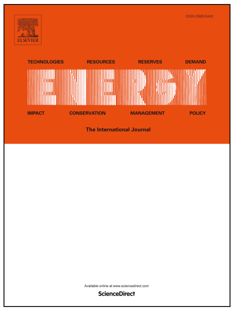


Power transformers as excess heat sources –a case study for Denmark

Stefan Petrović, Fabian Bühler, Uroš Radoman, Russell McKenna

PII: S0360-5442(21)02665-7

DOI: https://doi.org/10.1016/j.energy.2021.122416

Reference: EGY 122416

To appear in: *Energy*

Received Date: 15 March 2021

Revised Date: 11 September 2021

Accepted Date: 29 September 2021

Please cite this article as: Petrović S, Bühler F, Radoman Uroš, McKenna R, Power transformers as excess heat sources –a case study for Denmark, *Energy* (2021), doi: https://doi.org/10.1016/j.energy.2021.122416.

CRediT author statement

Stefan Petrović: Conceptualization, Methodology, Formal analysis, Investigation, Data Curation, Writing - Original Draft, Writing - Review & Editing, Visualization. **Fabian Bühler**: Conceptualization, Methodology, Formal analysis, Investigation, Writing - Original Draft, Writing - Review & Editing, Visualization. **Uroš Radoman**: Methodology, Formal analysis, Investigation, Writing - Original Draft, Writing - Review & Editing, Visualization. ***Russell McKenna**:* Investigation, Writing - Original Draft, Writing - Review & Editing, Supervision.

Power transformers as excess heat sources – a case study for Denmark

Stefan Petrović [a,b], Fabian Bühler [a,c] , Uroš Radoman [d], Russell McKenna [e]

[a] *Center for Global Cooperation, The Danish Energy Agency, Carsten Niebuhrs Gade 43, 1577 Copenhagen, Denmark,*

[b] *Technical University of Denmark, DTU Management, Lyngby, Denmark*

[c] *Technical University of Denmark, Department of Mechanical Engineering, Lyngby, Denmark*

[d] *Faculty of Electrical Engineering, University of Belgrade, Belgrade, Serbia*

[e] *School of Engineering, University of Aberdeen, Scotland, UK*

Abstract

Large-scale heat pumps (HPs), biomass CHPs and excess heat (EH) from industry and data centres are promising district heating (DH) sources. Electricity and thus power transformers (PTs) will be an important part of the future energy system, which opens the possibility to use the thermal losses occurring in PTs for DH. The present paper analyses high voltage PTs in Denmark as DH sources. First, we employ a thermodynamic model of PTs to determine the EH they produce. Subsequently, we analyse thermodynamic properties of heat exchangers and HPs necessary to utilise EH for DH. Finally, we perform GIS analysis to link the PTs with specific DH networks. From the theoretical amount of excess heat from power transformers (EHPT) available for DH of 0.28 TWh per year, 0.12 TWh or 0.5% of Danish DH demand can reach the consumers. 0.07 GWh-0.21 GWh can reach the consumers below the average DH price. The entire EHPT potential can be utilised through HPs, working with an average COP of 4. The sensitivity analysis showed that the EHPT can supply up to 2.26% of the Danish DH demand. Therefore, EHPT is a small DH source on the national scale but could be an important local option.

Keywords:

District heating, Waste heat, Power transformer, Thermal losses, Renewable energy sources.

Nomenclature

DH	District heating	CHP	Combined heat and power
EH	Excess heat	COP	Coefficeint of performance
PT	Power transformer	AN	Air natural
ON	Oil natural	AF	Air forced
OF	Oil forced	HEX	Heat exchanger
HP	Heat pump		

1. Introduction

District heating supplied around 54% of the Danish heating demand in 2018 and is considered as one of Danish energy trademarks [1]. The goals for the future Danish energy system emphasize the role of renewable energy. The Climate Law from 2020 [2] states that Denmark must reduce greenhouse gas emissions by 70% in 2030 compared to 1990 and reach climate neutrality by 2050, i.e. Denmark can only emit greenhouse gases if it makes sure to absorb a corresponding amount from the atmosphere. Denmark is also one of the signatories of the Paris Agreement. Consequently, district heating (DH) production needs to move away from coal and natural gas. Biomass can be a transitional replacement for coal, but the questions of sustainable biomass, food and biofuels production limit the usability of biomass in the long-term [3]. Therefore, future DH production needs to be based on electricity (electric boilers and large-scale heat pumps), solar heating and excess heat (EH).

Several studies agreed that DH should cover between 50% and 70% of the future residential heating demand and that DH should be one of the main elements of the future Danish energy system [4–6]. Some of the advantages of the fourth generation of DH are the possibility to integrate low-temperature heat sources, efficiently transmit and distribute heat and offer energy storage in the form of thermal storage. In some of these studies [6–10] it was stated that industrial EH brings socio-economic benefits, improves energy system efficiency and reduces primary energy demands. However, the potential role of industrial EH for DH production was not explained in more detail in these studies. A couple of recent studies focused on the use of EH from fuel production facilities for DH, but did not explain in more detail the role of industrial EH and EH from data centres. An analysis of the role of renewable gas in the transition to zero-emission energy systems stated that EH generation associated to bio-fuel production could supply a significant share of DH demand in the future [11]. Lester et al. [12] focused on EH from fuel production technologies, but their results showed that EH from fuel production technologies, data centres and industry, are utilised to satisfy around 30%, 13% and 2% of the Danish DH demand in 2050, respectively. The fuel production technologies and thus the associated EH are currently not existing and are expected to be built until 2050. Two studies analysed the role of renewable gases and liquid fuels in the Danish energy system in 2050 and highlighted that EH from biorefineries is efficiently used for DH. The remaining studies of the future Danish energy system did not analyse EH as an alternative for DH production [13,14].

