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

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ABSTRACT

This paper assesses the decarbonisation potential of utilizing industrial excess heat to meet the baseload heating requirements of a district heating network (DHN) located in the Portuguese capital. It performs an economical comparison between two integration procedures: (i) extending the pipeline to the excess heat source; and (ii) using a continuous string of portable thermal storage modules.

In this scope, this work assesses the integration of the excess heat from a municipal waste-to-energy plant located 5km from a district heating and cooling network and the decarbonisation potential achieved by meeting the baseload heating requirements of the DHN. For the characterization of excess heat and economic analysis, the EMB3RS platform was used. The analysis showed that laying out a new pipe route was 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 (LCOH) of the portable thermal storage solution is mainly due to the high daily replacement cost for the thermal stores.

KEYWORDS

District heating network; industrial excess heat; thermal energy storage; EMB3RS; thermal flow.

INTRODUCTION

District heating networks are comprised of insulated piping networks that deliver heat via steam or hot water to serve space and water heating demands of multiple buildings [1]. They are generally seen as a convenient, economic and environmental-friendly way to supply heat to a large number of buildings.

While the technical components of DHN are relatively mature [2], their integration into Europe's space and water heating market is somewhat unsuccessful in the southern countries (mainly due to the lower heating hours required when compared to the northern countries); whilst being significant in some northern countries such as Denmark (47%) and Sweden (55%) [1].

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There are two main limitations to significantly scale up DH. First, while DH is an inherently local infrastructure, it is competing in a liberal and private market, where the key players of international scope challenge the development of locally-specific systems [2]. Secondly, shifts in the role of local government, from providing services to enabling others to provide services, have led to a large increase of public and private service providers. This reduces the in-house capabilities of local authorities to plan, design and operate technically and financially viable schemes [2].

Integrating industrial excess heat into a DHN can offer the possibility to provide a cost-effective heat sorce, while also providing some financial benefit to the industry. However, the industry's distance to the DHN often minimizes its energy and economic gains through extended piping heat losses and cost [3].

The use of a string of portable thermal energy storage modules [4] 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. Deckert et al. [5] studied and optimized the thermal behaviour of these solutions and concluded that the portable system could provide a theoretical cost of heat around 50€/MWh (for a distance of 5.6km between the source and sink and transferring 1500kWh$_{th}$ in a whole year, considering 200 charging/discharging cycles), a competitive cost when compared with te 74€/MWh estimated for the DHN.

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

Municipal waste-to-energy plants are usually divided into 2 main categories: producing electricity only (best available technologies quote overall efficiencies of around 20% [6]) and electricity and heat combined (with best available technologies quoting overall efficiencies of around 40-45% [6]).

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 of a district heating and cooling network (DHC) located in the Portuguese capital of Lisbon. The grid is designed to supply 29MW$_{th}$ of heating demand using and 35MW$_{th}$ of cooling demand.

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 200ºC to 193ºC. This energy flow can indirectly heat the DHN water from 65 to 100ºC (for the pipeline solution) or heat a thermal fluid charging the portable thermal storages from 105 to 145ºC 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 DHC.

To perform the economic assessment of these two excess heat integration solutions, all costs considered for the various components to convert the industrial excess heat and deliver it into the DHN were based on the Knowledge Base from the EMB3RS platform [7].

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.

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 [7]. 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 [8]; however, such platforms do not perform pipe routing optimization or a detailed analysis of sink/source profiles mismatch. Other platforms such as THERMOS platform [9], 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 Figure 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).

