

The second case study is characterised by a much higher heat demand than the first, both in terms of peak load and therefore heating system capacity, and in terms of continuous operation and therefore annual heating demand.

If we compare Table 12, which contains the technical parameters and

Table 10
Comparison of blue water footprint in independent and collaborative configurations of case study 1 (Figures in italics refer to what-if scenarios with FAC. The net balance figures are highlighted in bold).

Case study 1	Blue water footprint with WCC	Blue water footprint with WCC	Blue water footprint with WCC	Net water balance from collaboration with WCC	*Blue water footprint with FAC*	*Blue water footprint with FAC*	*Net water balance from collaboration with FAC*
	Embedded	Direct	Indirect		*Embedded*	*Indirect*	
	[m^3]	[m^3]	[m^3]	[m^3]	*[m^3]*	*[m^3]*	*[m^3]*
A independent	104	284189	31	**2058**	*435*	*23959*	***8749***
A collaboration	226	277052	9104		*557*	*32585*	
B independent	116	284189	41	**−2490**	*447*	*23968*	***5647***
B collaboration	157	275509	6190		*488*	*29575*	
D independent	168	284189	80	**3444**	*499*	*24007*	***20375***
D collaboration	414	266128	21338		*745*	*44136*	
A + B independent	158	284189	72	**−114**	*489*	*23999*	***14757***
A + B collaboration	310	268327	15668		*641*	*38604*	
A + B + D independent	263	284189	152	**−3714**	*595*	*24079*	***26461***
A + B + D collaboration	631	251660	28599		*962*	*50172*	

Table 11
Effect of the explored what-if scenario of reduction in the temperature required at the users in case study 1 (Figures in italics refer to what-if scenarios. The subtotals and net balance figures are highlighted in bold).

		Case study 1 - Collaborative configurations			
		B (70 °C–50 °C)	*B (60°C – 40°C)*	A + B + D (70 °C–50 °C)	*A + B + D (60°C – 40°C)*
Pipe diameter	[mm]	28	*29*	51	*51*
Pump rated power	[kW]	1	*1*	15	*15*
Heat exchanger in C	[kW]	153	*164*	505	*505*
Hot water storage	[m^3]	0	*0*	10	*13*
Peak load boiler	[kW]	0	*0*	0	*0*
Heat pump	[kW]	28	*20*	105	*76*
Carbon emission savings	**[tCO2eq/30 years]**	**521**	***567***	**1632**	***1867***
Life cycle cost increase from *baseline*	**[€/30 years]**	**54386**	***37034***	**293247**	***239588***
Cost of carbon emission savings	**[€/tCO2eq]**	**104**	***65***	**180**	***128***

Table 12
Design parameters and primary energy consumption for *baseline* configurations of case study 2 (Figures in italics refer to what-if scenarios).

Case study 2	Pipe diameter	Pump rated power	Heat exchanger at source	Heat storage capacity	Heat pump capacity	Heating demand	AS IS Primary energy consumption	*AS IS Primary energy consumption*	TO BE Primary energy consumption
							Natural gas boiler at user	*Air-to-water HP at user*	
	[mm]	[kW]	[kW$_{th}$]	[m^3]	[kW$_{th}$]	[kWh/year]	[TOE/year]	[TOE/year]	[TOE/year]
G (*Baseline*)	155	38	3517	290	489	8563524	682	*541*	278
G (Central Italy)	*144*	*34*	*3035*	*195*	*422*	*7206214*	*575*	*445*	*240*

primary energy consumption for case study 2, with Table 11 of case study 1, and specifically with the collaborative configuration serving buildings A, B and D jointly, we note that, compared to case study 1, the diameter of the pipes connecting I to G in case study 2 is approximately three times as large, but the heating demand is more than twenty times as large. In this case study, substantial hot storage is introduced, which accounts for approximately 20 % of the total capital expenditure. The capital cost ratio of water heat pumps compared to district heating piping and storage is similar to that found in Case Study 1, of the order of 56 %.

The continuity of heating demand throughout the year has a critical impact on the economic feasibility of the investment. In fact, Table 13 shows that in case study 2 the life cycle cost of collaboration in the *baseline* scenario is approximately 30 % lower than the life cycle cost of the AS IS case. At the same time, in the *baseline* TO BE scenario, there is a reduction in total CO_2 equivalent emissions (direct plus indirect plus embedded) of more than 75 % of the emission values in the AS IS case. Therefore, unlike in case study 1, therefore, reducing emissions does not result in an additional cost but in an additional gain (shown as a negative cost in Table 13).