Bühler et al. [15,16] analysed the role of industrial EH and found that 1.36 TWh of DH could be provided annually with industrial EH from thermal processes which equals 5.1% of the current demand. More than half of this heat was found to be usable directly, without the need for a heat pump (HP). The analysis of the future Danish energy system [17] showed that data centres could supply around 20% of the DH production after 2040, while EH from production industries and biorefineries could contribute with around 10%.

The availability of EH from industries and data centres is largely linked to the increase of electrification of the future energy system. Substantial electrification of industries reduce the available high temperature EH, as it would be utilised on site or avoided through new technologies [18–21]. At the same time increased demand imposed by data centres increases available low-temperature EH [22,23]. Irrespective of the growth of electrification, power will continue to be transmitted at high voltages and consumed at medium and low voltages. Therefore, the use of power transformers (PTs) will become even greater than today. The purpose of the PTs is to convert voltage levels between two sections of the network to optimize conditions of transmission and consumption. During this conversion, relatively small losses occur [24], but all of them are converted into heat.

We have found very limited work on the utilisation of excess heat from power transformers (EHPT) for DH, mostly limited to local studies. A techno-economic analysis of the thermal energy saving options for high-voltage direct current interconnectors did not include DH as an alternative [25]. In the U.K., the EH from a 240-MVA 400/132-kV transformer was used to heat a school [26,27]. In Austria, another project was carried out to utilise EHPT for DH [28]. While in [26] the heat was directly recovered from the thermal oil, the Austrian-based system used the heat rejected to the air from the transformer's radiator. It was argued that such a system is easier to implement. Another study proved that the heat recovery unit from the power transformer can benefit from heating, prolong the transformer's lifetime, increase the power supply efficiency, and reduce the air conditioning load to save energy and to reduce global warming [29].

The novelty of the present work lies in:

- Geographic representation of EHPT relative to DH areas,
- The methodology for thermodynamic analysis of EHPT for DH, and
- Identification of the potentials and costs for the utilisation of EHPT for DH purposes in Denmark.

The present paper analysed the possibility to use EHPT for DH. This analysis was based on spatial, thermodynamic and economic considerations for using the EHPT for DH. Furthermore, the EHPT was determined based on their load profile and type.

The paper is structured as follows. The data and methods used in this analysis are introduced in Section 2, followed by the results in Section 3. After that, the sensitivity analysis is performed in Section 4 and results are discussed in Section 5. Finally, the conclusions are drawn in Section 6.

2. Methodology

2.1. Power transformer thermal model

While in operation, PTs generate heat due to power losses [30]. A part of these losses is generated in the core (these are called core losses, or *no-load* losses due to the fact that they exist even if transformer is only energized from the primary side, and no load is transmitted through it, i.e. secondary current is zero). When magnetic material is introduced in the alternating magnetic field two dominant phenomena are causing power losses – hysteresis of the magnetic material and eddy losses (due to the currents that are induced in the core).

The other part is generated in the windings and metallic constructive parts due to the electric current flow and stray magnetic flux caused by electric current (*load* losses). Winding losses are (usually, at rated conditions) dominant and consist of loss due to ohmic resistance of the winding, and some additional losses (eddy and circulating losses) [30]. Losses in metallic constructive parts (stray losses) are generated by the currents induced in the conductive materials by the magnetic field (generated by the winding currents).

Figure 1 shows schematic drawing of a PT. The core and windings are immersed in oil. Oil circulation is induced either by the pumps (“oil forced” cooling, or OF) or due to the thermal buoyancy (“oil natural” cooling, or ON) – the hot oil rises to the top, where it enters the cooling system. Radiators are commonly used for PT cooling; other common options are oil-to-water heat exchangers (HEXs). If the cooling system employs radiators, the hot oil is cooled down in the radiator plates by natural or forced convective cooling with air (commonly abbreviated as AN and AF, respectively).

The cold oil enters the PT at the bottom. The heat transferred from the oil to the air is seen as an EH source as it is rejected to the environment, unused and at relatively high temperature. The oil and thus the air temperature depend on the ambient temperature and losses which depend on the load of the PT. However, at rated conditions (loading and ambient temperature), for mineral oils, the top oil temperature should be up to 105°C (for ester and silicone liquids higher temperatures are allowed [31]). The rated power of PTs is practically determined by the maximum power at which certain temperatures (winding hot-spot and top oil temperature) exceed allowed values. These values are usually determined either by standards (e.g. IEC standards [31,32]) or, in some cases, by more specific user demands. Moreover, there are standards [33] specifying standard thermal tests (so-called heat-run tests) to be performed in scope of transformer acceptance tests. However, due to the introduction of the safety margins in the design process, majority of PTs are oversized [34], hence the characteristic temperatures at the rated loading conditions are substantially lower than the allowed ones.

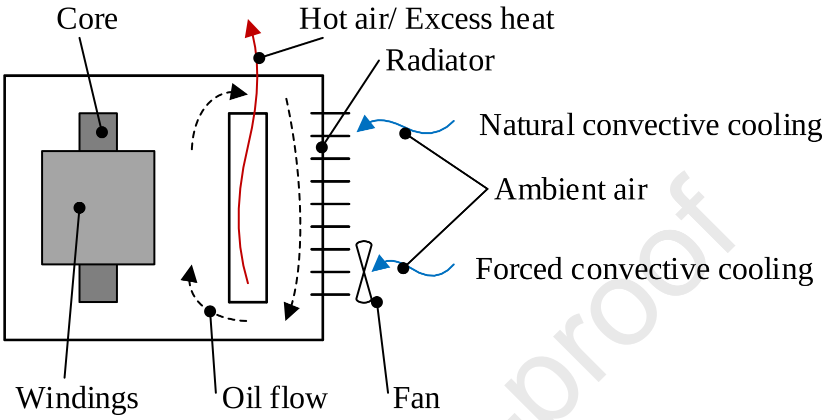


Figure 1. Simplified cooling scheme of a power transformer.

