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Exploiting waste heat potential by long distance heat transmission: Design considerations and techno-economic assessment

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HIGHLIGHTS

- Development of detailed techno-economic model for long distance heat transfer.
- Development of a shortcut equation associating the heat delivered with the maximum transfer distance.
- Maximum delivery distance is proportional to the square root of heat sent.
- Heat delivery from a remote power plant benefits from high retail and low wholesale power prices.

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ABSTRACT

Harvesting the waste heat from industrial processes or power plants is a very effective way to increase the efficiency of an energy system. Available usually as low-grade heat, it needs to be transferred to the points of consumption in order to be utilized. Feasible heat transmission distance is usually estimated by empiricism or by considering a limited number of parameters with the lack of a methodological tool to estimate this distance based on actual generic data. This work analyzes the particularities of long distance heat transmission by using a detailed techno-economic model for the estimation of heat transport costs including all relevant capital and operating expenditures. Sensitivity analysis is conducted to show the effect of transmission distance, supply temperatures and market prices, covering the most common technical and economic parameters found in literature. This model is also used to identify the maximum economically feasible transmission distance that meets a specified economic criterion and to derive a ‘rule of thumb’ equation.

1. Introduction

Currently, the mainstream energy carrier for long distance transmission is electricity, with AC grid lines covering hundreds of kilometres. On the contrary, heat transmission remains restricted to decentralised systems, aiming to cover the local end-user needs. It is however gaining increased attention, among others in the European Union (EU) policy scene, with the development of the heating and cooling strategy [1] and the Energy Efficiency Directive (EED) [2]. These recent policy papers recognize the importance of district heating networks and heat synergies in the energy system. Nevertheless, projects that utilize heat as long distance energy carrier are not as mature as in the electricity sector, among others for the following reasons:

- Electrical flows have a higher density than physical thermal flows ($\sim$0.5 MW/mm^2 for a high voltage direct current line [3] vs. $\sim$0.001 MW/mm^2 for heat transmission lines) and are therefore more cost effective.
- Long distance transmission in electric lines is made possible by increasing the voltage, thus decreasing the current. This cannot be transposed to heat lines, in which high temperatures entail higher thermal losses and low exergetic efficiencies on the production side [4].
- Electricity transmission and distribution losses are in average 8.2% in the world [5]. Typical heat distribution losses vary between 4% and 20%, depending mainly on the linear heat density [6].

However, using heat as energy carrier also presents a number of benefits, among which:

- Thermal storage (sensible heat) is orders of magnitude more cost-effective, even when comparing to the cheapest source of large scale

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electricity storage, namely hydroelectric energy [7].
- Exergy losses are much lower when satisfying end use heating purposes. This allows multiple utilization of energy streams, and waste heat energy streams from many industrial processes can be reused

In most cases, a new investment is required including the recovery/transforming of the desired amount of heat and the construction of a transmission line to the identified sink which is compatible in terms of heat quality, quantity and load coincidence. As a result, there is a maximum economically viable distance, whose identification is important for two reasons: (a) for plant owners it can be used for the identification of potential utilization of waste heat from industries and cogenerated heat from power plants and (b) for policy makers it can be used for the calculation of a threshold that heat could be transmitted economically. In EU legislation this work can be linked with the obligations of Article 14(6) of the Energy Efficiency Directive [2]. The following sections examine the current industry practices and expert literature.

1.1. Literature review

So far, there has been a lot of discussion on district heating systems technology and potential enhancements [8–10] but little discussion on the costs and the economic distance of heat transmission from the supply to the consumption point; either it is an individual consumer or a district network. In most studies the heat supply is already part of the district network and it is analysed as a component of its distribution pipeline [11].

A recent group of studies attempts to identify waste heat potential by focusing on the spatial analysis of excess heat. A critical element of such analysis is the proper accurate estimation of feasible waste heat delivery distances. Hammond et al. [12] used a flat distance threshold of 10 km for the estimation of the heat recovery potential in UK industries. The main barriers for the heat transport were identified as the cost of heat pipelines, the security of supply, the existence of a heat network, and the regulation of such a market. McKenna et al. [13] and Bühler et al. [14] performed also a spatial analysis to estimate the industrial waste heat in UK and Demanrk respectively. Both identify that one critical factor for the utilization of the industrial waste heat the ability to transport it economically, however in their analyses generic thresholds were used. In all of these studies, it is mentioned that the possible distance of transportation and transfer efficiency is subject to considerable uncertainty and that heat could be transported up to 40 km. Persson et al. [15] use a linear relationship as a function of heat delivered, with an upper limit of 30 km motivated partly with reference to two current applications and Swedish experience. Ma et al. [16], while exploring alternative transport options, mention that the transport of thermal energy, which are normally based in the form of sensible or latent heat of water, are limited to a certain range of temperature (less than 300 °C) and distance (less than 10 km).

Different studies focusing on specific cases are also met in the literature. Ammar et al. [17] mention that steam with a temperature of 120–250 °C can be transported over approximately 3–5 km while water with a temperature of 90–175 °C can be transported over 30 km. For lower grade heat, other sources cited in that same report mentioned that 15 km is the economic limit. Kapil et al. [18] developed a model that takes into consideration capital costs, market heat purchase price and heat losses. Considering 62 MW of low grade heat, they concluded that the break-even point for economic heat transfer distance is 86.5 km, with the assumption that 1% of heat is lost for every km of distance from the source to the DH network. However, the operating cost for pumping has not been considered in this simple calculation for the feasible distance of heat transmission.

A review on real projects and industry practices indicated similar facts while being skewed on the upper end demonstrating that even higher distances are feasible. In Helsinki, the Vuosaari power plant is connected to the central city area, by an approximately 30 km long tunnel, which is the longest continuous district heating tunnel in Europe [19]. In Denmark the distance from the CHP to the city centre of Aarhus is 20 km and the length from the CHP to the other end is around 45 km. The total length of the transmission network without considering distribution including a power station in one end, a waste incinerator along the line, and decentralised peak boilers is 130 km. The longest bulk heat transmission distance in Europe is found in Czech Republic, Prague. It is the line from the Melnik power station to the centre of Prague, whose length is 67 km for a direct distance of 32 km. This transmission pipe is for a large part above ground surface [20]. In Switzerland, a nuclear power plant in Beznau, supplies 81 MW of heat through a 31 km main pipeline to various surrounding cities [21]. Another study for a Swedish industrial plant assumes a 30 km distance to the nearest district heating network [22].

In addition to the above examples, some new feasibility studies of new projects explore the transmission of larger amounts of heat at various temperatures. Safa [23] states that new developments in insulation and pumping technologies may give hope in a near future for applications over long or even very long distances (> 100 km). In his case study, a 150 km long main transport line exhibits losses representing less than 2% of the total transported power.

A case study from Fortum Corporation for Loviisa Nuclear power plant concluded that available heat to be transported to the eastern Helsinki, which is about 80 km away, can reach 1 GW. The location of the Loviisa NPP site at the southern coast of Finland (approximately 75 km east of the Helsinki metropolitan area with one million inhabitants) offers a good opportunity for large-scale district heat generation for the region from the Loviisa 3 unit [24]. An even larger amount of heat (2 GW) was considered in the work of William Orchard Partners London Ltd., using 2×2 m diameter pipes. The cost of transferring this amount of heat to 140 km is about 0.0035 €/kWh for the delivered heat. Heat loss was 35 MW and the pumping losses 50 MW [20].

Another category of long distance heat transmission solutions includes technologies that are not based on the transfer of sensible heat. The following technologies have been considered: chemical reactions, phase change thermal energy storage and transport, hydrogen-absorbing alloys, solid–gas and liquid–gas adsorption [16]. Most of these technologies are not cost competitive yet, although the most prevalent one, phase change storage and transport, already has some commercial applications. In this technology, the heat is transported by a Phase Change Material in a container for transport by road to the user. These alternative technologies go beyond the scope of this study and will not be further examined in this work.