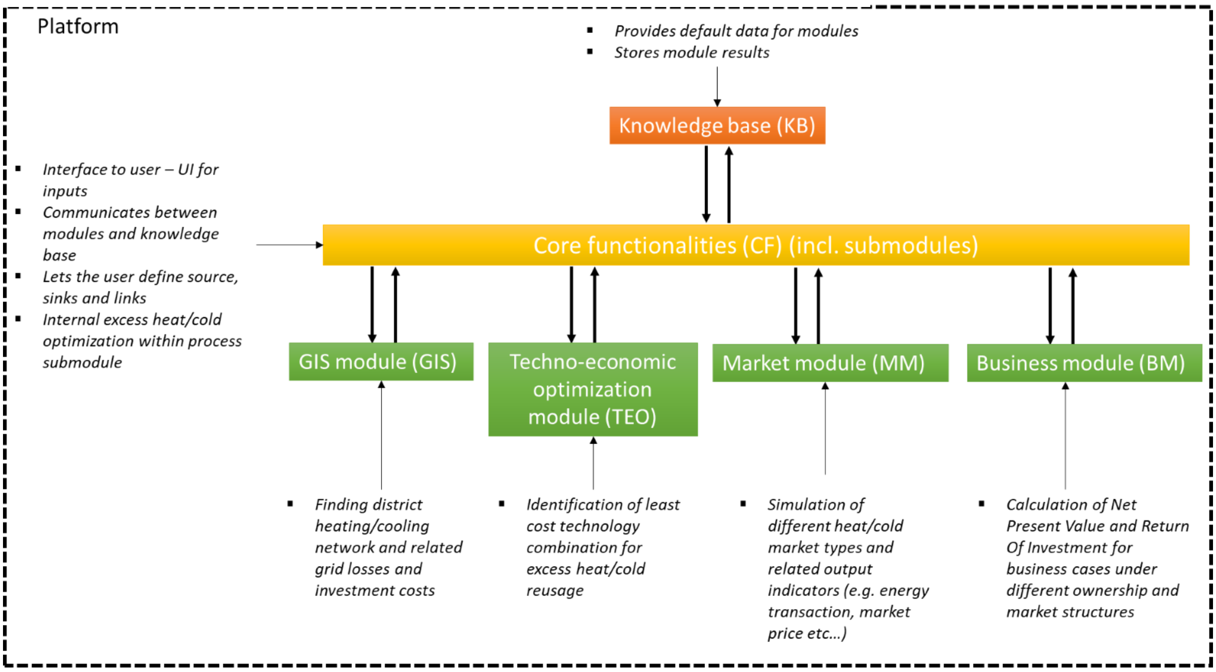

Figure 1 – Overview of the EMB3RS platform modules and its knowledge base.

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.

Portable thermal energy storage modules

To perform fast loading and unloading, the thermal storage system should be effective, consequently leading to very small PCM average thicknesses [10] and have a high storage density to promote more compact solutions. Latent heat storage systems can offer high energy storage density (above 80kWh/m^3) on a narrow temperature range and are therefore ideal candidates for these applications [11]. A compact latent heat storage geometry based on Colella *et al.* [4], was optimized to fit into a 25-foot cargo container, using Hitec Salt [12] as phase change material. This maximizes its storage capacity and thermal output for the 25 400kg 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 Figure 2.

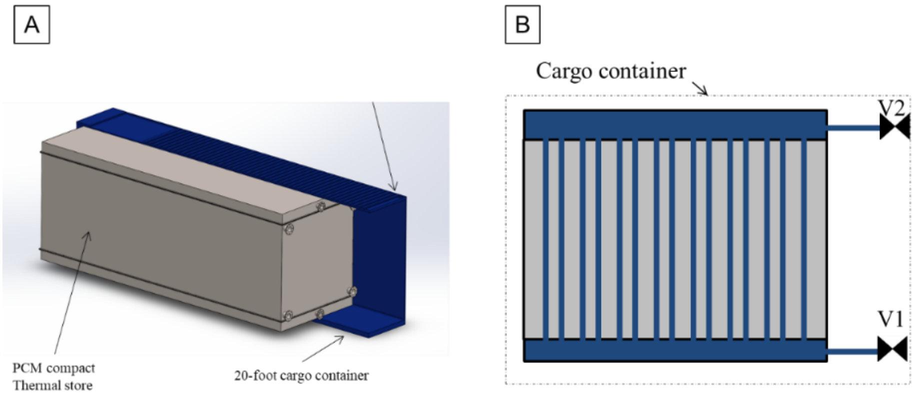

Figure 2 – Detailed view of the portable latent heat storage (LHS) system and simplified diagram of the fluid flow passing through the thermal storage, base on the geometry proposed by Collella et all [4].