In practice, it is common that large power transformer units[1] are custom made. As a result, thermal behaviour of PTs of the same rated power and voltage level could differ significantly due to design differences. The data from heat-run tests can be very useful for detailed studies; but they are often not publicly available. Additionally, data processing for each of the transmission PTs is very time consuming. Therefore, some approximations had to be made for the purpose of this study.

Publicly available data about transmission PTs in the Danish power grid [35] contain voltage levels, rated power, and split losses (load and no-load). The PTs with missing values were represented by one of the "average" transformers. The "average" PTs were created by grouping the PTs into three groups, according to the main winding number (2 or 3 winding transformers) and voltage level on the high voltage side (for 2 winding transformers only) and then averaging their values. Each "average" transformer was described by the ratio of core losses to rated load. All PTs were considered to be oil-natural air-natural cooled (ONAN) with radiators.

The present study required knowledge of top oil and bottom oil temperature increases in the outer cooling. The inlet temperature of the outer cooling medium was determined by the temperature in the DH grids. A thermal model of the power transformers was therefore adopted. The steady state top oil rise was calculated according to eq. (1) following the IEC recommendation [32]:

---

[1] According to the IEC standards [33], 100 MVA is the threshold for large 3-phase transformers, 33 MVA for the single-phase transformers.

$$\Delta\theta_{to} = \Delta\theta_{tor}\left(\frac{1+RK^2}{1+R}\right)^x \tag{1}$$

where:

$\Delta\theta_{to}$ is steady state top oil rise temperature [K],

$\Delta\theta_{tor}$ is rated steady state top oil rise temperature [K] (value of 55 K is adopted from [32]),

R is load losses to core losses ratio at rated load [-],

K is the load (current) [p.u.], and

x is oil exponent (0.8 for the ONAN cooled transformers).

The PT losses can be grouped into two categories - *load* and *no-load* losses. These losses are converted into EH, namely EHPT. No-load losses are constant over time assuming a constant grid voltage (i.e. they do not depend on current load), while load losses are dependent on the square of the current load. Figure 2 shows the power losses as a function of the load. Total losses, equal to the sum of load and no-load losses, for rated load (1 p.u.) amount to 1 p.u. The load losses to no-load losses (i.e. core losses) ratio for 2-winding higher voltage level “average” transformer are used for illustration. Temperature dependency as well as other effects of smaller importance for the losses are neglected in this paper. The oversizing of the PT was not considered in this case. The PTs are relatively underloaded in the Danish power system (annual average of around 30% [36]) resulting in the ratio of load to no-load losses at almost 1:1.

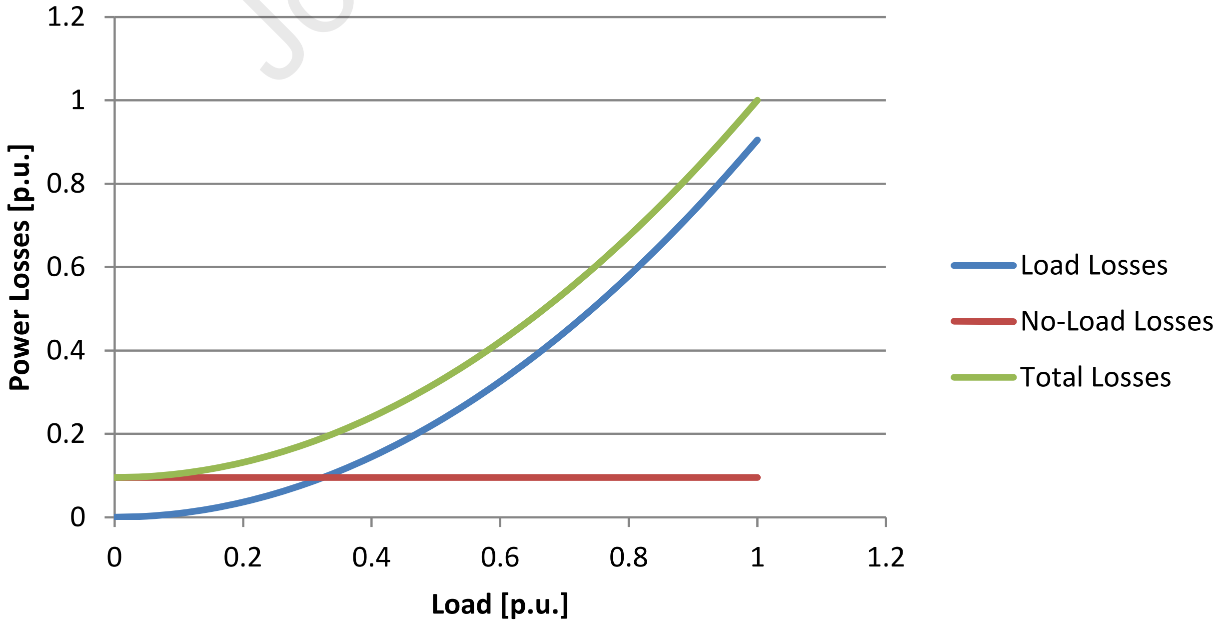


Figure 2. Transformer power losses as a function of the transformer load, for constant voltage level

For the calculation of the bottom oil temperature, the rated top-to-bottom oil gradient value was assumed to be 22 K [37]. The gradient change due to the load was also assumed to be a function of the oil exponent of 0.8, as shown in eq. (2).

$$\Delta\theta_{bo} = \Delta\theta_{to} - (\Delta\theta_{tor} - \Delta\theta_{bor})\left(\frac{1 + RK^2}{1 + R}\right)^x \tag{2}$$

where:

$\Delta\theta_{bo}$ is steady state bottom oil rise temperature [K], and

$\Delta\theta_{bor}$ is rated steady state bottom oil rise temperature [K] ($\Delta\theta_{tor}$ - $\Delta\theta_{bor}$ is rated top-to-bottom oil gradient).