Table 1 summarizes various examples of heat transmission lines around the world for which data could be found in the open literature. The provided references are limited to those which are still operational in 2016. Since the focus of the paper is point-to-point heat transmission, this Table ignores the "heat transmission networks" which are highly interconnected and comprise several consumption points along the lines. It seems that current heat pipelines rarely exceed 30 km in length, with an observed maximum of 60 or 70 km.

Complimenting Table 1, we present a summary of parameters notified by European Union's Member States in order to fulfil the obligation of Articles 14.5 and 14.6 of the Energy Efficiency Directive [2]. According to Art. 14.5 "*Member States shall ensure that a cost-benefit analysis is carried out when there is plan for a new or refurbished electricity generation installation or any other facility generating waste heat in order to assess the cost and benefits of providing for the operation of the installation as a high-efficiency cogeneration installation*". Article 14.6 allows Member States to *a priori* exempt some cases from this obligation setting thresholds based on different criteria "*expressed in terms of the amount of available useful waste heat, the demand for heat or the distances between industrial installations and district heating networks*". These notifications

Table 1
Literature review of heat transmission pipelines.

Location	Country	Heat capacity (MW)	Heat pipeline Length[a] (km)	Diameter (mm average)	Ref.
Linkoping – Mjolby	Sweden	25	28		[25]
Lindesberg	Sweden	26	17		[26]
Oslo	Sweden	275	13	600	[27]
Helsinki	Finland	490	20	1000	[20]
Turku	Finland	340	25	800	[20]
Tilburg	Netherlands	170	25	500	[20]
Diemen - Almere	Netherlands	260	8.5	700	[28]
Almere	Netherlands	170	10	500	[20]
Viborg	Denmark	58	12		[29]
Oradea	Romania	546	86.3		[30]
Akranes	Iceland	60	62	400	[31]
Aachen	Germany	85	20		[32]
Gothenburg - Mölndal	Sweden	10	1.1		[33]
Gothenburg - Kungälv	Sweden	19	22		[33]
Sankt Pölten	Austria	50	31	425	[34]
Lippendorf – Leipzig	Germany	300	15	800	[35,36]
Mannheim – Speyer	Germany	40	21.2	300	[36,37]
Boxberg - Weißwasser	Germany	40	16	400	[36]
Zolling – Flughafen München	Germany	150	28	500	[36]
NESJAVELLIR - riykjavik	Iceland	290	27	800	[38]
Kozani	Greece	137	16.5	500	[39]

[a] Distance from the CHP power plant to the centre of the supplied district heating.

are publicly available in the website of the Energy Efficiency Directive.[1]

The reported thresholds are summarized in Table 2. These values capture the belief of different Member States for a feasible heat transmission project.

Finally, to set things into perspective, we summarize the above and compare the most common transmission distances among different energy carriers. Values are plotted in log-log axes to allow the comparison between distances and energy flows varying by several orders of magnitudes. For this analysis, the following data sources are used:

- High Voltage Direct Current lines (HVDC): BNEF's global HVDC interconnector database was used [40]. Projects built later than 2005 and with a voltage higher than 400 kV are used.
- High Voltage Alternative Current lines (HVAC). A simplified formulation of the European transmission system was used as a source [41]. In this dataset the transmission system comprises 2,156 lines. Only high voltage lines with a rating of 220 kV or 380 kV are considered.
- Heat transmission pipelines: The information gathered in Table 1 is collected here. As mentioned before project information is scarce in the open literature, which limits the number of available data points.

Fig. 1 clearly shows that electricity is currently used for transmission over longer distances and for larger transmission power. For HVAC lines there is no noticeable trend between transmitted energy and distance as they usually have a fixed rating per voltage (e.g. in Italy a single line of 380 kV has a nominal power capacity of 2000 MVA). On the contrary, HVDC lines present a larger fixed cost overhead because of the required transforming station on both ends, which explains the noticeable trend between distance and energy transmitted. This Figure confirms the lessons learned from past experiences in heat transmission: they are limited to lower energy transfer rates than in electrical systems.

1.2. Scope of the work

It is clear that the maximum feasible distance depends on several factors. It is a function of site-specific parameters (quantity and quality of heat), market conditions (electricity and heat price), climate data (ambient temperatures, heating season, etc.) and design data (pipe material and diameter and efficiency of its insulation). However, the literature review indicated that the feasible distance is usually estimated by empiricism via generic thresholds or by using a limited subset of the above-mentioned parameters and is not general enough to consider a wide variety of cases. The scope of this work is to bridge this gap by defining a unified techno-economic model including the main parameters influencing the feasibility of a project. The main challenge is to propose a techno-economic model with the following characteristics:

- All major capital and operating expenditures are identified and included
- The levelized cost of delivered heat is computed and the maximum economically feasible transmission distance is derived
- The model is generic enough to be applied very diverse situations across Europe.

This model is used for the estimation of heat transport costs, including all major capital and operating expenditures. The levelized cost of delivered heat is computed and the maximum economically feasible transmission distance is derived. It is clear that the above requirements are constraining and that the proposed model cannot take into account the specificities of each individual project. The tool should therefore be considered for macro-studies or for policy making purposes. It should be complemented by more detailed technical and cost quotations by vendors in the case of feasibility study relative to a specific project. Finally, a sensitivity analysis is performed for the most critical factors affecting the economics of heat transmission, using typical technical and economic ranges found in literature and industry practice.

2. Model overview

The proposed model structure is presented in Fig. 2. The main inputs are the heat supplied and the transfer distance. The calculations are split into two main parts. The first part (technical model) estimates the required equipment needed for the recovery and transmission of the heat (pipes, heat exchanger, insulations, etc.) as well as the energy needed for this transfer. The second part estimates all the costs

[1] https://ec.europa.eu/energy/en/topics/energy-efficiency/cogeneration-heat-and-power.

Table 2
Summary of thresholds defined by Member States under Article 14.6 of the EED.

Member State	Thresholds				
	Maximum Distance (km)	Minimum peak Heat (MW)	Minimum Heat supplied	Minimum Temperature (°C)	Minimum operating Hours per year
Austria	5	1.5	50 TJ/yr	80	1500
Cyprus					
Denmark	5			Surplus of + 10	1500
Finland	5–20			80	1500
Germany		10			
Greece			5.4 TJ/yr/km		
Ireland					1500
Italy					1500
Netherlands	3		2.5–25 TJ/yr		
Poland	20	10% of total heat supply			
Slovakia					
Slovenia			5.4 TJ/yr/km		
Sweden					
UK	2–15				

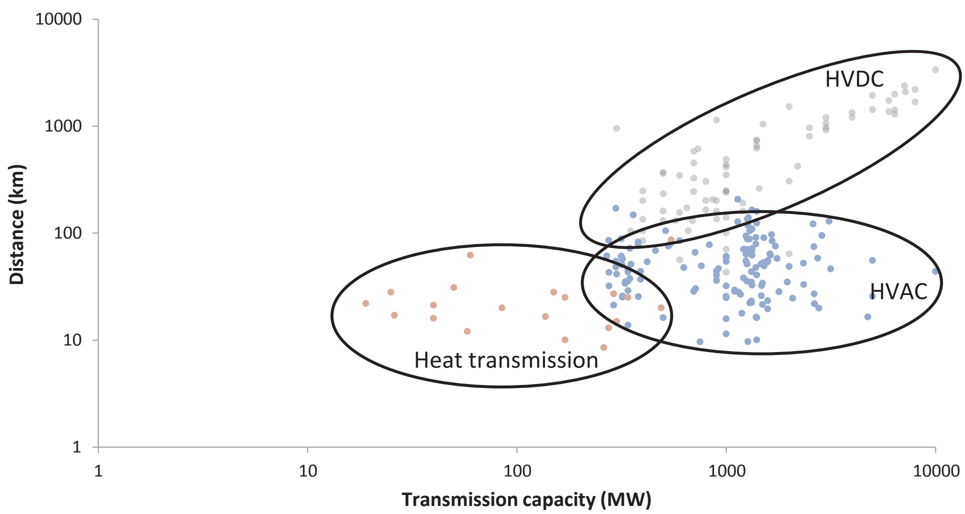

Fig. 1. Comparison of energy transmission different energy carriers.

