Cleaner Energy Systems 1 (2022) 100005

Contents lists available at ScienceDirect

Cleaner Energy Systems

journal homepage: www.elsevier.com/locate/cles

Decarbonization potential of integrating industrial excess heat in a district heating network: The Portuguese case

José M. Cunha[a,*], António S. Faria[b], T. Soares[b], Z. Mourão[b], João Nereu[c]

[a] INEGI – Institute of Science and Innovation in Mechanical and Industrial Engineering, University of Porto, Porto, Portugal
[b] INESC TEC – INESC Technology and Science, Porto, Portugal
[c] Climaespaço, Portugal

ARTICLE INFO

Keywords:
District heating network
Industrial excess heat
Thermal energy storage
Emb3rs
Thermal flow

ABSTRACT

The paper performs an assessment of the decarbonisation potential in utilizing industrial excess heat to meet the baseload heating requirements of a district heating network in Portugal. The excess heat source considered was a municipal waste-to-energy plant located 5 km from a district heating and cooling network. It performed an economical comparison between two integration procedures: (i) extending the existing pipeline to the excess heat source; and (ii) using a continuous supply of portable thermal storage modules. For the excess heat characterization and tecno-economic assessment, the EMB3RS platform was used. The analysis demonstrated the pipeline alternative more economically feasible (with a levelized cost of heat of 17,25 €/MWh), meeting the baseload consumption with a decarbonisation reduction potential of 30%. The higher levelized cost of heat of the portable thermal storage solution is mainly due to the high daily replacement cost for the thermal stores.

Introduction

District heating networks are cost effective systems to provide heat in an closed circulation loop to meet space heating and domestic hot water demands of a large number of buildings (Snodin et al., 2020) in an environmental friendly way.

Centralized heating and cooling solutions can provide a cost effective heating and cooling to heavily populated areas, with the added benefit of a CO2 emissions reduction potential. Due to their agnosticism regarding its heat sources, there are no major technical obstacles to the operation of DHNs to the integration of industrial excess heat assuming that it meets the grid supply temperature and has its own pumping unit on the connection point.

While the main components of district heating networks (DHN) are technically established (Hawkey, 2012), their integration into Europe's space heating market is not very sucessful in the southern countries (mainly due to the lower heating degree days required when compared to the northern countries); whilst being significant in some northern countries such as Denmark (47%) and Sweden (55%) (Deli and Shilken, 2020).

The two main limitations to significantly scale up DH is the competitive cost of individual gas boilers (Deli and Shilken, 2020), and the lack of state incentives to decarbonize the building heating sector (Snodin et al., 2020).

Industrial excess heat integration into DHNs can potentially to provide a cost-effective heat source, while also providing some financial benefit to the industry and promoting its further decarbonization targets (Manz et al., 2021). Li et al. (2021) studied the implementation of thermal energy storage to meet the mismatch between the excess heat from a data centre and the heat demand of a campus district heating network in Norway, concluding to have a reduction of peak heat demand of 31% and a subsequent yearly energy savings of 5%. Su et al. (2021) estimated that there is 3527 GWh of excess heat potential from data centers (91%) and supermarkets (9%) in Stockholm, able to meet 50% of its heat demand.

There are several industries that posses excess heat streams able to be integrated into DHNs, being exhaust gases the predominant energy flow (Manz et al., 2021). However, the industry's distance to the DHN can minimize its energy and economic benefits through extended piping heat losses and cost (Hering et al., 2021).

The use of a string of portable thermal energy storage modules (Colella et al., 2012) to continuously provide heat to a DHN could be a viable option when there are some physical constraints to the deployment of a new pipeline (e.g., railway crossings, river, etc.) where the required changes to the pipeline would make its pumping costs prohibitive (Du et al., 2021). Deckert et al. (2014) studied and optimized the thermal behaviour of these solutions and concluded that the portable system could provide a levellized cost of heat around 50 €/MWh (for a

* Corresponding author.
E-mail addresses: jmcunha@inegi.up.pt (J.M. Cunha), antonio.s.faria@inesctec.pt (A.S. Faria), tiago.a.soares@inesctec.pt (T. Soares), zenaida.mourao@inesctec.pt (Z. Mourão), joao.nereu@climaespaco.pt (J. Nereu).

https://doi.org/10.1016/j.cles.2022.100005
Received 10 December 2021; Received in revised form 21 February 2022; Accepted 23 March 2022
Available online 24 March 2022

Nomenclature

CAPEX	Capital expenses
DHN	District heating network
DHC	District heating and cooling network
EMB3RS	Heat and cold matching platform (www.emb3rs.eu)
LHS	Latent heat storage
LCOH	Levellized cost of heat
MSW	Municipal solid waste
OPEX	Operational expenses
PCM	Phase change materials

distance of 5.6 km between the source and sink and transferring 1500 kWh_{th} in a whole year, considering 200 charging/discharging cycles), a competitive cost when compared with te 74 €/MWh estimated for the pipeline alternative.

Although proven economically competitive for lower exchanged capacities, there are no reports studying the integration of larger capacities (in the order of the MW_{th}).

Thus, this work studies the decarbonization potential of utilizing the excess heat of a municipal waste-to-energy plant that currently does not produce process heat, to provide the baseload heat demand of a district heating and cooling network (DHC) located in the Portuguese capital of Lisbon. The grid is designed to supply 29 MW_{th} of heating demand and 35 MW_{th} of cooling demand.