The relative load of all PTs in the present study were based on representative power transformer operated by Energinet (the Danish TSO) [36]. The representative power transformer is averagely loaded amongst the transformers operated by Energinet, with a nominal power of 75 MVA and a voltage level of 150 kV. The smallest power transformer operated by Energinet was 45 MVA, the usual range is 80-160 MVA, so the representative one is on the lower side. The hourly loads of Energinet's representative power transformer were averaged into four seasonal values and used in the present analysis. However, it should be noted that the load power losses are proportional to the square of the load (cf. Figure 2). Therefore, any load oscillation (both daily and periodically during the season) causes the load losses to be higher than in case of the constant load.

2.2. Excess heat recovery from power transformers

The radiators used in existing transformers to cool the system can be replaced by HEXs coupled to the DH network or coupled with a HP. Alternatively, the radiators could be kept and an air-to-water HEX used to recover the EHPT. The entire EHPT, irrespectively of its temperature can be considered as theoretical potential DH potential and is represented by first pair of bars in Figure 6.

As stated in Section 2.1, all the analysed PTs were considered ON ("oil natural") cooled [36]. That means that a pump is not present in the oil circuit. The hypothetical HEX was introduced in the outer cooling circuit of the PT instead of the transformer's radiators. It was assumed that this hypothetical HEX does not influence the internal distribution of the oil flow, keeping the same oil temperature gradient, and to have the same cooling power as the existing radiators do. In reality, compact HEXs tend to be used along with the oil pumps due to the significant pressure drop. In these cases, the transformer becomes OF ("oil forced") cooled (see Figure 3). For OF cooling, the top to bottom oil gradient is usually significantly lower than for ON cooling.

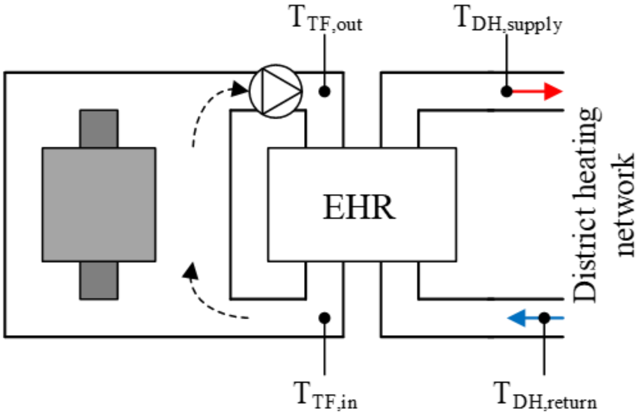


Figure 3. Schematic drawing of excess heat recovery from the transformer

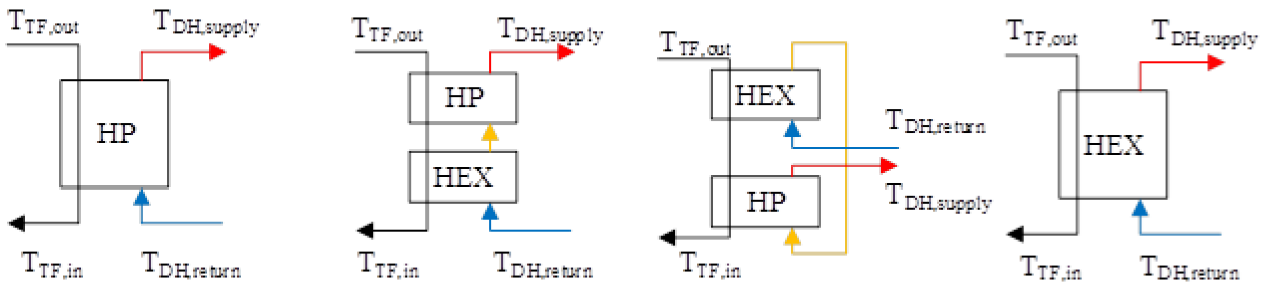
2.3. Thermodynamic analysis

The temperature $T_{TF,out}$ and $T_{TF,in}$ at the transformer side and the temperatures $T_{DH,supply}$ and $T_{DH,return}$ on the DH side determine if a HP, a direct heat exchange or a combination of both is required. Furthermore, a minimum temperature difference in the HEXs must be respected, with a magnitude typically defined based on economic considerations [38].

In Fig. 4 several possible combinations for excess heat utilisation from a power transformer are shown. The direct utilisation of the EHPT (Fig. 4 d) is typically possible when the top oil temperature $T_{TF,out}$ is above the supply temperature of the DH area $T_{DH,supply}$. As the bottom oil temperatures are fixed to obtain the necessary cooling effect, complete direct heat transfer is only possible if the DH return temperature is a minimum temperature difference below the required bottom oil temperature. If no complete direct heat transfer is possible, a HP will be required to provide all the temperature lift or part of the heating or cooling, as shown in Figure 4 a to c. This can be beneficial as shown in [39] and [40]. In the cases analysed in this work the most frequent configurations were the ones shown in Figure 4 a and Figure 4 b. The entire EHPT which has high enough temperature to be used for DH, with or without HP, is considered as accessible potential and is presented with second pair of bars in Figure 6.