The collaboration is also favourable in respect of the water footprint, showing a reduction of approximately 10 % due to the direct water consumption avoided at the condenser, which offsets the increase in indirect consumption linked to additional electricity consumption in the TO BE configuration.

4.4. *Case study 2 – results of what-if scenarios*

Tables 12 and 13 also report the results for the alternative what-if scenario under the climatic conditions of lower heat demand, modelled as a reference example based on data from a seaside location in central Italy, both for the *baseline* configuration, with the greenhouse powered by NG boilers, and for the second what-if scenario, i.e. the AS IS configuration with the greenhouse powered by an air-to-water heat pump (AHP) supplying the greenhouse air heating system.

In the Central Italy scenario, the primary energy demand of the greenhouse is about 16 % lower than in the *baseline* scenario (Table 12). Even under these less favourable climatic conditions, the cost-

Table 13
Design parameters and primary energy consumption for *baseline* configurations of case study 2 (Figures in italics refer to what-if scenarios. Subtotals and net balance figures are highlighted in bold).

Case study 2		G AS IS (NG)	*G AS IS (AHP)*	G TO BE	*G Central Italy AS IS (NG)*	*G Central Italy AS IS (AHP)*	*G Central Italy TO BE*
Capital costs	[€]	245698	*449949*	767008	*226589*	*415382*	*694793*
Natural gas	[€/year]	359668	*0*	0	*302661*	*0*	*0*
Electricity and water	[€/year]	76219	*435886*	287128	*76219*	*443237*	*10373*
Life cycle cost	**[€]**	**6243492**	***7663751***	**4717889**	***5439976***	***6516463***	***4248863***
Embedded CO_{2eq} emissions	[tCO_{2eq}]	224	*268*	625	*224*	*239*	*201*
Direct CO_{2eq} emissions	[tCO_{2eq}]	70450	*0*	0	*59283*	*0*	*0*
Indirect CO_{2eq} emissions	[tCO_{2eq}]	402	*28626*	15259	*402*	*23547*	*13306*
Net CO_{2eq} balance with collaboration	**[tCO_{2eq}]**	**−55191**	***−13010***	**-**	***−46402***	***−10279***	**-**
Cost of CO2eq emission savings	**[€/tCO_{2eq}]**	**−28**	***−226***		***−26***	***−221***	
Embedded blue water footprint	[m^3]	1835	*2640*	3328	*1669*	*2364*	*2805*
Direct blue water footprint (WCC)	[m^3]	2724721	*2724721*	2106094	*2724721*	*2724721*	*2202449*
Indirect blue water footprint	[m^3]	3066	*585013*	297983	*2580*	*479735*	*256809*
Net blue water balance with collaboration	**[m^3]**	**−322216**	***−904968***	**-**	***−266908***	***−744757***	**-**

effectiveness of the collaboration is largely maintained compared to the *baseline* configuration with gas boilers.

The environmental benefits of collaboration, both in terms of carbon and water footprint, are slightly lower than in Northern Italy in absolute terms, but comparable in percentage terms (Table 13).

Regarding the use of AHPs to heat the greenhouse in non-collaborative configurations, they are more expensive than NG boilers for the energy market situation taken as a reference for this study, and the economic benefit of collaboration is therefore comparatively higher.

From the point of view of carbon equivalent emissions, the use of AHPs in the stand-alone scenario leads to a reduction of about 60 % compared to the stand-alone scenario with boilers, but emissions in TO BE collaborative configurations are nevertheless much lower than in standalone cases.

Conversely, regarding the water footprint, collaboration yields a greater advantage compared to the existing scenarios with AHPs than to those with NG boilers. This advantage stems from the fact that replacing AHPs eliminates electricity usage, which affects indirect water consumption more significantly than NG does. All these results are observed both in the actual Northern Italian climate and in the representative Central Italian climate.

4.5. *Comparative discussion of results and sensitivity analysis*

The two real-life case studies analysed, both from the food industry, share similarities in temperature levels and the distance between the source and the user. However, they differ significantly in size and context: one involves renovation with existing buildings, while the other is an ex-novo project requiring new building designs. Consequently, distinct what-if scenarios were created for each case study, based on the same *baseline* reference conditions, which may lead to conclusions that seem very specific to each case.