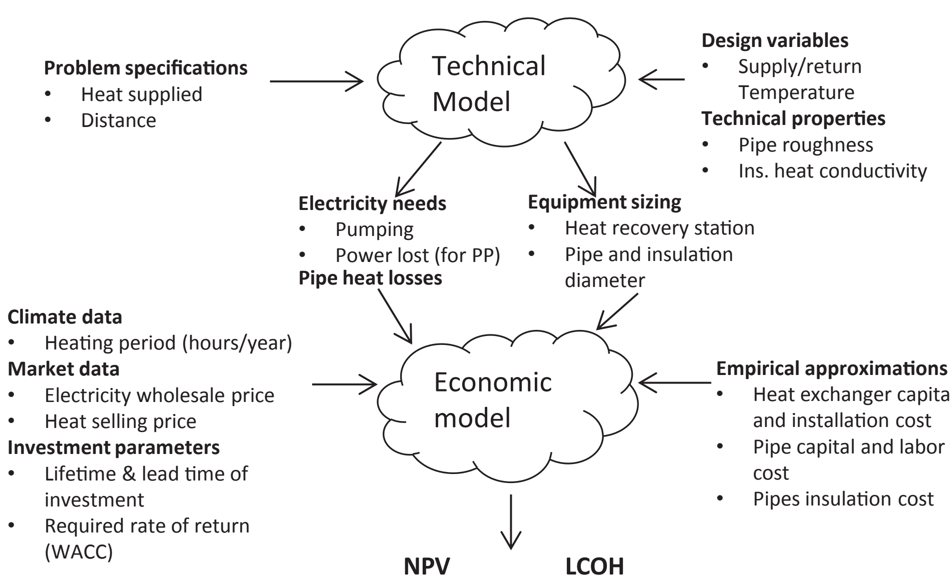

Fig. 2. Model structure.

involved, based on the results of the first part of the model. The design variables are subject to an optimization, and in case not enough data is available, they are selected based on best available practices. Technical properties and market data (prices, rates) are also necessary for the estimation of the model. In the following sections, guidance is provided for the selection of the most appropriate values of these variables. The

Table 3
Input variables.

Variables		Units
Problem specification variables		
Q	Heat transferred	MW
L	Distance (Pipe length)	m
$T0$	Ambient Temperature	°C
Ts	Soil Temperature	°C
Design variables		
T_h	Supply Temperature	°C
T_c	Return Temperature	°C
s	Insulator thickness	mm
ε	Pipe roughness	–
Technical/physical properties		
$\mu(T)$	Viscosity (as function of Temperature, see Appendix A)	Pa s
$\rho(T)$	Density (as function of Temperature, see Appendix A)	kg/m^3
$C_p(T)$	Specific heat capacity (as function of Temperature)	kJ/kg K
ε	Pipe roughness height	mm
h_i	Insulator conductivity	W/m K

result of this model is the net present value (NPV) of the investment or the levelized cost of heat. Modifying the distance and numerically solving the model for NPV = 0 leads to the maximum economically feasible distance.

The equations describing the proposed model are analysed in the following two sections.

2.1. Technical model

Before equipment capital and operating costs can be estimated, it is necessary to determine the equipment size from basic mass and energy balances. Each case is specified according to the variables presented in Table 3:

- Q depends on the availability of heat at the required temperature by the end consumer.
- L is solved numerically for NPV = 0 which corresponds to the distance between the supply and the point of consumption. This is usually terminal station at a district heating network or an ad-hoc user e.g. industry.
- T_O is the ambient temperature which relates to the cooling of the cogeneration plant and the lost work potential.
- T_s is the average soil temperature along the pipeline. This variable affects the heat losses

The second part of Table 3 describes the variables that relate to the design of the district heating network. The most important variable is the heat temperature, which is affected by the availability of the waste heat and by the consumer requirements. Usually, for a 3rd or 4th generation district heating network, heat at around 50–120 °C [42] has to be available at the entry point of the central distribution station of the network. In principle, CHP power plants can deliver any temperature below 300 °C but industrial processes are constrained by their design specifications.

Table 4 describes the variables that are estimated by the model.

2.1.1. Pumping needs

The pumping model is described in this section. The hydraulic diameter (Dh) is usually an optimization parameter, but in this model it is estimated using a best-practice empirical formula as a function of volumetric flow and density (Eq. (2), see also Appendix A for details) [43]. The basic properties of the fluid flow can be estimated (viscosity, laminar/turbulent type of flow, Reynolds number) in Eqs. (3)–(5) using the mean temperature of the fluid in the considered line.

In order to calculate the pumping needs, the pressure drop along the pipe has to be estimated. The Darcy–Weisbach equation is a

Table 4
Estimated model variables.

Solution variables		Units
Dh	Pipe's hydraulic diameter	mm
ni	Kinematic viscosity	m^2/s
A_{pi}	Pipe's cross-sectional area	m^2
V	Volumetric flow rate	m^3/s
Re	Reynolds number	–
f	Friction factor	–
DP	Pressure loss	%Pa
Q_{lsp}	Specific heat loss	W/m
Q_l	Heat losses	MW$_{th}$
n_p	Pumping efficiency	%
P_{na}	Electric power lost	MW$_e$
P_p	Pumping power	MW$_e$
V_i	Insulation used	m^3

phenomenological equation, which relates the pressure loss due to friction along a given length of pipe to the average velocity of the fluid flow. The dimensionless friction factor f (Darcy friction factor), is estimated by means of the Colebrook–White correlation (Eq. (6)) [44], which is solved numerically via Sergeidhes approximation. The distance is multiplied by two in order to consider the return line. The electricity consumption is then estimated from the pressure drop (Eq. (7)) and the pump efficiency in (8). More details about the approximations and model hypotheses are available in the Appendix A. It has to be noted that the routing of the pipeline and the topological characteristics of the area will affect both the operational costs, and the configuration of the pump houses. This model only captures the overall energy needs due to friction losses.

$$V = \frac{Q}{\rho\left(\frac{Th+Tc}{2}\right)\cdot C_p\cdot(T_h-Tc)}10^3 \tag{1}$$

$$Dh = 0.34\cdot V^{0.45}\cdot\rho(T)^{0.133}\cdot 10^3 \tag{2}$$

$$ni = \frac{\mu(T)}{\rho(T)}\cdot 10^3 \tag{3}$$

$$A_{pi} = \pi\left(\frac{Dh\cdot 10^{-3}}{2}\right)^2 \tag{4}$$

$$\Re e = V\cdot\frac{Dh}{ni\cdot A_{pi}\cdot 10^3} \tag{5}$$

$$\frac{1}{\sqrt{f}} = -2\log_{10}\left(\frac{\varepsilon}{3.7Dh} + \frac{2.51}{\Re e\sqrt{f}}\right) \tag{6}$$

$$DP = f\cdot\frac{2\cdot L}{Dh\cdot 10^3}\cdot\frac{\rho(Th)\cdot(\frac{V}{A})^2}{2} \tag{7}$$

$$Ep = DP\cdot\frac{V}{n_p}10^{-6} \tag{8}$$

2.1.2. Heat losses

The pipe heat transfer equation that estimates heat losses is estimated by means of:

$$Q_{lsp} = 2\pi\cdot\frac{hi}{\ln(1+2\frac{s}{Dh})}(T_h-T_s) \tag{9}$$

$$Q_l = Q_{lsp}\cdot L\cdot 10^{-6} \tag{10}$$

The insulator thickness (s) is estimated by optimization depending on the amount of heat and pipe diameter. For the examined ranges the optimum s can vary around 50–200 mm. The total volume of required insulation material is given by:

$$Vi = \frac{\pi}{4}\cdot((Dh+s)^2 - s^2)10^{-6}\cdot L \tag{11}$$

2.1.3. Power loss from steam extraction

If the heat source of the final consumer, e.g. a district heating network, is a CHP plant, there is an interaction between heat and power generation. The power loss factor (PLF) [45], also referred-to as the inverse of the Z-factor in some publications [20], is required to compute the economics of the cogeneration activity. It is defined as the substitution rate between heat and generated power, i.e. the number of electrical kWh made unavailable by the extraction of one thermal kWh. Seen from a different perspective, the heat supply is analogous to that of a virtual heat pump: heat is provided to the process by elevating its temperature level, at the expense of an electricity consumption [46]. In the present model, the power loss factor depends on the district heating temperature since the latter is a case-specific variable related to the design of the network. It should moreover be applicable to different CHP technologies (e.g. back-pressure or extraction turbines).