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

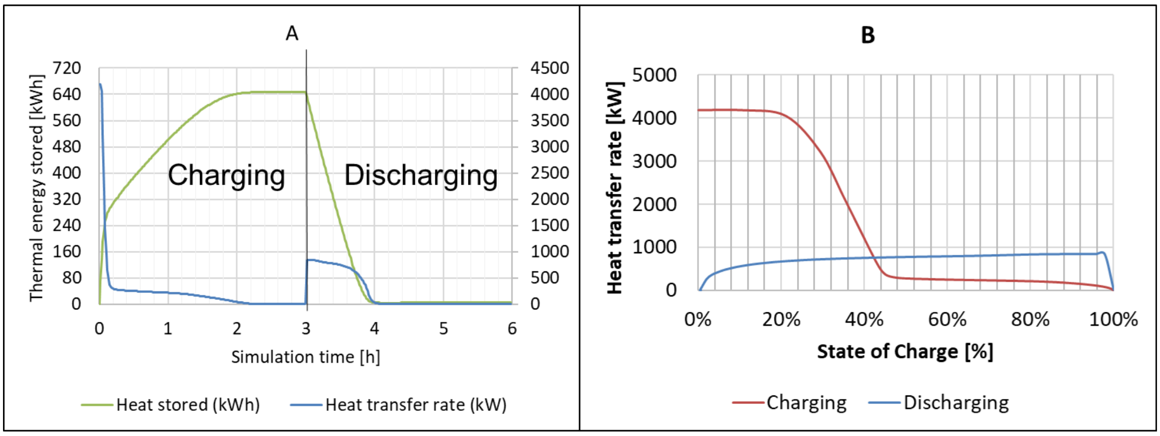

Figure 3 – Simulation predictions of the thermal storage heat rate and thermal storage capacity (A) and calculated charging and discharging performance according to the simulated results (B).

Figure 3 presents the simulated results for the chosen thermal storage geometry. Using Hitec salt as the PCM, the storage charging would be longer than its discharging process, due to the closer proximity of the maximum temperature to the PCM's melting point of 142°C. That would eventually lead to a steadier discharging heat rate. The average heat transfer rate was measured counting only values above 50kW. 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
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 28ton/h burning capacity of municipal solid waste (MSW), continuously supplying superheated steam (52,5bar at 420ºC) to a steam turbine with a capacity of 50MWel. The best available technologies quote that waste-to-energy plants would have overall efficiencies of around 20% [6], with the treated flue gas exiting the chimney stack at around 200ºC. Subtracting the energy recovered on the steam generator of 88.19MW from the total amount burned on the furnace of 182.47MW would lead to an excess heat source with a thermal capacity of 94.28MW [6].

The Portuguese district heating (and cooling) network installed in Parque das Nações in 1997, is managed by Climaespaço [13]. Its energy centre consists of a 5MW gas turbine and 2 steam generators: one with 12MW capacity for cooling the turbine exhaust gases up to 161ºC and another of 2MW capacity for cooling those gases further up to 105ºC [13]. 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 16MW backup steam boiler. The DHN operates at 100/65ºC supply/return temperatures designed for 29MW of heat demand without thermal storage, with the main heat exchangers operating only to meet the demand. The district cooling network operates at 4/12ºC supply/return temperatures, designed for 35MW of heating demand, is supplied by 2 Li-Br adsorption chillers with 4.8MW capacity driven by the surplus heat from the steam generators to cool from 12ºC to 8ºC; and 4 mechanical chillers (2 with 5.85MW 1 with 6.3MW and 1 with 7.3MW capacity) to cool from 8 to 4ºC. The cooling from the energy centre is supplied directly to a thermal storage system comprising 15000m^3 of water (20MW of constant thermal output for 6h), also acting as a buffer to the gas turbine operation when the heating demand is low.

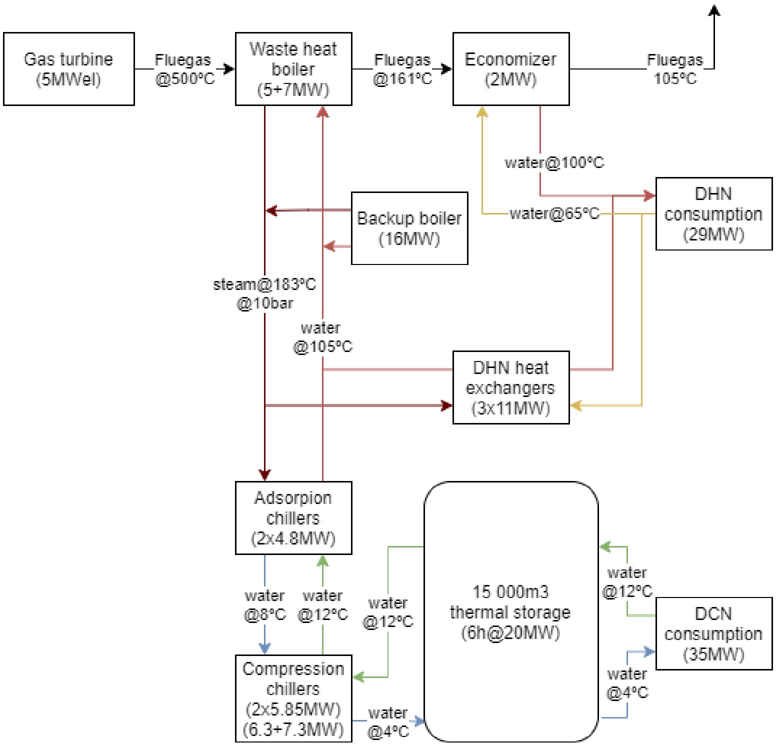

Figure 4 - Schematic diagram of the energy centre installed to supply heating and cooling to Climaespaço DHC network.