The broader applicability of our model can be appreciated when comparing these case studies to one another, when considering some changes in baseline conditions, and in relation to some outcomes for similar systems found in the literature.

For both case studies, a sensitivity analysis was carried out for the *baseline* scenarios with regard to the dependence of economic performance on increases in electricity and NG prices.

For case study 1, the analysis is shown in Fig. 7 only for the two configurations closest to feasibility, i.e. the connection of building B alone and of the set of buildings.

As expected, the payback period for case study 1 is mostly too long: the collaboration would only be profitable if the gas price quadrupled, a scenario that occurred in certain European nations (excluding Italy) amid the energy crisis of June 2022. Conversely, case study 2 (Fig. 8) maintains its profitability despite significant hikes in electricity costs, especially when comparing the TO BE configuration with AHP-based stand-alone configurations at the user level.

To generalise, the economic performance of 4DH-based inter-firm cooperation depends on the ratio of electricity cost to NG cost, which is typical for heat pumps and more generally for electrification-based decarbonisation options. Nevertheless, it is mainly affected by the ratio of energy demand to installed capacity, which is mostly the case for capital intensive infrastructure such as DH.

For collaborative solutions, the relative weight of capital costs to life-cycle cost can be three or four times as high as in stand-alone solutions, whether the latter are based on NG or on air-source heat pumps. Obviously, for this effort to be economically viable, the price of electricity must not be too high in relation to the price of gas, and the number of operating hours must be sufficient to balance the higher system cost.

To interpret the results of the case studies, it may be useful to compare them with literature findings on the use of heat pumps for industrial heat recovery. For instance, as per reference [29], a price ratio of kWh of electricity to kWh of natural gas lower than 3.5, which was the case in Europe in 2020, rendered heat pumps economically viable for industrial heat recovery with temperature lifts between 26 and 43 K. In this study, similar temperature lifts (between 20 and 35 k) were examined for case study 2 and case study 1, respectively, leading to full economic viability for case study 2, having high capacity and continuous demand, and poor performance for case study 1 due to its low operational continuity. Furthermore, even in case study 1, if the price of natural gas were high enough to pay back the capital costs of the DH, economic viability could be achieved even if the price ratio of kWh of electricity to kWh of natural gas remained unchanged (this would happen e.g. moving from 0.12 €/kWhel and 0.08 €/kWh natural gas to 0.24 €/kWh electricity and 0.16 €/kWh of natural gas).

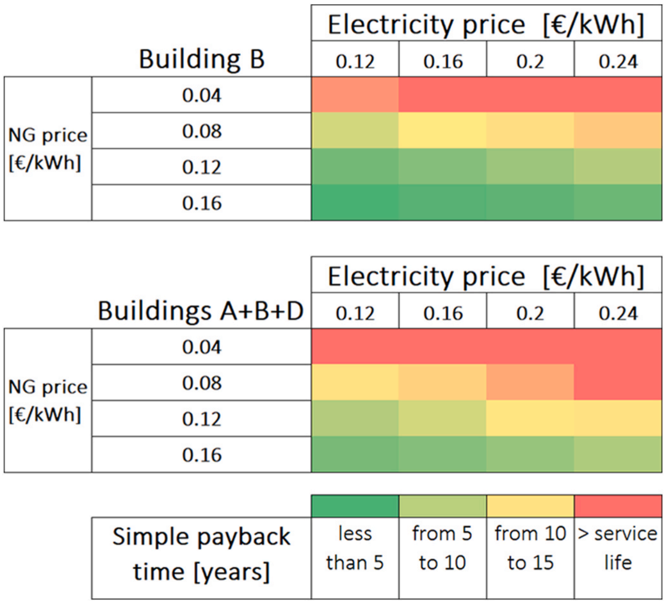

Fig. 7. Sensitivity analysis of payback times to the costs of energy carriers – case study 1.