To estimate PLF, a generic thermodynamic model is defined, which considers that the extracted thermal power is not available for electricity generation in the last stage of the expansion (e.g. in the low pressure turbine). This last stage expands the vapour from a saturation pressure corresponding roughly to the district heating temperature down to the pressure corresponding to the ambient temperature. The power loss factor is equal to the specific expansion work, which is written:

$$PLF = \frac{h(T_h, x=1) - h(p_{T0}, s = s(T_h, x=1))}{\eta_{turbine}} \tag{12}$$

where h, T, p, s are the enthalpy, the temperature, the pressure, the entropy and the vapour quality, respectively. $\eta_{turbine}$ is the turbine isentropic efficiency, assumed to be 80%.

The non-available (lost) power is obtained by multiplying PLF by the thermal demand:

$$P_{na} = PLF\cdot Q \tag{13}$$

As a result, the operational costs of extracting heat i.e. the electricity penalty to the power plant, are attributed to the heat costs in terms of lost revenues caused by the reduced production of electricity. The incremental capital costs of setting up a district heating connection in a conventional extraction/condensing turbine are less than 1% of the total turbine capital costs and are neglected in this study.

2.2. Economic model

Using the sizing variables from the previous section the capital and operating costs can be estimated. The cost calculations are based on a discounted cash flow analysis based on the total revenue requirement method which corresponds to the revenue that must be collected in a given year through the sales of all products to compensate the system operating company for all the expenditures incurred in the same year and to ensure sound economic plant operation [47]. The main variables of this model are presented in Table 5.

The capital and operating expenditures and revenues that are used to calculate the annual cash flows are calculated by means of Eqs. (14)–(20). The main operating expenditures are the pumping power and the power penalty, of the cogeneration plant. Two deflationary factors (f_{lp}, f_{lp}) were introduced in order to account for expected reductions in heat demand due to energy efficiency improvements or changes in pricing policy during the lifetime of the project.

$$C_{tot} = C_{hr} + C_{pi} + C_{in} \tag{14}$$

$$CFh_t = CFh\cdot(1+f_{ld})^t \tag{15}$$

$$Q_{sold,t} = (Q - Q_l)\cdot CFh_t\cdot 10^{-3} \tag{16}$$

Table 5
Variables of financial model.

Variables		Units
Input variables		
Le	Technical lifetime	Years
i	Discount rate	%
C_{th}	Heat selling price	€/kWh
C_{el}	Electricity cost	€/kWh
f_{lp}	Price (de)escalation factor	%
f_{ld}	Demand (de)escalation factor	%
CFh	Capacity factor of transmission line	%
C_{hr}	Heat recovery station capital costs	M€
C_{pi}	Piping costs (including installation)	M€
C_{in}	Insulation cost	M€
Solution variables		
C_{tot}	Total overnight capital costs	M€
Q_{sold}	Total heat sold	GWh(th)
P_{used}	Total electricity used	GWh(el)
C_{op}	Operating costs	M€
TAR	Total Annual Revenue	M€
CF_t	Cash Flow for year t	M€

$$P_{used} = (P_p + P_{na})\cdot 8760\cdot CFh_t\cdot 10^{-3} \tag{17}$$

$$C_{op,t} = P_{used}\cdot C_{el} \tag{18}$$

$$TAR_t = C_{th}\cdot Q_{sold}\cdot(1+f_{lp})^t \tag{19}$$

$$CF_t = TAR_t - C_{op,t} \tag{20}$$

where the variable t ($\{t\in\mathbb{Z}|1\leqslant t\leqslant Le\}$) indicates a given year, from the construction to the end of the lifetime.The annual cash flow is summed over Le years and discounted by i to get the net present value (NPV):

$$NPV = -C_{tot} + \sum_{t=0}^{Le} CF_t\cdot(1+i)^{-t} \tag{21}$$

In order to find the maximum economic transmission distance, the model is solved iteratively till NPV = 0.

Alternatively, if we ignore the revenues, the levelized cost of heat (LCOH) is calculated by:

$$\mathrm{LCOH} = \frac{\sum_{t=0}^{Le}[(\mathrm{CAPEX_t} + \mathrm{OPEX_t})\cdot(1+i)^{-t}]}{\sum_{t=0}^{Le}[\mathrm{Q_{sold\ t}}\cdot(1+i)^{-t}]} \tag{22}$$

$$\text{where } \mathrm{CAPEX_t} = \begin{cases} \mathrm{C_{tot,t}}, & t=0 \\ 0, & 1 > t \geqslant Le \end{cases}$$

$$\mathrm{OPEX_t} = \begin{cases} 0, & t=0 \\ \mathrm{C_{op,t}}, & 1 > t \geqslant Le \end{cases}$$

3. Results and discussion

In this section the results of the model are discussed, exploring the interactions the critical variables and their sensitivity on the results. To demonstrate the above, we define a reference case using the parameters in Table 6. These values are used all over the analysis. The selection of the most important values is discussed in the following paragraphs.

As the model is highly non-linear, the sensitivity analysis depends on the starting point, so there were four cases examined:

- high supply Temperature (*50 °C*) and low delivery distance (10 km)
- high supply Temperature (*50 °C*) and high delivery distance (100 km)
- low supply Temperature (*100 °C*) and low delivery distance (10 km)
- low supply Temperature (*100 °C*) and high delivery distance

Table 6
Parameters used for the central scenario.

Variable	Name (units)	Central value
Heat amount	Q (MW)	50; 500
Distance	L (km)	10; 100
Price (de)escalation factor	f_{lp} (%)	0%
Demand (de)escalation factor	f_{ld} (%)	−1%
Supply Temperature	T_h (°C)	100
Return temperature	T_c (°C)	30
Ambient Temp	T_O (°C)	30
Soil Temp	T_s (°C)	15
Pipe Roughness height	ε (–)	0.2 (see Appendix A)
Insulator conductivity	hi (W/m K)	0.05 (see Appendix A)
Insulator thickness	S (mm)	Optimized (see Appendix A)
Cost of insulation	Cs_{in} (€/m^3)	100 (see Appendix A)
Pipe cost	C_{pi} (€/m)	See formulas in Appendix A
Capacity Factor	CFh (%)	40%
Lifetime	Le (years)	20
Discount rate	i	12%
Cost of electricity (wholesale)	C_{el} (€/MWh)	80

(100 km).

The cost of wholesale electricity (C_e) is what is attributed to the heat costs, following the "power loss" method explained in Section 2.1.3. It has to be noted that in reality electricity prices are dynamic: There can be times that heat production is free (e.g. due to very low wholesale prices) and times where the heat production is very costly. This value should indicate the expected average price for the time that the power plant will operate. The decision to operate (or not operate) the plant at any given moment, is an operational decision linked also to contractual obligations.

