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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