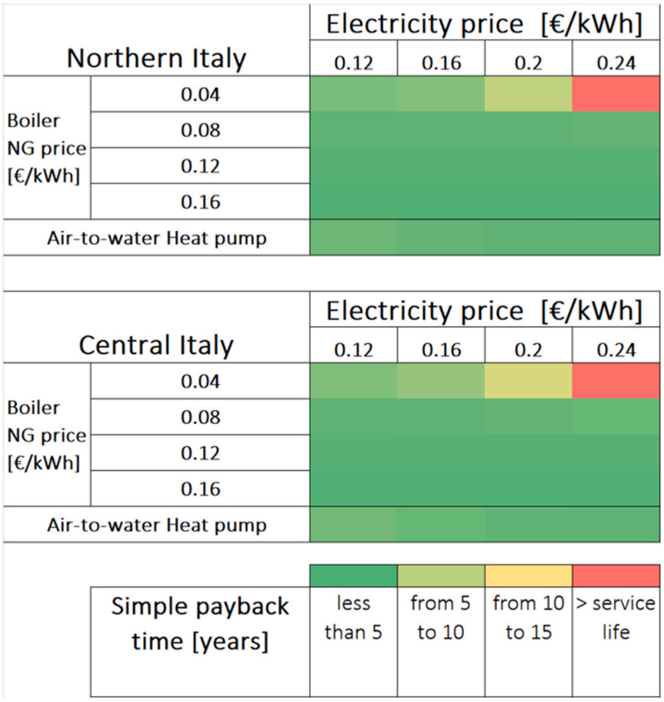

Fig. 8. Sensitivity analysis of payback times to the costs of energy carriers – case study 2.

The simulation of electricity and gas price variations depicted in Fig. 8 shows that the payback always remains below 5 years except if the gas price is 0.04 €/kWh and the electricity price is 0.2 €/kWh or more, and only if this rises to 0.24 €/kWh does the system become economically unviable. This applies to both the *baseline* climate conditions of Northern Italy and to the Central Italy what-if scenario. Compared to independent heating of the AS IS greenhouse by means of air-source heat pumps, the simple payback is in the order of 1–2 years, slightly higher in the Central Italy scenario.

For case study 2 where the greenhouse is currently only planned, a sensitivity analysis was also carried out with respect to the distance of this user from the source under *baseline* climatic conditions. Fig. 9 shows the threshold distances above which the life cycle cost of the collaborative system becomes higher than that of the corresponding independent systems. These distances are depicted for varying electricity prices (x-axis) and for different gas price levels. Correctly, the threshold distances with respect to AS IS systems with gas boilers increase (up to more than 10 km) as the gas price rises, and decrease almost linearly as the electricity price rises. On the other hand, the threshold distance for which the proposed collaboration is economically equivalent to an independent supply of the greenhouse by means of an AHP (dashed line in Fig. 9) is in the order of 2 km. For AHP AS IS systems the threshold distance is obviously independent of the price of gas, and instead increases slightly with the price of electricity. This is correct because the cost effectiveness of the collaboration compared to stand-alone AHPs is based entirely on electricity savings (due to recovery from an excess heat source warmer than air), and therefore improves as the price of electricity increases.

These distances can also be compared with similar results in the literature. For example, using the function reported in Ref. [9] maximum distances for economic viability of systems with similar annual heating demand as the greenhouses in case study 2 should be in the order of 750–850 m for the case of Central Italy and Northern Italy, respectively. In our case, the distances are greater, of the order of 2 km for the *baseline*, probably because in Ref. [9] the user are municipal district heating systems, and residential space heating demand, even under the Danish conditions studied in Ref. [9], is more discontinuous than that of the greenhouses of our case study 2. For the buildings from our case study 1, the maximum viable for feasibility according to Ref. [9] would vary between about 30 m for case B and 80 m for case A + B + D: the non-feasibility of connections in case 1 is thus in line with the findings by the authors of [9] for what they call hyper-local urban studies. Maximum viable distances in the order of 5 km are mentioned in Ref. [7] for systems having a levelized cost of heat in the order of 17.25 €/MWh. From the data reported in Tables 12 and 13 a levelized cost of heat in the order of 18.4–19.7 €/MWh can be estimated for case study 2 for Northern and Central Italy, respectively, hence distances should be comparable. However, in Ref. [7] no heat pump is considered as waste heat sources considered are at a higher temperature than the sink, therefore it makes sense that economically feasible distances are lower in our case.

Fig. 9 also shows, as thin horizontal grey lines, the distances above which the blue water footprint of the collaborative system is higher than that of the corresponding independent systems. In the *baseline* case, with a NG-fuelled AS IS system, this distance is in the order of 5 km and could be exceeded if high gas prices (>0.1 €/kWh) make such remote collaborations economically viable.

However, compared to heating with AHP, the threshold distance increases to 13 km and is only reached when the electricity demand for pumping becomes so high that it cannot be compensated by the reduction in electricity consumption made possible by collaborative heat recovery with 4DH.