The total amount of heat delivered and sold is a function of the design variable (Q) and the capacity factor. The capacity factor (CFh) represents the expectation of the utilization of this transmission line and is used to estimate the actually amount of heat to be delivered. A flat demand curve corresponds to high capacity factors (100%), whereas fluctuating (peaky) demand curve correspond to low capacity factors. The size of the heat sink, the existence of storage, the seasonal and diurnal demand patterns and the dynamic prices will affect the operating capacity factors so they have to be selected carefully. A sensitivity analysis on this variable can make the decision maker understand the impact of this uncertainty. As in some cases, heat demand is expected to have a negative trend during the considered technical lifetime due to energy efficiency improvements a negative compound factor is used.

The return temperature (T_c) is fixed at 30 °C, assuming that this is the lowest return temperature achievable, no matter what is the supply Temperature. This assumption facilitates the comparison of different temperature differences on the capital and operating expenditures.

The selection of the discount rate (i) depends on the required return for the equity as well as the bank loan interest rate. In feasibility analyses, the weighted average cost of capital (WACC) is usually used in order to simplify the assumptions related to financing costs. A high enough discount rate was used in this case to reflect the perceived riskiness of the cash flows of such investments.

3.1. Levelized cost of delivered heat

In order to demonstrate the effects affecting the cost of delivered heat, a sensitivity analysis is performed by varying the supply temperature, heat quantity and transmission distance. In all cases examined below, the insulation thickness was optimized. Indicatively Fig. 3 shows the effect of insulation thickness on heat losses and consequently to heat costs. In most cases the optimal insulation falls into the range of 100–250 mm.

Fig. 4 explores the effects of the ten most dominant factors on the levelized cost of heat. This plot, also known as tornado plot, shows how the LCOH would vary by modifying all variables (one at a time) by ± 20%.

For high distances, the capacity factor is the most important variable, whereas for low distances the cost of heat source (as described by cost of electricity) is more important. Discount rate is in any case important, but mostly in higher distances as they are more capital intensive.

In order to understand why the sensitivity of the variables changes, it is necessary to identify the dominant factor for each of the cases. Fig. 5 breaks down the main components of the levelized cost of delivered heat: capital cost investments (pipeline, labor costs and heat recovery stations), pumping energy and power penalty. The red[2] dot corresponds to the central value of this scenario which is the same as the central value of Fig. 4.

It is clear that heat costs benefit greatly from economies of scales; the larger the amount of heat transmitted, the lower the cost for any given condition. Moreover, the cost of larger projects is less sensitive to variations in temperature or distance.

The effects of both distance and heat quantity are prevalent. As expected, the highest costs are obtained in the case of high distance and small heat quantities. For higher distances, capital costs become dominant and have a proportional relationship with the supply temperature because the flow rate is rising as temperature interval is falling. On the contrary, for smaller distances, the pumping costs become dominant and have an inversely proportional relationship with supply temperature. This explains why the relationship between LCOH and heat supply temperature is inversed in the two extreme cases.

Similarly, for high amounts of heat, power penalty costs becomes predominant (higher extraction temperatures have higher energy penalty from cogeneration power plants), which explains the proportional dependency of costs versus temperature, even for long distances.

The effect of return temperature is illustrated in Fig. 6. Its importance has been emphasized in the recent literature [48]. If the consumer fails to utilize the deliver heat as planned this has a big impact in the results. It is observed that in any case a smaller return Temperature is desirable. This is important in order to maximize the temperature difference and avoid increased costs related to high water flows and large pipe requirements. Another interesting behaviour is the "inversion" of the supply Temperatures profitability. In case of higher distances the effect of a smaller ΔT – as implied by a higher return Temperatures – is magnified because the piping costs become the dominant factor.

3.2. Country-specific comparison with alternative heat supply technologies

In Fig. 7 we apply the model in order to present a preliminary comparison of levelized cost of heat for different options: CHP and heat transmission, heat pumps and gas boilers. As electricity and gas prices are significantly different among countries, the comparison is performed for the 28 EU countries, taking into account their specific market prices. The following assumptions were used:

- For heat transmission: 100 MW line, supply temperature 80 °C, using annual average wholesale electricity prices to value the power lost of a cogeneration plant. [49]
- For boiler: n = 85% and cost of retail gas for domestic price band for the first semester of 2017 [50]; Capital costs: 200 EUR/kWth [51]
- For heat pump: COP = 4 and cost of retail electricity for domestic price band for the first semester of 2017 [50]; Capital costs: 450 EUR/kWe [51]
- Weighted average cost of capital (WACC) = 10%;

[2] For interpretation of color in Fig. 5, the reader is referred to the web version of this article.

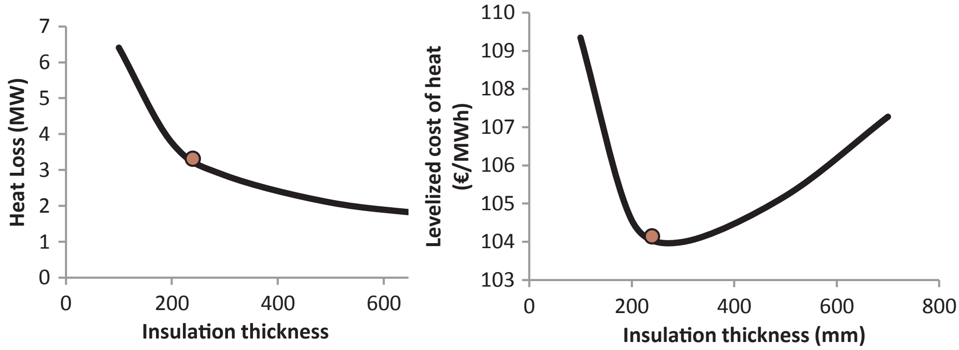

Fig. 3. Sensitivity of optimal insulation level (Q = 50 MW, L = 100 km).

Lifetime = 20 years.

The break-even points between individual production and heat delivered from a remote place are indicated by the intersection of the black line with the red or green line. For most countries, this falls into the range of 40–80 km which is in line with the literature review. As expected, countries with low wholesale prices – implying lower value of power lost – and higher taxation on retail markets are favouring remote heat supply.

3.3. Sensitivity analysis of maximum delivery distance

This model can be used to estimate the maximum economical heat transmission distance. For this purpose, the model is solved iteratively by modifying the distance (L) till NPV converges to zero.

The values of Table 6 were used by modifying two parameters: amount of heat (x-axis) and the heat selling price (4 curves). The latter is usually the defining variable that will define the feasibility of the project and it usually depends on the market conditions, e.g. price of competing sources of heat supply, subsidy schemes, etc. the results are presented in Fig. 8 which are plotted on log-log axes. Interestingly, the computed curves are well described by a power law ($f(x) = aX^n$) and, when plotted in a log-log plot, form straight lines.