Municipal waste-to-energy plants are usually divided into 2 main categories: producing electricity only (best available technologies quote overall efficiencies of around 20%) and electricity and heat combined (with best available technologies quoting overall efficiencies of around 40–45%) (Albores et al., 2016).

The excess heat stream from ValorSul (a waste-to-energy plant) can be integrated into the district heating and cooling network by installing an economizer in each chimney stack to cool the exhaust gases from 200 °C to 193 °C. This energy flow can indirectly heat the DHN water from 65 to 100 °C (for the pipeline solution) or heat a thermal fluid charging the portable thermal storages from 105 to 145 °C onsite, being discharged into the DHN. The main contribution of this study lies in the analysis and comparison of the two potential solutions to utilize ValorSul's excess heat stream in the DHN.

The novelty of the current work is the system proposed for the integration of portable thermal energy storage modules to transport the excess heat from a waste to energy plant in a large scale (2.64 MW_{th}), and its techno-economic assessment and comparison with a conventional pipeline integration.

In the next sections, a brief description of the EMB3RS platform will be made, followed by a description of the proposed portable thermal energy storage solution. A description of the case study will be performed, followed by an economical comparison of the proposed solutions and conclusions from this study.

Methods

To perform the tecno-economic assessment of these two excess heat integration solutions, the method adopted for this case study was to proceed initially with a characterization of the industrial excess heat source (temperature settings, fluid utilized, flowrates and operation profiles). After the source characterization, a similar approach was made to characterize the sink. Being a district heating and cooling network, it was considered the sink as the aggregated demand of the building. After obtaining the capacity, supply and target temperatures of the sinks and sources, the EMB3RS platform was utilized to convert the excess heat from the source into supply heat to the grid.

The conversion made, based on the diagrams presented in Fig. 1, estimated the installation of a set of heat exchangers and closed loop circuits to provide the supply heat required to the grid. After costing all of the equipment and heat exchangers detailed in the diagram above (CAPEX, OM fix and variable) to meet the capacity required for the baseload heating consumption of the DHN, and considering the excess heat source operating continuously, a tecno-economic assessment is performed to compare both solutions presented. The EMB3RS platform knowledge base (ESCI and PDM, 2021) was used to obtain all the costing parameters.

The EMB3RS platform, a planning tool for matching sources and sinks

The EMB3RS platform is designed as a simple matchmaking tool, made to meet the main requirements when planning a new DHN or extending an existing one, focused on the utilization of industrial excess heat (ESCI and PDM, 2021). The platform, still under development, will quickly assess the potential sinks for sources with available excess heat or vice versa, depending on user requirements.

Industrial users with considerable amounts of excess heat, will provide the essential parameters, such as their location and the characteristic of the available excess heat. The EMB3Rs platform will then autonomously and intuitively assess the feasibility of new business scenarios and identify technical solutions. End-users such as energy communities will be able to determine the costs and benefits of industrial excess heat and cold utilisation routes and define the requirements for implementing the most promising solutions. Matching excess heat providers with end-users will enable win-win partnerships and reduce CO_2 emissions.

Up to date, there are a few platforms mapping the potential of installing a new DHN based area density and type of buildings, such as the Hotmaps project (Scaramuzzino et al., 2019); however, such platforms do not perform pipe routing optimization or a detailed analysis of sink/source profiles mismatch. Other platforms such as THERMOS platform (EU, 2021), do provide automatic pipe routing for a given open street map zone and perform an analysis based on the total yearly heat demand and peak demand, although there is not a detailed analysis of sink/source profiles mismatch.

The EMB3RS platform will be intended to perform the following list of actions

- Mapping heat/cold sources and sinks;
- Distance calculation between sources and sinks;
- Automatic pipe routing;
- Calculate thermal losses in network based on the distance between sources and sinks and their temperature levels;
- Calculate costs of network installation/construction;
- Costs of excess heat/cold integration into a district heating/cooling network;
- Costs of excess heat/cold integration into the processes on-site;
- Savings in energy carriers and related expenditures due to use of excess heat and cold;
- Calculation of economic impact (revenue and cost) for all actors involved in the energy community, e.g. supermarket and consumers;
- CO_2 reduction through the use of excess heat/cold;
- Cost of converting excess heat into electricity.

The platform is divided into five modules and a knowledge base, as shown in Fig. 1. The knowledge base will be a dynamic database to provide reference values (and default generation and demand profiles) to the various modules to be used in their simulations. This includes the: specific cost of equipment; expected equipment efficiencies; fuel and electricity cost; DHN cost; characterization of heat exchangers and their associated cost, etc.).

For this study, all the parameters necessary to cost the various components required to integrate the industrial excess heat into the DHN were retrieved from the EMB3RS Knowledge Base module.