The abbreviations in Figure 4 have the following meaning:

- $T_{TF,in}$, $T_{TF,out}$ – Bottom and top oil temperature
- $T_{DH,supply}$, $T_{DH,return}$ – Supply and return DH temperature, respectively
- HP – Heat pump
- HEX – Heat exchanger



a) Heat pump
b) Heat pump and heat exchanger
c) Heat pump and heat exchanger
d) Heat exchanger

Figure 4. Configurations for the possible excess heat recovery systems using the power transformer as the heat source.

The HP was modelled using the Lorenz cycle and was corrected by the Lorenz efficiency η_{Lor} to obtain the real COP as shown in [41]. The logarithmic mean temperature of the heat source, $T_{lm,C}$, and heat sink, $T_{lm,H}$, were used to find the theoretical COP, COP_{Lor}. The approach is explained in detail in [42] and the main equations are presented in the following. The COP was estimated using Eq. 3, where the logarithmic mean temperature is found using Eq. 4 applied to the case of this paper. In this work, a Lorenz efficiency of 0.45 was assumed further.

$$\mathrm{COP} = \eta_{Lor}\ COP_{Lor} = \frac{T_{lm,H}}{T_{lm,H} - T_{lm,C}} \tag{3}$$

$$T_{lm,H} = \frac{T_{DH,supply} - T_{DH,return}}{\ln(T_{DH,supply} - T_{DH,supply})} \text{ and } T_{lm,C} = \frac{T_{TF,out} - T_{TF,in}}{\ln(T_{TF,in} - T_{TF,out})} \tag{4}$$

The temperature levels for the DH, where the actual average DH temperatures for each DH network in Denmark for spring, summer, autumn and winter. The supply temperature ranged from 165°C to 65°C, with the average at 76°C and the return temperature ranged from 85°C to 34°C, with the average at 42°C. The temperatures of the transformers were found as described in Section 2.1.

2.4. Spatial analysis

The present paper analysed the amount of EHPT that can be utilised for DH. This section describes two constraining factors for utilisation of EHPT for DH:

- The economical transmission of EHPT for DH was determined by the amount of EHPT and the distance between the EHPT source and DH demand. Namely, the maximum distance over which EHPT can be economically transmitted grows with the amount of EHPT.
- The utilisation of EHPT is limited by the heating demand in a DH area, i.e. DH produced from EHPT cannot be fully exploited if it is greater than the heating demand in DH area to be supplied.

The present methodology was inspired by the methodology applied in [15] for the case of industrial EH; the differences between the methodologies is highlighted in the following. GIS tools incorporated in ArcGIS 10.6 were applied to find the total heating demand which can be covered by EHPT. The applied procedure was as follows:

1. High voltage power transformers [35] and official DH areas [43] were projected on top of a background map in ArcGIS 10.6. Within ArcGIS 10.6 power transformers appear as points, while DH areas as polygons. As in [15], annual district heating statistics published by the Danish District Heating Association [44] were used to assign average annual efficiencies and seasonal supply and return temperatures to DH areas.
2. The annual heating demands of buildings supplied by DH was adopted from [15]. The difference from [15] is that buildings not currently supplied by DH are not considered connectible to DH. The implicit assumption is that it is highly unlikely that DH produced from EHPT can be greater than existing DH supply, i.e. EHPT is assumed to only displace existing DH supply.
3. As in [15], for each PT, the nearest DH area was identified. It was assumed that the EHPT is delivered to the nearest DH area.
4. If a high voltage PT was located outside of a DH area, the cut-off distance was identified, i.e. the maximum allowed distance from EHPT source to the nearest DH area. As in [15], the maximum allowed distance was calculated from maximum connection costs per MWh of heat delivered and the costs for transmission pipes per unit of capacity. The PTs located within existing DH areas were assumed to be always connectible. If EHPT could be connected to a DH area, the deliverable EHPT amount was reduced for transmission and distribution losses (third pair of bars in Figure 6).
5. If no DH area fulfilled the criteria from point 4, the EHPT was not included in the total represented by the fourth bar in Figure 6, namely “Within cut-off distance”.
6. For each DH area, the heating demand of buildings supplied by DH is summed. Subsequently, this quantity is compared to the heating demand, which can be supplied from EHPT. If the heating demand of buildings supplied by DH is greater, the entire EHPT potential could be utilised for DH. This potential is considered as realistic potential in this study and presented by the utmost right pair of bars in Figure 6. If the heating demand of buildings supplied by DH is smaller, only a part of EHPT potential can be utilised.

2.5. Economic analysis

This subsection presents the method for calculating the costs of DH from EHPT and comparing them with alternative ways of producing DH. For each pair of PT and its closest DH area, the costs of DH from EHPT is calculated by taking into account the investment costs of DH pipes and HP, as well as their fixed and variable O&M costs and electricity costs necessary to run the HP, as presented in Equation 1.

$$C_{DH,i} = \frac{INV_i \cdot CRF + FIXOM_i + VAROM_i}{DH_i} = \frac{\left(INV_{p,i} + INV_{HP,i}\right) \cdot CRF + FIXOM_{HP,i} + VAROM_{HP,i}}{DH_i}$$
$$= \frac{\left(inv_{P,i} + inv_{HP,i}\right) \cdot CAP_i \cdot CRF + fixom_{HP,i} \cdot CAP_i + varom_{HP,i} \cdot DH_i + EL_{HPi} \cdot c_{el}}{DH_i}$$

Equation 1

The symbols used in Equation 1 have the following meaning:

$C_{DH,i}$ – Cost of DH from EHPT i (in EUR/MWh)

$INV_i, FIXOM_i, VAROM_i$ – Investment, fixed and variable O&M costs needed to transfer EHPT i to the nearest DH grid (in EUR)

$INV_{p,i}$, $INV_{HP,i}$ – Total investment costs in pipes and HPs related to PT i, respectively (in EUR)