The two following effects are observed:

1. As the amount of transmitted heat increases, the optimum economic diameter of the pipe increases as well.
2. In a larger pipe, the fraction of heat lost becomes smaller, since the heat loss surface area in relation to the total volume of fluid gets smaller. Moreover, the materials needed per unit of transferred fluid

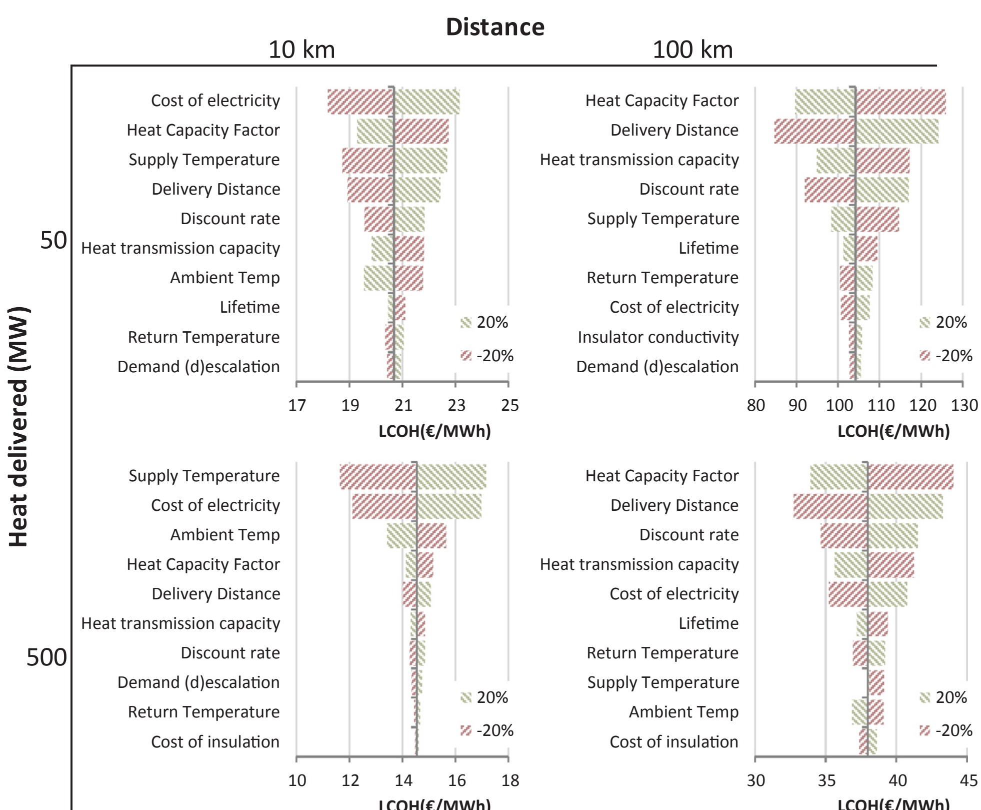

Fig. 4. The effect of ten most sensitive variables on LCOH for different distances and amounts of heat.

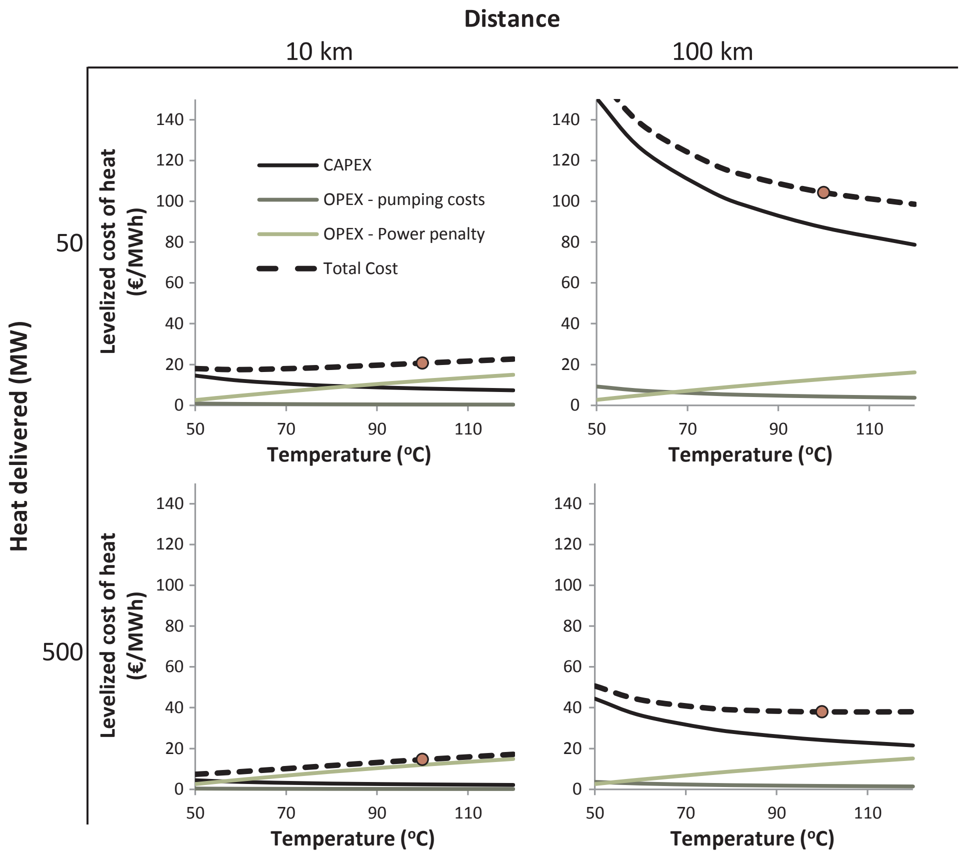

Fig. 5. Sensitivity of LCOH for different supply temperatures, distances and amount of heat.

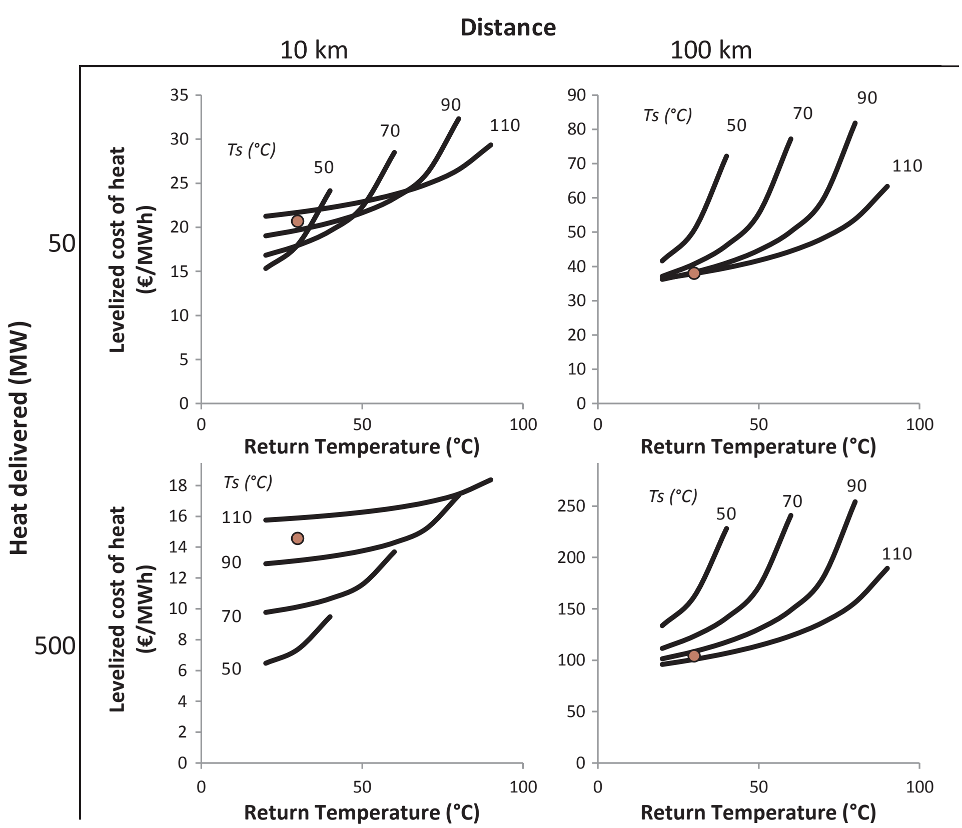

Fig. 6. Effect of return Temperature on costs of delivered heat for different amount of heat delivered, transmission distances and supply Temperatures. (Note that y-axis scale is different).