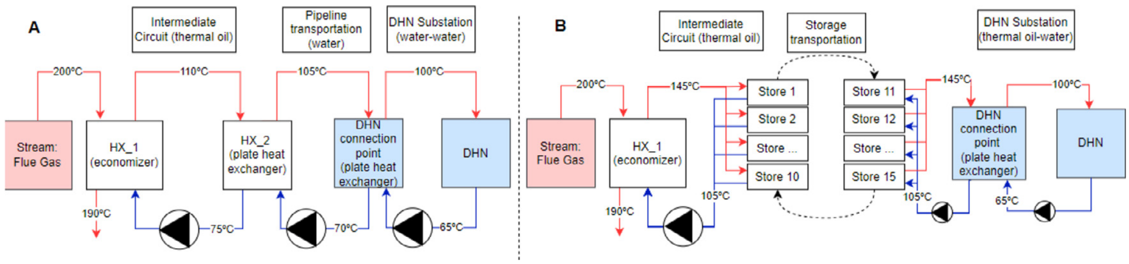

Fig. 1. Schematic diagram of the integration technique adopted utilizing a pipeline (A) and utilizing portable thermal store (B).

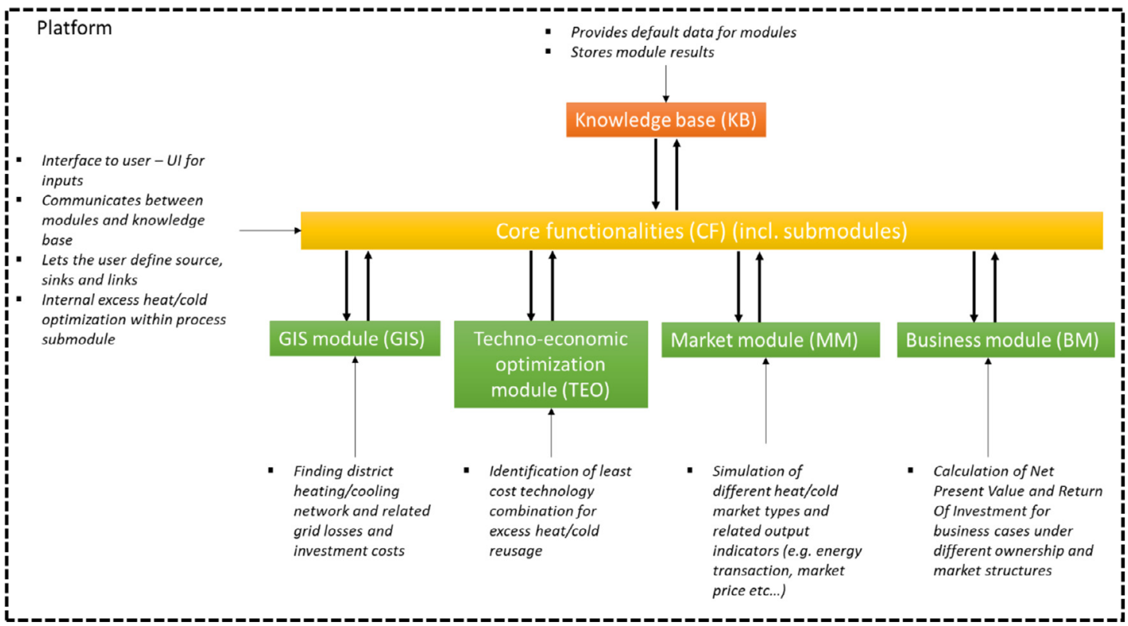

Fig. 2. Overview of the EMB3RS platform modules and its knowledge base.

Portable thermal energy storage modules using phase change materials (PCMs)

To perform fast loading and unloading, the thermal storage system should be effective, consequently leading to a very small PCM average thicknesses (Wei et al., 2005) and have a high storage density to promote more compact solutions. Latent heat storage systems can offer high energy storage density (above 80 kWh/m^3) on a narrow temperature range and are therefore ideal candidates for these applications (da Cunha and Eames, 2018). A compact latent heat storage geometry based on Colella et al. (Colella et al., 2012), was optimized to fit into a 25-foot cargo container, using Hitec Salt (Wang et al., 2013) as phase change material. This maximizes its storage capacity and thermal output for the 25 400 kg weight limit, and minimizes its heat losses by inserting thermal insulation on the spare volume. A simplified view of the proposed portable thermal store is presented in Fig. 2.

Due to the weight limitations, the designed portable thermal storage could store 647 kWh$_{th}$ using Hitec Salt from 105 to 145 °C, corresponding to a PCM mass of approximately 9 t The proposed storage geometry was simulated under operating conditions to assess its charging and discharging performance, designed for a charging time of 2 h and to be fully discharged in 1 h.

Fig. 4 presents the simulated results for the chosen thermal storage geometry. Using Hitec salt (PCM) in the compact thermal store, the storage system charging process would bemore prolongued than its discharging process, due to the PCM's melting point of 142 °C being to the storage system maximum temperature of 145 °C. That would eventually prompt a steadier discharging heat transfer rate, as seen in Fig. 3B. The average heat transfer rate was measured counting only values above 50 kW. Table 1 details the properties of the thermal storage studied.

Table 1
Main thermal performance parameters and properties of the thermal storage studied.