The Portuguese district heating and cooling network had an estimated yearly heating and cooling demand of 76817MWh and 93356MWh, 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 Figure 5. The proposed solutions aim to meet the network minimum heating requirement baseload of 2,64MW per hour.

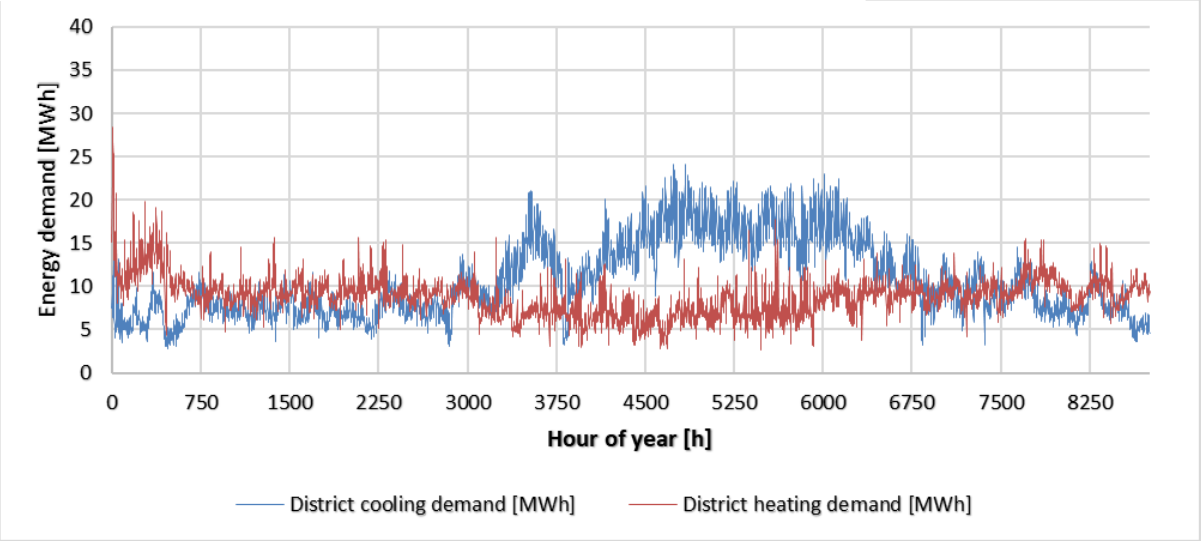

Figure 5 –Annual district heating and cooling demand profile from Climaespaço, data obtained from [13].

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 193.43ºC, heating a thermal oil from 105 to 145ºC.

In the pipeline solution, a plate heat exchanger would heat up the DHN hot water from 60 to 100ºC, providing a continuous 2,64MW of constant heat supply to the network.

In the portable solution, 5 thermal storage units were required to meet the 2,64MW 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 hours at the waste-to-energy plant. This would lead to the replacement of a thermal storage unit every 12minutes (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, 23160MWh, 30% of the total amount of heat demand required by the grid.

Economical comparison of the proposed solutions

A general price assessment of the whole system was made in order to assess the levelized cost of heat for both cases studied. The LCOH for each solution was calculated using equation (1), from [14].

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

For a 20-year cycle and considering an annual interest rate (r) of 3.5% [15], [16], the LCOH obtained for each solution is presented in Table 2.

Table 2 presents the initial capital expense (CAPEX) and operational expense (OPEX) costs for the cases studied. Regarding the PCM cost, a price assessment research was performed in Alibaba and retrieved the price of 108€/m^3 [17]. For the rock wool insulation of thermal storage units, an indicative price of 4.98€/m^2 was used, based on [18]. 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.

For the 25-foot cargo container, reference [19] indicated that 2000€/unit as a reference price. The heat transfer oil used in the simulation was the shell S2 heat transfer fluid, with an indicative price of 2.83€/L when sold in 209L barrels [20]. The annual replacement costs of the LHS units accounted for the 5km distance from the DHN substation to the waste-to-energy incinerator, with a truck fuel consumption of 45L/100km at 50km/h and an hourly driver rate of 10€/h.

For costing all the other components, the EMB3RS knowledge base [7] was used. The circulation pumps were selected from GRUNDFOS [21], and the pumping power and cost correlations are presented below (Q is the circulation requirement in liters per minute).