Viable inter-firm collaborations based on 4DH are essentially a form of electrification of heating systems, in which electricity consumption for upgrading heat and pumping water into DH systems subsitutes either natural gas consumption or electric consumption by the heating systems that are less energy efficient than the cooperation itself. The nexus between carbon emissions and water consumption depends on the mix of sources used to generate electricity: if decarbonisation relies on low water sources such as solar-wind energy systems [40], which could even be integrated locally through inter-enterprise cooperation systems, there will be simultaneous reductions in carbon and water footprints. Conversely, if low-carbon, high-water energy sources such as nuclear and hydropower [40] dominate the energy mix, even efficient practices such as the external recovery of excess industrial heat with 4DH may result in an increased water footprint.

For 4DH systems a threshold distance for the carbon footprint can also be determined. In fact, for the current emission factor of the Italian

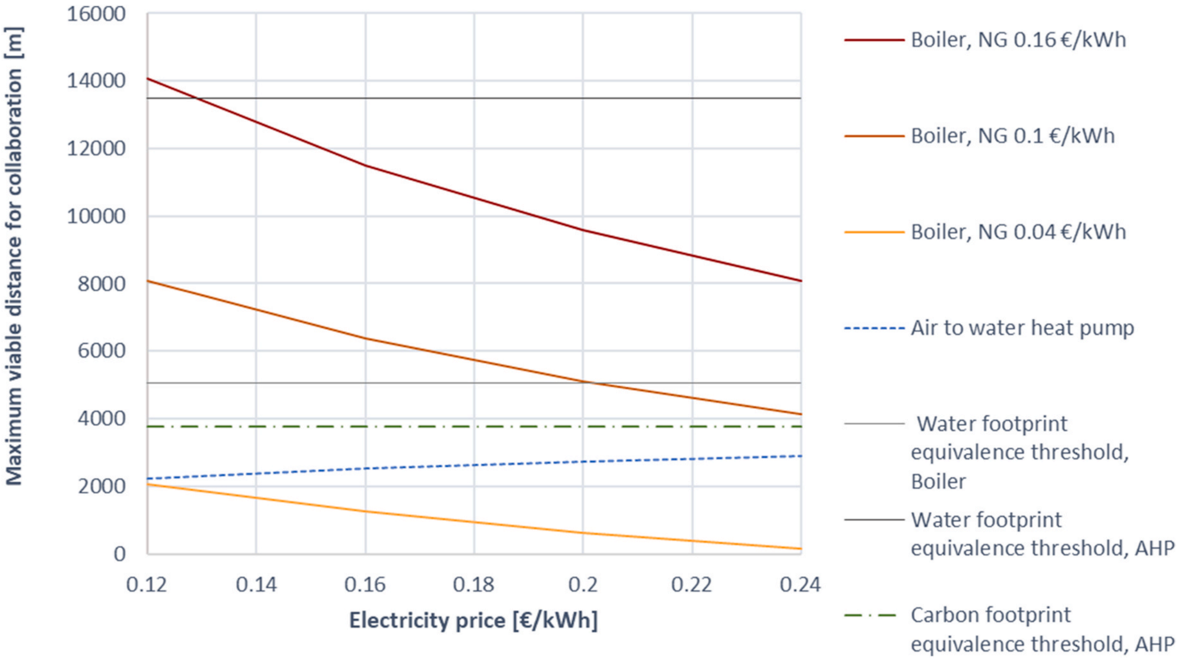

Fig. 9. Threshold distances for the economic viability of collaboration between source I and greenhouse G at *baseline* climatic conditions in case study 2.

national electricity mix, in collaborations with thermal flows of this amount that are above 3.8 km (dashed green line with dots in Fig. 9) the carbon footprint of the collaboration is higher than that of independent systems using AHPs. However, this distance is greater than the economic threshold of collaborations against AHPs. An analogous threshold, in the order of 16 km, could be identified in the case of NG *baseline* configuration as well, and again it is well above the economically viable distances.

5. Conclusions

In this research, a calculation model was developed to evaluate the economic feasibility of industrial collaborations for the recovery of excess heat by sharing it from a potential source to a potential user via low-temperature district heating networks involving the integration of heat pumps and storage systems (4th generation DH networks). To investigate the cost and benefits of such collaborations, this paper presented the structure of the model and applied it to two case studies within the food industry in Italy.