Key performance indicator (KPI)	Value
Storage capacity [kWh]	647
Storage density [kWh/m^3]	64.4
Storage heat loss [kWh/d]	20.63
Power density [kW/m^3]	52
PCM volumetric ratio [%]	45.79
Temperature range [°C]	105–145
Average charging rate [kW]	360
Average discharging rate [kW]	684
Charging/Discharging time [h]	1.8/0.94
Charging/Discharging flowrate [L/min]	1800/360

Case study: industrial excess heat source in a district heating and cooling network

The excess heat source studied in this paper is a waste-to-energy incinerator operated by Valorsul, located 5,2 km from the district heating and cooling network. The incinerator has 3 operating lines, each with a 28 t/h burning capacity of municipal solid waste (MSW), continuously supplying superheated steam (52,5 bar at 420 °C) to a steam turbine with a capacity of 50 MW$_{el}$. Best available technologies quote that waste-to-energy plants would have overall efficiencies of around

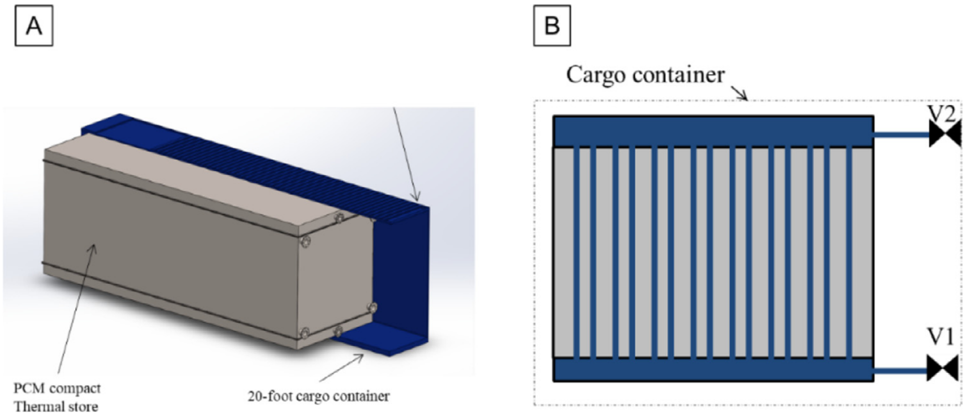

Fig. 3. Detailed view of the portable latent heat storage (LHS) system and simplified diagram of the fluid flow passing through the thermal storage, base on the geometry proposed by Collella et all (Colella et al., 2012).

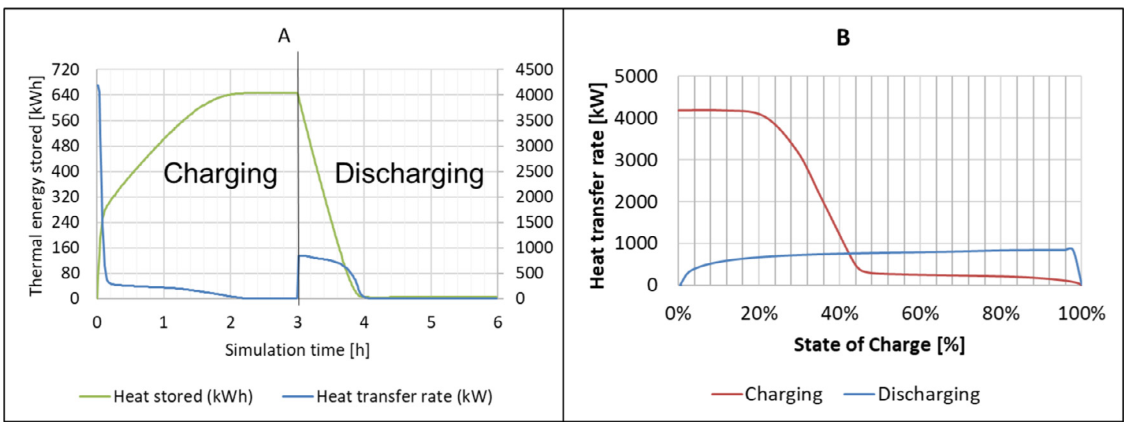

Fig. 4. Simulation predictions of the thermal storage heat rate and thermal storage capacity (A) and calculated charging and discharging performance according to the simulated results (B).

20% (Albores et al., 2016), with the treated flue gas exiting the chimney stack at around 200 °C. Subtracting the energy recovered on the steam generator of 88.19 MW from the total amount burnt on the furnace of 182.47 MW would lead to an excess heat source with a thermal capacity of 94.28 MW (Albores et al., 2016).

The Portuguese district heating (and cooling) network installed in Parque das Nações in 1997, is managed by Climaespaço (Engie, 2021). Its energy centre consists of a 5 MW_{el} gas turbine and 2 steam generators: one with 12 MW capacity for cooling the turbine exhaust gases up to 161 °C and another of 2MW capacity for cooling those gases further up to 105 °C (Engie, 2021). The heating system has a quoted overall efficiency of 85%. The district heating and cooling network is supplied by these steam generators, along with a 16 MW_{th} backup steam boiler. The DHN operates at 100/65 °C supply/return temperatures designed for 29 MW of heat demand without thermal storage, with the main heat exchangers operating only to meet the demand. The district cooling network operates at 4/12 °C supply/return temperatures, designed for 35 MW of heating demand, is supplied by 2 Li-Br adsorption chillers with 4.8 MW capacity driven by the surplus heat from the steam generators to cool from 12 °C to 8 °C; and 4 mechanical chillers (2 with 5.85MW 1 with 6.3 MW and 1 with 7.3 MW capacity) to cool from 8 to 4 °C. The cooling from the energy centre is supplied directly to a thermal storage system comprising 15,000 m^3 of water (20 MW of constant thermal output for 6 h), also acting as a buffer to the gas turbine operation when the heating demand is low.