$inv_{P,i}$, $inv_{HP,i}$ – Relative investment costs in pipes and HPs related to PT i, respectively (in EUR/MW)

$FIXOM_{HP,i}$, $VAROM_{HP,i}$ – Total fixed and variable O&M costs in HPs related to PT i, respectively (in EUR)

$fixom_{HP,i}$, $varom_{HP,i}$ - Relative fixed (in EUR/MW/year) and variable O&M (in EUR/MWh) costs in HPs related to PT i, respectively

$EL_{HP,i}$, c_{el} – Electricity use in HPs related to PT i and electricity cost (69 EUR/MWh), respectively

DH_i – DH from EHPT *i* reaching the consumer (in MWh)

CAP_i – Capacity of heat pump and pipes needed to connect EHPT *i* to the nearest DH grid (in MW)

$CRF = 0.064$ – Capital recovery factor calculated with the lifetime of 25 years and interest rate of 4%

The investment and operation costs of heat pumps for the PT and future electricity price of 69 EUR/MWh were adopted from [45]. The capacity of HP and DH pipes (in MW) was calculated from EHPT and assumed full load hours, 4000 for PTs and 3500 for flue-gas, air-source and ground-source HPs. The full load hours were estimated, considering the requirement for cooling of the PT during all operating modes and the constant availability of heat from the PT. As the exact costs for the heat pump and auxiliary equipment (pumps, piping and heat exchangers) can vary significantly based on local conditions, the standard costs from the references were chosen. The investment costs of DH pipes were not accounted for competing HPs because they could either be located at a favourable location or replace existing DH plants. The investment costs for flue-gas, air-source and ground-source HPs were adopted from [46] while O&M costs come from [45]. The cost of DH pipes depend on the size and were adopted from [15], while price of DH from industrial EH, average DH price for 2016 and average solar DH price were from [16,45]. The values for the COP of the different heat pumps, used for comparison, were based on data from [45]. These values refer to the average temperatures in DH networks in Denmark and the expected average temperatures of the heat sources. For groundwater heat pumps, the assessment of the COP was done with the assumption of a constant water temperature of 9°C. The values are summarised in Appendix A.

3. Results

First, the results of the geographical mapping of EHPT are shown, followed by the potential of using these sources for DH and cost calculations.

The analysis of the PTs showed that the average top oil temperature in summer was 33.4°C and in winter 33.5°C. The bottom oil temperature was 28.1°C in summer and 28.3°C in winter. The temperatures were relatively constant over the seasons, with only minor load variations. However, the low temperatures also mean that a HP will be necessary to exploit the heat in all cases.

3.1. Excess heat from power transformers

The spatial distribution of EHPT on a national level is shown in Figure 5. The distribution of EHPT is spatially referenced to the 5 km by 5 km Danish square grid. This rough resolution was chosen for two reasons: 1) more detailed resolution would reveal the locations of the PTs which are confidential, 2) we found this resolution sufficient for a resource assessment on the national level.

The EHPT is not uniformly distributed all over the country, with a higher density of EHPT around the main cities in Denmark. From the regional perspective, the largest amount of EHPT, namely around 40% is located in Decentral[2] areas of West Denmark. The rest of the EHPT is almost equally split between Central and Decentral areas of East Denmark and Central areas of west Denmark, namely between 45 GWh and 48 GWh in each of the regions. Two PTs are further located on offshore wind parks in the Baltic Sea.

The total EHPT is 283 GWh per year or around 0.6% of Danish DH production. The majority of EHPT originates from 132 kV, 165 kV and 400 kV voltage levels. 133 GWh per year (58%) originates from 132 kV and 165 kV, while 91 GWh per year (40%) is from 400 kV transformers. The remaining EHPT comes from transformers on 110 kV and 232 kV voltage levels.

On average each 132 kV transformer provides 985 MWh of EH per year and each 165 kV transformer 865 MWh per year. The larger 400 kV transformers generate in average 4.3 GWh of EH a year. There are several outliers – the largest transformer located in Viborg generates 50 GWh of heat per year.

---

[2] District heating (DH) producers in Denmark are characterised as Central and Decentral. Accordingly, DH areas they supply are named Central and Decentral, as presented in Figure 5. Central DH areas are located in bigger cities, have higher installed capacities, more consumers and higher grid efficiency compared to Decentral areas.