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

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

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).

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

For the heat delivery connection to DHN, the substation specific costs of 46.11€/kW were obtained based on [7]. 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 [7].

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 [7], assuming a total of 0.79€/MWh$_{th}$ produced per year. For the standard electricity tariff, a price of 0.2134€/kWh provided by Eurostat was used [22].

Table 2 – CAPEX and OPEX costs comparison for the systems studied.

System		**Pipe connection**	**15 LHS**	Ref.
Thermal stores	PCM cost (volume)		7 420 (69m^3)	[23]
	Insulation cost (area)		2 872 (576.7m^2)	[18]
	Tubes cost (unit)		276 749 (2 070 000)	[24]
	Enclosure cost (area)		10 122 (576.7m^2)	[25]
	25-foot container		6 000	[19]
	Total (€)	**0**	**327 163**	
Heat connection	Flue gas economizers (kW)	343 452 (3x928kW)		[7]
	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**	**802 443**	
LHS yearly replacement cost (€/year)		0	328 712	[4]
OM pumping (€/year)		3 494	13 635	[7]
OM heat network (€/year)		21 635	0	
Total OPEX [€/year]		**25 129**	**342 348**	
LCOH [€/MWh$_{th}$]		**17.25**	**18.70**	

The main capital component in the pipe connection CAPEX is the respective layout 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.

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

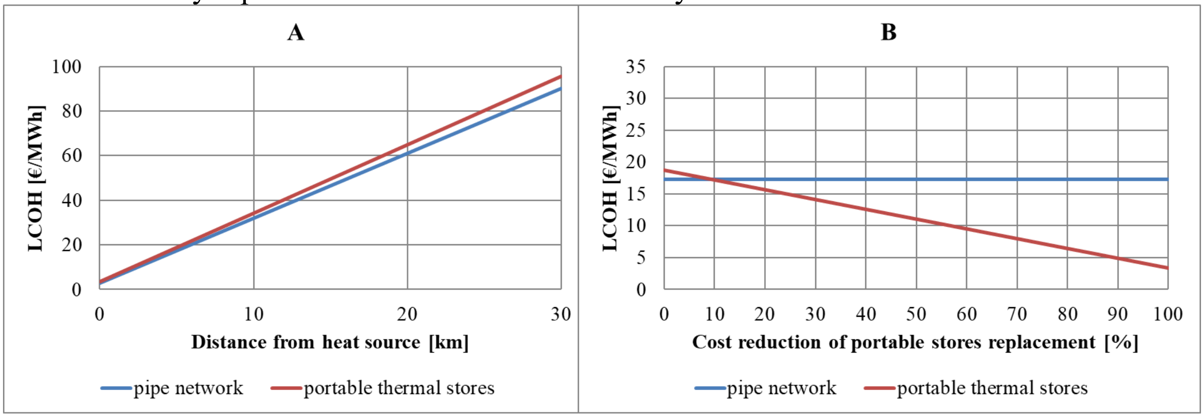

Figure 6 – Sensitivity analysis of the LCOH with the distance from the source (A) and the reduction in the daily replacement cost of the portable thermal stores (B).

Conclusions

The integration of district heating networks requires strong local governments to involve and aware local communities of the economic potential and CO2 emissions reduction potential of centralized heating and cooling solutions. Due to their agnosticism regarding its heat sources, the integration of industrial excess heat does not impose any major technical obstacles to te operation of DHN assuming that it meets its supply temperature.

The industry sector possesses various continuous thermal processes able to be integrated into DHNs, mainly in the refineries flue gases from the distillation and coking processes, flue gases from sugar evaporators, exhaust air from vacuum pumps in the pulp and paper sector and flue gases and cooling air from the various kilns used in the cement, glass and ceramic producers.

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.

Via a string of 15 25-foot cargo containers with 4.6m^3 of Hitec salt topped at 125°C and discharged to 85°C can store around 647kWh$_{th}$, in the required temperature band for an indirect discharge (supply temperature of 100ºC and return temperature of 65ºC) into district heating network connection point. A string of these containers being constantly charged at a nearby waste-to-energy incinerator and discharged 5km away has been studied to have an levellized cost of heat of 18.70 €/MWh$_{th}$ to supply Climaespaço district heating network

Via the pipe 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 analyse economically the proposed solutions.

The main economic limitations of the portable thermal stores 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 os 2,64MW$_{th}$, a system yearly decarbonisation potential of 30%.

By cooling the exhaust gases from 200 to 140ºC there would be around 32MW$_{th}$ of excess heat available at the waste-to-energy 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 practical terms, 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 solution proposed in this study.

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