The Portuguese district heating and cooling network had an estimated yearly heating and cooling demand of 76,817 MWh and 93,356 MWh, respectively. This estimate highlights the higher need for space cooling for this southern European climate, as can be seen by the consumption profiles illustrated in Fig. 5. The proposed solutions aim to meet the network minimum heating requirement baseload of 2,64 MW_{th} per hour.

Two solutions to integrate the industrial excess heat into the DHN were studied, one by installing a new pipeline and the other by using a string of portable latent heat thermal energy storage modules.

To convert the excess heat from the Portuguese waste-to-energy incinerator located in Loures into useful heat, an economizer would have to be installed in the chimney stack for cooling the exhaust gases from 200 to 193.43 °C, heating a thermal oil from 105 to 145 °C.

In the pipeline solution, a plate heat exchanger would heat up the DHN hot water from 60 to 100 °C, providing a continuous 2,64 MW_{th} of constant heat supply to the network.

In the portable solution, 5 thermal storage units were required to meet the 2,64 MW_{th} continuous heat demand baseline of the DHN. In order to maintain a continuous operation, 15 thermal storage units were needed, 5 units at the DHN connection point and 10 units at the excess heat source. Each thermal storage unit would discharge up to 18% of its total capacity in 1 hour at the DHN feed in point and fully charge for 2 h at the waste-to-energy plant. This would lead to the replacement of a thermal storage unit every 12 min (performing each thermal storage unit 8 charging-discharging cycles each day), maintaining a continuous supply of excess heat into the DHN.

Assuming a continuous operation of the waste-to-energy incinerator, both solutions would deliver the full amount required by the DHN baseload, 23,160 MWh, 30% of the total amount of heat demand required by the grid.

Economical comparison of the proposed solutions

A general cost analysis of the whole system was perfomed in order to calculate the levelized cost of heat for both cases studied. The levellized

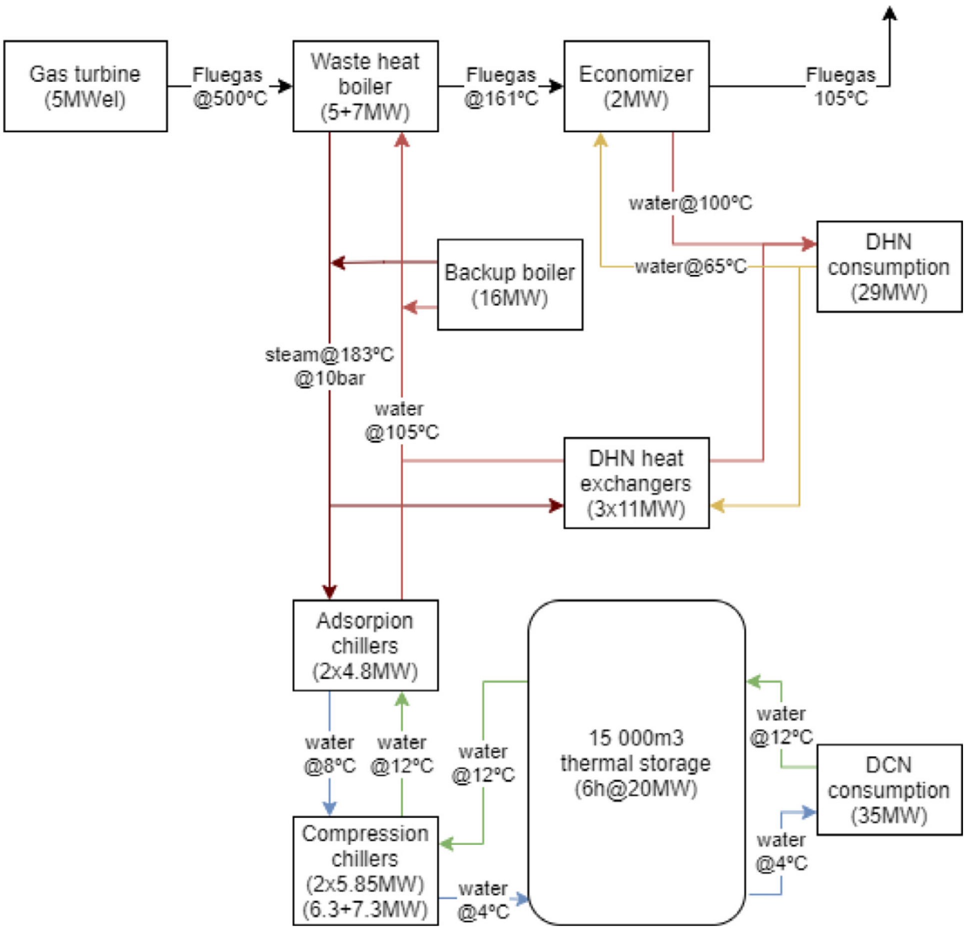

Fig. 5. Schematic diagram of the energy centre installed to supply heating and cooling to Climaespaço DHC network.

cost of heat (LCOH) for each solution was calculated using Eq. (1), from (Smallbone et al., 2017).

$$LCOH = \frac{\frac{CAPEX \times r}{1-(1+r)^{-n_{years}}} + OPEX}{Heat_{produced}} \left[\frac{€}{kWh}\right] \quad (1)$$

Considering an estimated system lifetime of 20 years and an annual interest rate (r) of 3.5% (Nussbaumer and Thalmann, 2016, 2014), the calculated LCOH for each solution is shown in Table 2.