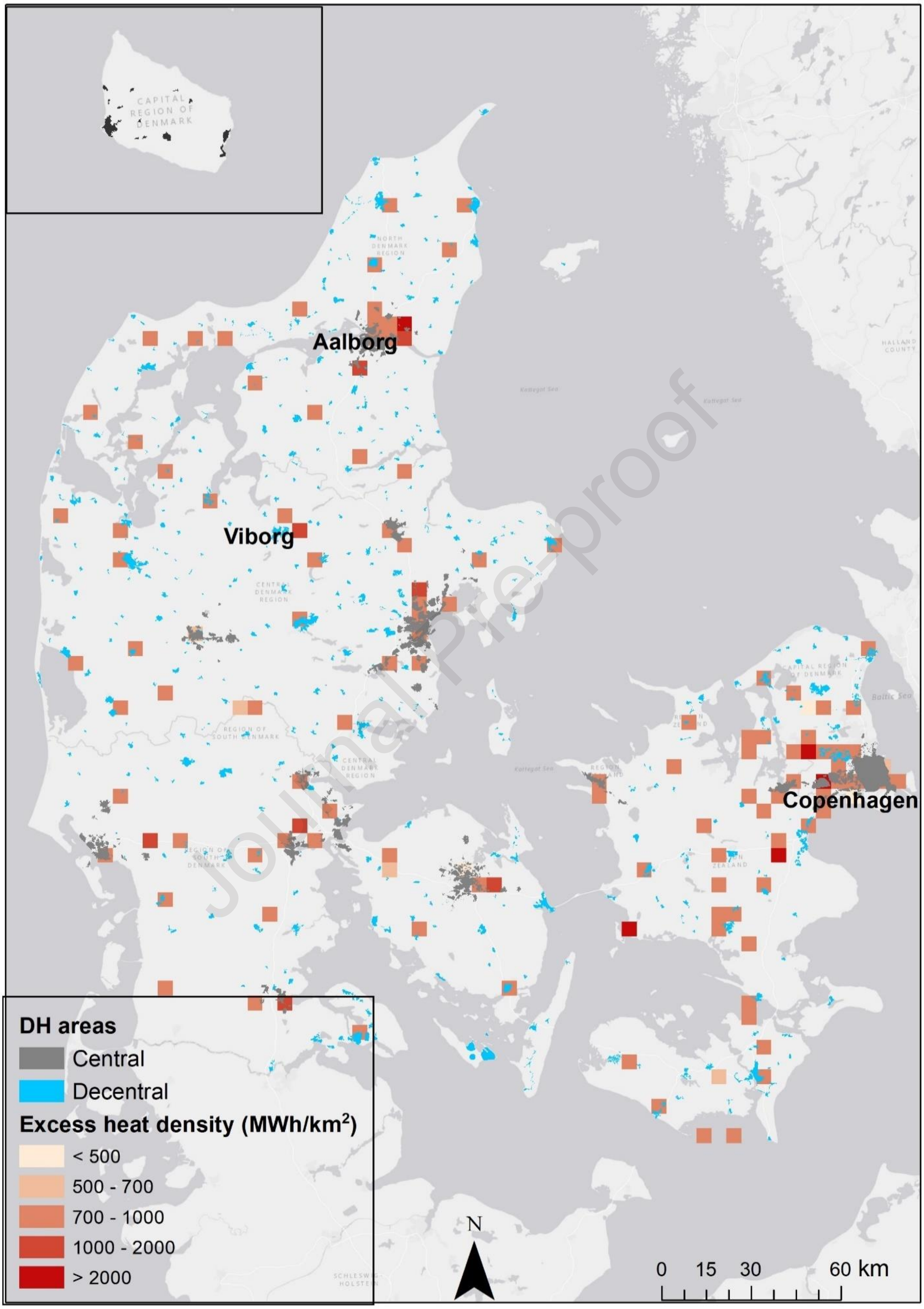


Figure 5. Spatial distribution of excess heat from transformers in Denmark on the 5 km by 5 km square grid.

3.2. Excess heat from power transformers for district heating

The different levels of potentials (from theoretical to real) for using EHPT for DH are presented in Figure 6. From the theoretical maximum EHPT potential for DH of 0.28 TWh per year, 0.12 TWh of DH can be supplied to the consumers. The electricity needed to run the HPs is presented on the secondary axis in Figure 6.

The recovery of the accessible EHPT is reduced by considering network losses and eliminating excess heat sources, which are outside the cut-off distance. The DH network losses is the difference between DH produced and DH delivered to the consumers and is mainly affected be the following parameters: overall network heat transmission, temperature gradient between the DH heat media and external environment and network diameter and length [47]. Average annual DH network losses are assigned to DH areas based on [44]. As shown in Figure 6, the losses in DH networks reduce the heat, which can be delivered to DH consumers by 0.06 TWh to 0.22 TWh.

The share of EHPT which cannot be economically transmitted to DH networks, due to large distances reduces the annual potential by 0.09 TWh (to 0.12 TWh, third bar in Figure 6). The majority (around 85%) of the PTs had to be within a close distance to a DH network (between 400 and 500 m) to be considered. For some of the largest EHPT emitters, larger distances of above 1000 m were feasible. As in [48], to obtain the realistic potential, we have checked for the EHPT which cannot be used due to a lack of demand[3]. In the present analysis, lack of demand is not a constraining factor. Therefore, the third and fourth bar in Figure 6 are equal and amount to 0.12 TWh. This means that the DH demand that can be covered from EHPT is 0.12 TWh per year or around 0.5% of the existing DH demand. The entire potential assumes heat recovery using heat pumps. The HPs would require 31 MWh per year of electricity, thus operating at an average COP of 4 when assuming a (conservative) Lorenz efficiency of 45%.

The share of DH demand, which can be replaced by EHPT, is shown on the map in Figure 8. Large quantities of EHPT are located in the vicinity of large cities, such as Copenhagen and Aalborg. As a result, these cities have large DH demands and resulting share of DH demand that can be replaced by EHPT, is relatively low. The city of Viborg as well as DH areas northeast of Aalborg and northwest of Copenhagen could have around 20% of their DH demand covered by EHPT.

---

[3] Lack of demand refers to a case in which the amount of EH reaching the specific DH area is greater than the DH demand in that DH area.

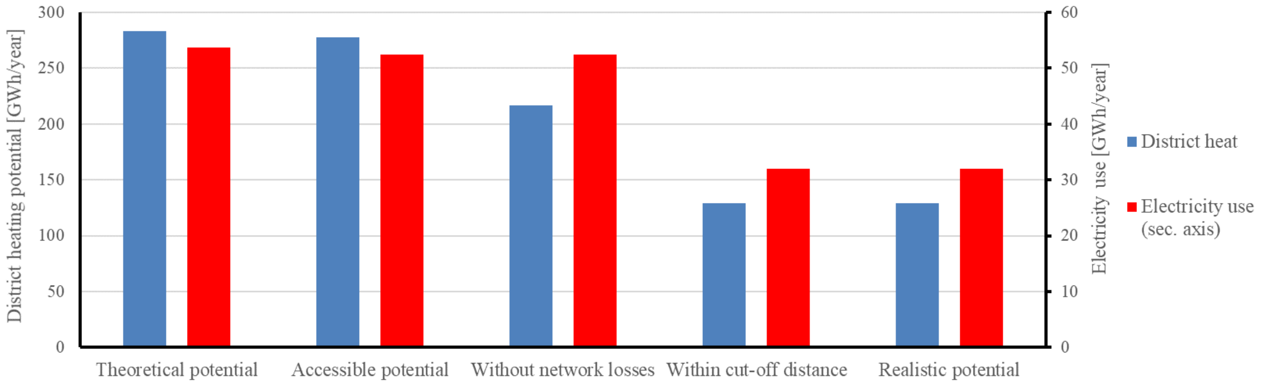


Figure 6. District heating potential of excess heat from transformers and electricity use for heat pumps.