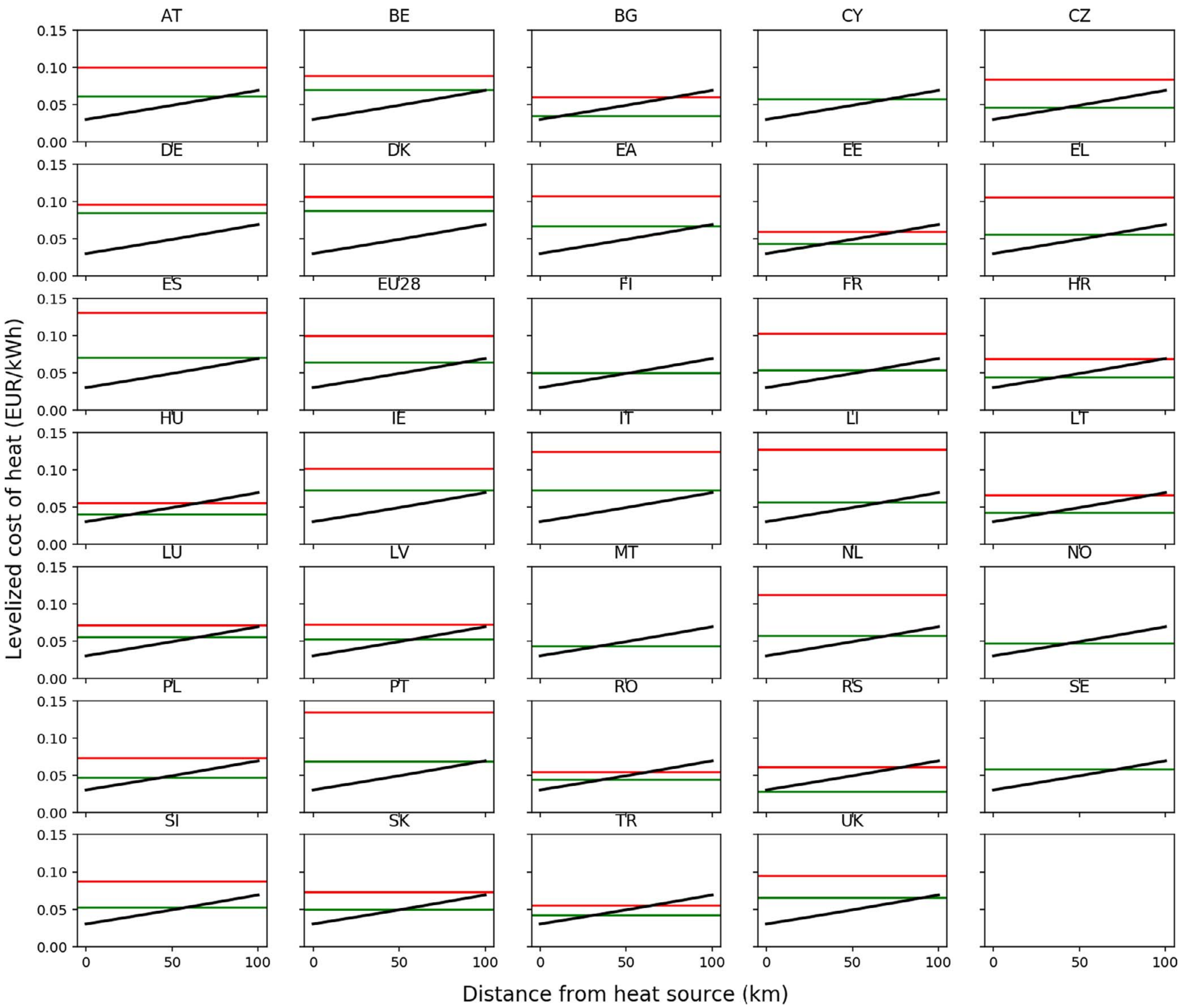

Fig. 7. Cost of heat via different options. A 100 MW heat transmission line was considered (black line) vs a gas boiler (red line) vs a heat pump (green line). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

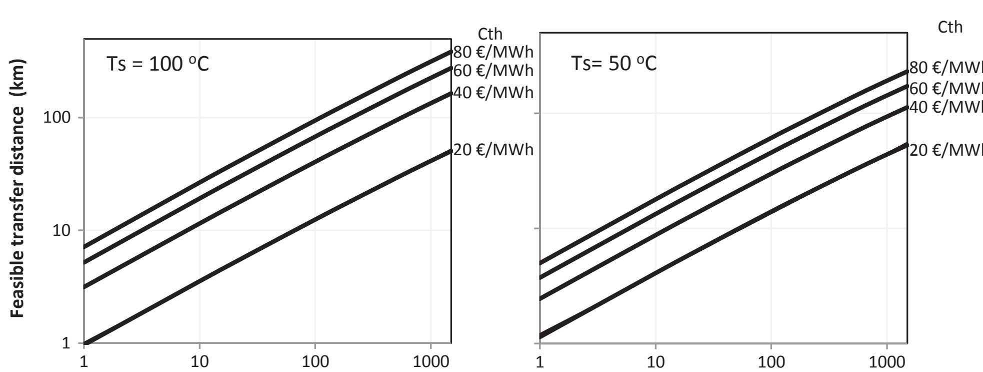

Fig. 8. Sensitivity analysis of the feasible transfer distance for various qualities (temperature) and quantities of heat delivered.

Table 7
Fitted Parameter (α) of Eq. (22) for various combinations of temperatures and heat selling prices.

Cth (€/MWh)	*Ts* = 50 °C	Ts = 100 °C
20	1.21	1
40	2.59	3.3
60	3.95	5.4
80	5.29	7.5

are also reduced, which results in reduced specific capital costs. This is explained by the carrying capacity of the pipe, which increases in proportion to the square of the diameter whereas the pipe cost increases only in proportion to the diameter.

These observations involve that the effect of economies of scale is significant and that large heat quantities can be transmitted over large distances without significant losses. If the results are fitted in a power law equation, the exponent (n) ranges from 0.45 to 0.55. This sublinear behaviour can be easily explained by the fact that the expenses (insulation, piping, thermal losses) are proportional to the pipe length and diameter. On the other hand, the benefits are proportional to the heat delivered. Recognizing that the delivered heat is proportional to the flow rate and thus to the square of the diameter, the NPV function can be approximated by a function of the type:

$$NPV \approx \alpha_0 \cdot Q - \alpha_1 - \alpha_2 \cdot L \cdot D = \alpha_0 \cdot Q - \alpha_1 - \alpha_3 \cdot L \cdot \sqrt{Q}$$

where α_x are constants, Q is the delivered heat and L is the pipe length.

The NPV is maximized by deriving the equation by Q, which results in a quadratic dependency between the optimal length and the delivered heat:

$$\frac{dNPV}{dQ} = 0 <=> 2 \cdot \alpha_0 \cdot \sqrt{Q} \approx \alpha_3 \cdot L$$

Based on the above all curves can be fitted based on the following empirical formula:

$$Maximum\ Feasible\ Distance\ (km) = a \cdot \sqrt{Heat\,(MW)} \tag{23}$$

where α takes the following values described in Table 7.The above mentioned interactions among supply Temperature, heat selling price and maximum distance are illustrated as contours in Fig. 9.

4. Conclusions

In this work a detailed techno-economic model for the estimation of heat transport costs including all relevant capital and operating expenditures was developed in order to analyse the feasibility of waste heat delivery projects. While most literature sources use a common threshold for feasible heat transmission distance in the range of 30–50 km, the analysis of the techno economic model suggests that longer distances are feasible for specific techno-economic parameters and market conditions. Delivering heat from a remote power plant can be more cost-effective than decentralized production even over large distances, and especially in case of high retail power prices or low wholesale power prices.

By assuming a zero net present value, the economic model also allowed to evaluate the shape of correlation between the maximum distance and the heat power. It was demonstrated that, in good approximation, the maximum delivery distance is proportional to the square root of the amount of heat transmitted.

Finally, the proposed sensitivity analysis highlighted key parameters affecting the profitability of heat transmission, such as the heat transmission temperature and the electricity and heat prices. A comparison with existing installations was also performed, but should be extended in the future when more experience and cost data become available.