Table 2 presents the calculated capital (CAPEX) and operational (OPEX) costs for the cases studied. For the Hiec salt cost, a price of 1860 €/m^3 was considered, based on a previous assessment made (Pereira da Cunha and Eames, 2016). For the rock wool insulation of the thermal storage units, an estimated price of 4.98 €/m^2 was used, based on (Materials, 2018). For the stainless steel tubes and thermal storage enclosure costs, another price assessment was performed in Alibaba and an indicative cost of 1,5 €/kg for bulk stainless steel was assumed.

To estimate the cost for the 25-foot cargo containers, ("Shipping container prices online," 2018) indicated that 2000 €/unit as a reference price. For the heat transfer oil, shell S2 heat transfer fluid was considered, with an indicative price of 2830 €/m3 when sold in oil barrels (Shell, 2018). For the annual replacement costs of the compact latent heat storage units, it was considered the 5 km distance from the DHN substation to the waste-to-energy incinerator, having the truck an average fuel consumption of 45 L/100 km at 50 km/h and an hourly driver rate of 10 €/h.

For costing all the other components, the EMB3RS knowledge base (ESCI and PDM, 2021) was used. The circulation pumps were selected from GRUNDFOS (Grundfos, 2018), and the pumping power and cost correlations are presented below (Q is the circulation requirement in L/min).

$$Cost_{pumping} = 105,4.Q^{0,52}[€] \quad (2)$$

$$Power_{pumping} = 1,655.Q - 57,28\ [W] \quad (3)$$

For the cost of the economizers selected for the waste-to-energy incinerator, it was used the correlation presented below (providing the economizer capacity in kW).

$$Cost_{economizer} = 1319600.P_{economizer}^{0,52}\ [€] \quad (4)$$

For the heat delivery connection to DHN, the substation specific costs of 46.11 €/kW were obtained based on (ESCI and PDM, 2021). In the pipe connection case, for the new pipe layout to be installed, 616.6 €/m was used for the construction cost and 222.7 €/m for installing the piping required, based on (ESCI and PDM, 2021).

In regards to the operation and maintenance (OM) costs, for the substation at DHN, only the pumping power required to circulate the hot water in the DHN was assumed, based on correlation (2). For the new pipe operation and maintenance, costs were also based on (ESCI and PDM, 2021), assuming a total of 0.79 €/MWh$_{th}$ produced per year, considering the standard electricity tariff of 0.2134 €/kWh (EC, 2020).

The main capital component in the pipe connection CAPEX is the respective installation of the piping required (representing 90% of the initial capital cost for the pipe case) as seen in Table 2.

Even though the CAPEX of the pipe connection is higher than the portable thermal storage solution, the latter has very high OM costs due to the need for continuous replacement of the thermal storage units.

Fig. 6 presents a sensitivity analysis made to the LCOH of both solutions. It can be seen that even when the distance from the source increases, the pipe connection still presents the most economic solution.

Table 2
Tecno-economic comparison of the systems studied.

System		Pipe connection	15 latent heat storage modules	Ref.
Thermal stores	PCM cost (volume)		128 460 (69 m^3)	(Kenisarin, 2010)
	Insulation cost (area)		2 872 (576.7 m^2)	(Materials, 2018)
	Tubes cost (unit)		276 749 (2 070 000)	(Metals4U, 2018)
	Enclosure cost (area)		10 122 (576.7 m^2)	(Guangxi Chengde Group, 2018)
	25-foot container		6 000	("Shipping container prices online," 2018)
	Total (€)	**0**	**448 203**	
Heat connection	Flue gas economizers (kW)	343 452 (3 × 928 kW)		(ESCI and PDM, 2021)
	Pumping required (LPM)	4 142 (1 164)	9 912 (6 934)	
	Network construction (m)	4 196 327 (5 000)	0	
	Substation cost (kW)	121 916 (2 644)		
Total CAPEX [€]		**4 665 837**	**923 483**	
LHS yearly replacement cost (€/year)		0	328 712	(Colella et al., 2012)
OM pumping (€/year)		3 494	13 635	(ESCI and PDM, 2021)
OM heat network (€/year)		21 635	0	
Total OPEX [€/year]		**25 129**	**342 348**	
LCOH [€/MWh$_{th}$]		**17.25**	**19.12**	