The life cycle costs of independent configurations (AS IS) were compared with collaborative configurations (TO BE), and the carbon footprint and blue water footprint, including embedded, direct and indirect emissions and consumption, were also calculated and compared as environmental performance indicators for various configurations and scenarios.

The results obtained from the application of the model were in line with initial expectations and with similar results from the literature, and confirmed that, with respect to *baseline* configurations where potential users have NG boilers, inter-firm collaboration is not only economically viable at a hyperlocal scale in the order of 500 m but even at urban collaboration distances in the order of 2 km. Collaborations for excess heat recovery invariably result in a substantial reduction in primary energy consumption and in greenhouse gas emissions, which could reach zero if the electricity used for pumping and for temperature upgrades comes entirely from renewable or nuclear sources. The impact of the emissions and of the blue water consumption embodied in equipment on the overall carbon footprint is negligible compared to the weight of operations, even for networks of several kilometres.

The ability to calculate water footprints is a distinctive feature of this model, which allowed to highlight that inter-firm collaboration by means of 4DH can result in an increase in the total water footprint. It has been demonstrated that within the context of Italy’s national energy mix, the overall water footprint for the proposed TO BE configurations typically exceeds that of the existing AS IS configurations. This is particularly true when waste heat dissipation is managed through FAC systems that do not directly consume water but do so indirectly in proportion to electricity use. While it may seem beneficial to replace FAC heat dissipation methods involving energy-intensive fans with DH pumps, the increased electrical demand of water-to-water heat pumps can overturn this equilibrium. Even in the presence of water-intensive dissipation systems, such as cooling towers and water-cooled condensers, an unfavourable water footprint balance of cooperations may occur if the heat transferred to the users over the lifetime of the system is too low compared to the energy used for construction, heat upgrade and heat transport. It is therefore confirmed that the water consumption of the heat dissipation system is a parameter to be evaluated in heat recovery applications, as there is also a water-energy-carbon nexus at the individual system level.

Of course, the model developed has limitations: the main one is related to the use of only two typical days to represent the load profiles over a whole year, which may lead to over- or underestimation of the annual heating demand or of peak loads, depending on the way the approximation is made. However, the request for hourly load profiles on only two typical days (which, with appropriate adjustments to the number of days they are repeated, can be made to correspond not to the season but to the type of work commitment, weekday or holiday) allows this tool to be used more quickly as it requires less data from the decision-makers.

Another limitation that could be overcome with more accurate modelling is the approximate sizing of tanks, which neglects thermal losses over time and considers hot water storage as only technology option.

Nevertheless, the value of this model is mainly in terms of excluding infeasible investments: if the results of this first assessment are negative, as in the first case study presented in this paper, no further investigation will be carried out. Conversely, in the second case study, users can be advised to use more accurate models for simulating buildings, to gather more data on available waste heat flows, and to use or develop advanced models for sizing the heating systems, e.g. optimisation models that take as input the behaviour of the potential supplier and the user, at least for average monthly days, possibly divided into holidays and weekdays, and that allow simultaneous optimisation of equipment size and waste heat utilisation.

Future developments may include the incorporation of the costs and impacts of refurbishing user heating systems so that they can work at lower temperatures, allowing for a more comprehensive comparison of the benefits to be gained from working with low-temperature excess heat sources. Finally, this system took the pure heating demand into account. The growing need for cooling - in summer, but not only - even in industries and in production areas in general requires that cooling demand is considered as well, favouring technologies that are able to satisfy both heat and cooling demand, in some cases even simultaneously. It may be important to develop the model further in this direction.

CRediT authorship contribution statement

D. Chinese: Writing – original draft, Visualization, Project administration, Methodology, Investigation, Data curation, Conceptualization. **A. Meneghetti:** Writing – review & editing, Visualization, Supervision, Methodology, Formal analysis. **G. Cortella:** Writing – review & editing, Software, Methodology, Investigation, Data curation. **L. Giordano:** Writing – review & editing, Supervision, Software, Project administration, Conceptualization. **E. Tomasinsig:** Writing – review & editing, Validation, Investigation, Formal analysis, Data curation. **M. Benedetti:** Writing – review & editing, Supervision, Software, Resources, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: The work was supported by public funding from the authors’ institutions or Governmental institution (Italian Ministry for Economic Development) as declared in the paper acknowledgements. This does not generate any form of conflict of interest for the authors. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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