The proposed methodology should not be considered as a tool for detailed techno-economic evaluation of a specific system. It mainly aims at improving and refining the generic rules and thresholds used by policy makers or energy system modellers. This analysis constitutes a useful point of reference for further research and for energy planning purposes. In particular, future work will use the developed model to match a GIS database of heat demand, power plant and waste heat locations, for the estimation of the waste heat sources that could satisfy nearby heating and cooling demands.

Acknowledgements

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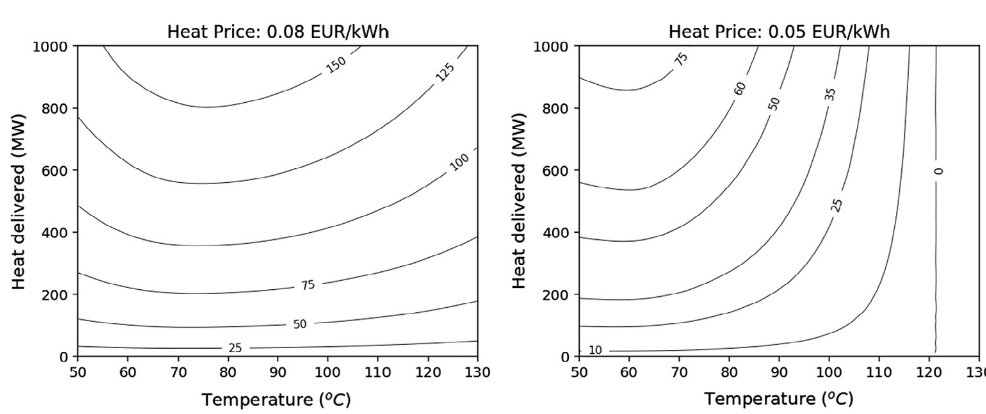

Fig. 9. Effect of heat quantity and quality on maximum feasible distance (contours in km) for two different heat market prices.

Appendix A

A.1. Empirical approximations

Genic et al. [43] propose the following relationship for estimating the optimal economic pipe diameter (mm) (Fig. 10). It is advised that the volume flow in a pipe should not exceed 4 m^3/s [23].

$$Dh = 0.34 \cdot V^{0.45} \cdot \rho(T)^{0.133} \cdot 10^3$$

Indeed, a sensitivity analysis on the pipe diameter shows that this equation gives solution very close to the optimum (Fig. 11).The efficiency of a centrifugal pump is given by the following relationship $np = 0.823 \cdot V^{0.046}$

A.2. Costs approximations

The approximations of this section can be used if no other data is available is a generic estimation. Since the estimation is for a feasibility study a ± 25% accuracy is acceptable. A detailed quote from a vendor will be needed for a definitive estimation of costs.

A variety of pipe costs can be found in literature. For piping experimental data over a range of pipe sizes show that an exponential curve can be used for pipe material costs and a linear curve for associated labour costs [52]. Svensson et al. [22] estimates the pipe cost at 436 €/m for distance of 30 km. Kapil et al. [18] estimate the cost of pipe and related equipment for a district heating network at $1460/m. Regarding the notified exemptions summarized in Table 2 only Greece and UK have used a pipe cost figure for their analyses, which is 230 €/m and £800/m respectively. For this study an approximation was derived using detailed tables of pipes provided by 'Svensk Fjarrvarme Kostnadskalkyl' [53]. According to the same study the total cost of the welding, construction, and digging was around 3–4 times more than the cost of the pipes. A power law formula is fitted in those data as shown in Fig. 12.

The insulation parameters and costs shown in Table 8 were used in this case study [54,55].

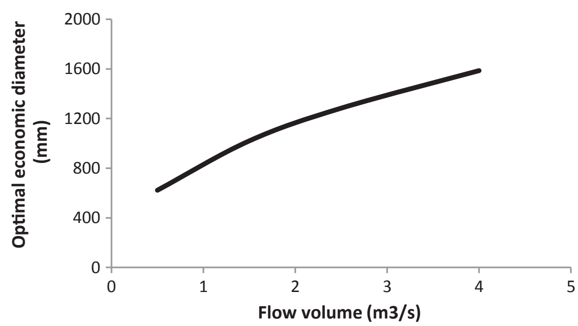

Fig. 10. Optimal economic pipe diameter as a function of flow volume (for T = 100 °C).

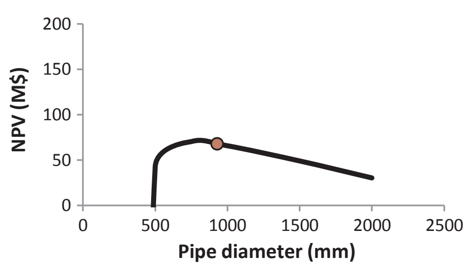

Fig. 11. Effect of pipe diameter to NPV.

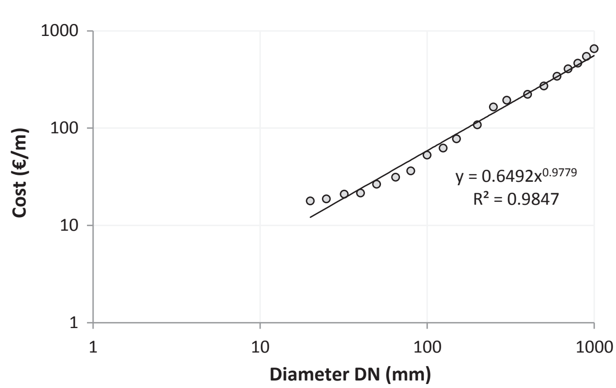

Fig. 12. Pipe cost approximation based on empirical data.

Table 8
Insulation conductivity and costs.

Insulators	λ (W/m K)	Cost ($/m^3)
Rock wood	0.04	95
Polyurethane Foam	0.03	110
Rigid PUR	0.028	
Soft PUR	0.023	

Table 9
Roughness height for various materials.

Material	ε (mm)
Concrete	0.3–3.0
Cast Iron	0.26
Galvanized Iron	0.15
Asphalted Cast Iron	0.12
Commercial or Welded Steel	0.045
PVC, Glass, Other Drawn Tubing	0.0015

Pipe roughness for various materials can be found in Table 9. For the case study presented in this study it was assumed that $\varepsilon = 0.2$ which corresponds to an iron pipe.

A.3. Physical properties approximations

Water density	$\rho(T) = \left(1 - \frac{(T + 288.94)}{508929.2 \cdot (T + 68.1)}\right)(T - 3.98)^2 \cdot 10^3$	kg/m^3
Water viscosity	$\mu(T) = 0.02414 \cdot 10^{\frac{247.8}{T + 273 - 140}}$	Pa s

A.4. Sergeidhes solution for the Darcy–Weisbach friction factor

The traditional way to estimate the Darcy–Weisbach friction factor is either with a graphical method via the well-known Moody chart or via the Colebrook–White equation. Sergeidhes approximation of the estimates the latter with an accuracy of 0.0023% by means of:

$$A = -2\log_{10}\left(\frac{\varepsilon}{3.7D} + \frac{12}{\mathfrak{R}}\right)$$

$$B = -2\log_{10}\left(\frac{\varepsilon}{3.7D} + \frac{2.51A}{\mathfrak{R}}\right)$$

$$C = -2\log_{10}\left(\frac{\varepsilon}{3.7D} + \frac{2.51B}{\mathfrak{R}}\right)$$

$$f = \left(A - \frac{(B - A)^2}{C - 2B + A}\right)^{-2}$$

where f is a function of: roughness height, ε (m); pipe diameter, D (m); Reynolds number, Re (–).

The above equation applies only for turbulent flow ($Re > 2300$). For laminar flow, the friction factor can be estimated as follows:

$f = 64/Re$.

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