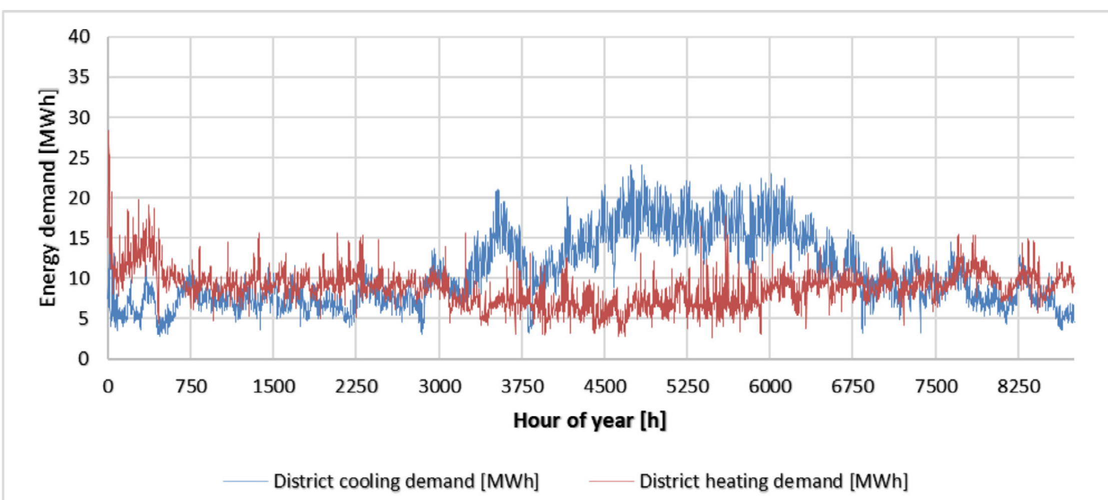

Fig. 6. Estimated annual district heating and cooling demand profile from Climaespaço, data obtained from (Engie, 2021).

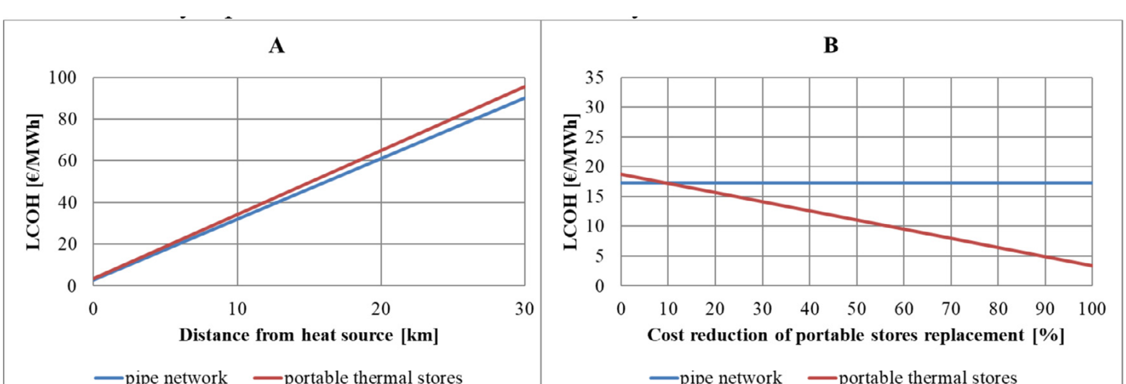

Fig. 7. Sensitivity analysis of the LCOH with the distance from the source (A) and the reduction in the daily replacement cost of the portable thermal stores (B).

To obtain the same LCOH as in the pipe connection, a reduction of 10% in the daily replacement cost would be necessary.

Considering that the tri-generation energy system from Climaespaço has a yearly generation of 43, 800GWh$_{el}$ 3.356GWh$_{th}$ cooling and 76,817GWh$_{th}$ heating with a benchmark CO2 emissions value of 190 gCO2/kWh (Engie, 2021), the integration of exces heat can meet 30% of the total heat demand (a total of 23,16 GWh$_{th}$), that would represent 4400 t of CO2 emissions avoided. The energy reduction provided by the excess heat would lead to a overall system decarbonization potential of 10.8%, a CO2 emissions value of 169 gCO2/kWh for the energy supplied.

Conclusions

The integration of the excess heat from a waste-to-energy plant to meet the baseload of DHN was assessed by 2 alernatives: connecting a pipe to the plant and via a string of portable thermal stores.

Transporting a continuous string of 15 25-foot cargo containers (a container change every 12 min) with 4.6 m^3 of Hitec salt topped at 145 ˚C and discharged to 105 ˚C had the thermal energy storage capacity to store 647 kWh$_{th}$ in each module, in the required temperature range to discharge (supply temperature of 100 ˚C and return temperature of 65 ˚C) into the district heating network connection point. The continuous supply of these containers being charged at a nearby waste-to-energy incinerator and discharged 5 km away to supply Climaespaço district heating network, obtained a levellized cost of heat of 19.12 €/MWh$_{th}$.

Via the pipeline connection, the obtained levellized cost of heat was 17.25 €/MWh$_{th}$, proving to be more economic than the portable thermal stores solution.

The Knowledge Base module from the EMB3RS platform cost correlations provided a useful tool to perform a tecno-economic analysis of the proposed solutions.

The main economic limitations of using portable thermal stores in this solution is the relatively high cost of its required daily replacement, value that could be minimized if electric vehicles with autonomous driving are utilized instead. Both solutions successfully met their heating baseload of 2,64 MW$_{th}$, a system yearly decarbonisation potential of 10.8%.

There is an estimated excess heat potential of 32 MW$_{th}$ at the waste-to-energy plant by cooling the exhaust gases from 200 to 140 ˚C plant, enough to meet the full heating requirements of Climaespaço´s DHN. This heating capacity would only be feasible utilizing a pipe connection, due to the infeasible number of thermal stores required to meet such demand. In order to minimize the daily storage replacement cost, one portable thermal store should be enough to meet the full capacity of a sink for at least one hour, leading to a maximum sink capacity of 640kW$_{th}$ for the storage solution proposed in this case sutdy.

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.

Acknowledgments

The authors wish to thank the cooperation of the Heat Roadmap Europe 4 project. This work is supported by the European Union's Horizon 2020 through the EU Framework Program for Research and Innovation, within the EMB3Rs project under agreement No. 847121.

References

Albores, P., Petridis, K., Dey, P.K., 2016. Analysing Efficiency of Waste to Energy Systems: using Data Envelopment Analysis in Municipal Solid Waste Management. Procedia Environ. Sci. 35, 265–278.

Colella, F., Sciacovelli, A., Verda, V., 2012. Numerical analysis of a medium scale latent energy storage unit for district heating systems. Energy 45, 397–406.

da Cunha, J.P., Eames, P., 2018. Compact latent heat storage decarbonisation potential for domestic hot water and space heating applications in the UK. Appl. Therm. Eng. 134, 396–406.

Deckert, M., Scholz, R., Binder, S., Hornung, A., 2014. Economic Efficiency of Mobile Latent Heat Storages. Energy Procedia 46, 171–177.

Deli, K., Shilken, P., 2020. Developing 4th Generation District Heating and Cooling in Cities. Recommendations for policy makers, Brussels.

Du, K., Calautit, J., Eames, P., Wu, Y., 2021. A state-of-the-art review of the application of phase change materials (PCM) in Mobilized-Thermal Energy Storage (M-TES) for recovering low-temperature industrial waste heat (IWH) for distributed heat supply. Renew. Energy 168, 1040–1057.

EC, 2020. Eurostat online statistical database [WWW Document]. European Comission. URL http://epp.eurostat.cec.eu.int

Engie, 2021. Climaespaço company website [WWW Document]. URL http://www.climaespaco.pt/

ESCI, PDM, 2021. EMB3RS -Heat and cold matching platform [WWW Document]. URL https://www.emb3rs.eu/

EU, 2021. THERMOS Heat Mapping Tool [WWW Document]. URL https://www.thermos-project.eu/home/ .

Grundfos, 2018. Grundfos product center [WWW Document]. URL product-selection.grundfos.com

Hawkey, D.J.C., 2012. District heating in the UK: a Technological Innovation Systems analysis. Environ. Innov. Societ. Transit. 5, 19–32.

Hering, D., Cansev, M.E., Tamassia, E., Xhonneux, A., Müller, D., 2021. Temperature control of a low-temperature district heating network with Model Predictive Control and Mixed-Integer Quadratically Constrained Programming. Energy 224, 120140.

Kenisarin, M.M., 2010. High-temperature phase change materials for thermal energy storage. Renew. Sustain. Energy Rev. 14, 955–970.

Li, H., Hou, J., Hong, T., Ding, Y., Nord, N., 2021. Energy, economic, and environmental analysis of integration of thermal energy storage into district heating systems using waste heat from data centres. Energy 219, 119582.

Manz, P., Kermeli, K., Persson, U., Neuwirth, M., Fleiter, T., Crijns-Graus, W., 2021. Decarbonizing District Heating in EU-27 + UK: how Much Excess Heat Is Available from Industrial Sites? Sustainability 13.

Materials, B., 2018. Rockwool 100mm Acoustic slab [WWW Document]. Build. Mater. Nationwide Ltd. URL www.buildingmaterials.co.uk .

Metals4U, 2018. Stainless Steel 304L tube quotation [WWW Document]. Metals4Uc LTD. URL www.metals4u.co.uk

Nussbaumer, T., Thalmann, S., 2014. Sensitivity of System Design On Heat Distribution Cost in District Heating Zürich.

Nussbaumer, T., Thalmann, S., 2016. Influence of System Design On Heat Distribution Costs in District Heating. Energy.

Shell, 2018. Shell Heat transfer Oil S2 [WWW Document]. Olieonline. URL www.olieonline.co.uk

Pereira da Cunha, J., Eames, P., 2016. Thermal energy storage for low and medium temperature applications using phase change materials – a review. Appl. Energy 177, 227–238.

Scaramuzzino, C., Garegnani, G., Zambelli, P., 2019. Integrated approach for the identification of spatial patterns related to renewable energy potential in European territories. Renew. Sustain. Energy Rev. 101.

Shipping container prices online [WWW Document], 2018. Containers Direct, Studiowide. URL www.shippingcontainersuk.com

Smallbone, A., Jülch, V., Wardle, R., Roskilly, A.P., 2017. Levelised Cost of Storage for Pumped Heat Energy Storage in comparison with other energy storage technologies. Energy Convers. Manag. 152, 221–228.

Snodin, H., Kirkup, B., Garside, C., Lygnerud, K., 2020. International Review of Heat Network MArket Frameworks London.

Guangxi Chengde Group, 2018. Stainless steel sheet [WWW Document]. The Metals Wharehouse, web2market. URL http://www.metalswarehouse.co.uk

Su, C., Dalgren, J., Palm, B., 2021. High-resolution mapping of the clean heat sources for district heating in Stockholm City. Energy Convers. Manag. 235, 113983.

Wang, T., Mantha, D., Reddy, R.G., 2013. Novel low melting point quaternary eutectic system for solar thermal energy storage. Appl. Energy 102, 1422–1429.

Wei, J., Kawaguchi, Y., Hirano, S., Takeuchi, H., 2005. Study on a PCM heat storage system for rapid heat supply. Appl. Therm. Eng. 25, 2903–2920.