Assuming the estimated full load hours for the economic analysis, the total installed capacity for district heating which would be added to the Danish system would be 70.72 MW. It has to be considered though that the heat from the PT is quite evenly distributed over the year. The actual capacity of delivered heat will thus be lower.

3.3. Cost of excess heat from power transformers

The calculation of costs of DH from EHPT are presented in Figure 7 together with the DH costs from technologies which likely will be present in the future Danish energy system, such as flue-gas, ground-source and air-source HPs. The minimum and maximum ranges come from different specific investment costs depending on the size of the HP. For comparison, we have included cost of DH from industrial EH, average solar DH cost and demand weighted average DH price from 2016. The cost of DH from EHPT is presented in two forms – with (denoted as “EHPT”) and without the PTs which are considered outside of the cut-off distance (denoted as “EHPT-only within”) as defined in Section 2.4.

The cost of DH from PT can be seen in competition with existing and future DH supply. First, DH from EHPT can supply between 70 GWh and 211 GWh per year at prices lower than the average DH price and 77 GWh and 233 GWh per year below the cost of solar DH. This translates into 4000 to 13000 average single-family houses[4] in Denmark. The span in cost-effective potentials originates from different accounting for the PTs located outside of the cut-off distance – they are included in the larger potential, not in the smaller. The realistic potential of around 120 GWh presented in Figure 6 is both greater than 70 GWh and smaller than 211 GWh, which points in the direction that the cut-

---

[4] An average existing single-family house from before 1979 with average improvements and average extensions in floor area, is defined to have an annual heat demand of 18 MWh [55]

off criteria presented in Section 2.4 was strict. However, due to inherent imprecision of potential assessment studies such as this one, we consider realistic potential of around 120 TWh to be on a safe side and will continue to use it as our central result.

Second, DH from flue-gas and industrial EH is almost always cheaper than DH from EHPT. There is a minor potential of between 13 GWh and 87 GWh where DH from EHPT is cheaper than from large air-source and ground-source HPs. EHPT can supply between 64 and 193 GWh and between 75 and 227 GWh at costs lower than from ASHPs and GSHPs between 0.5 and 1 MW (resulting in high specific investment cost), respectively. Practically, this means that EHPT cannot compete on a cost basis with industrial EH, flue gas HPs and large scale air-source and ground-source HPs, while it is competitive with small air-source and ground-source HPs.

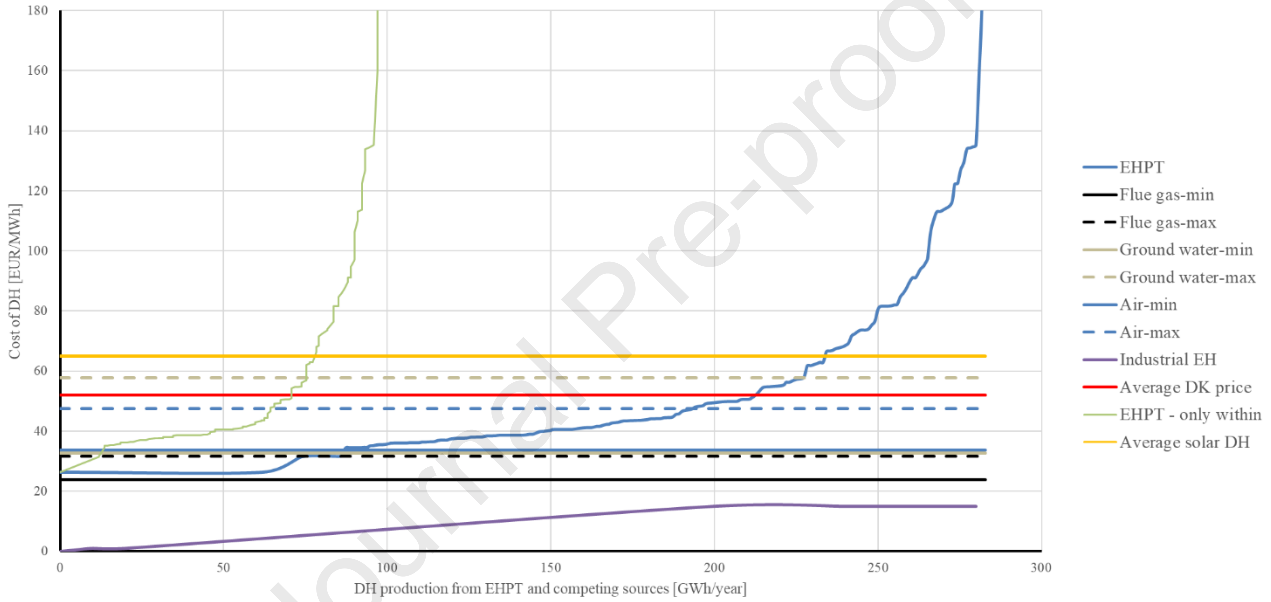


Figure 7. Costs of DH from EHPT compared with DH costs from industrial excess heat, solar heating, heat pumps of different sizes and sources and average DH price

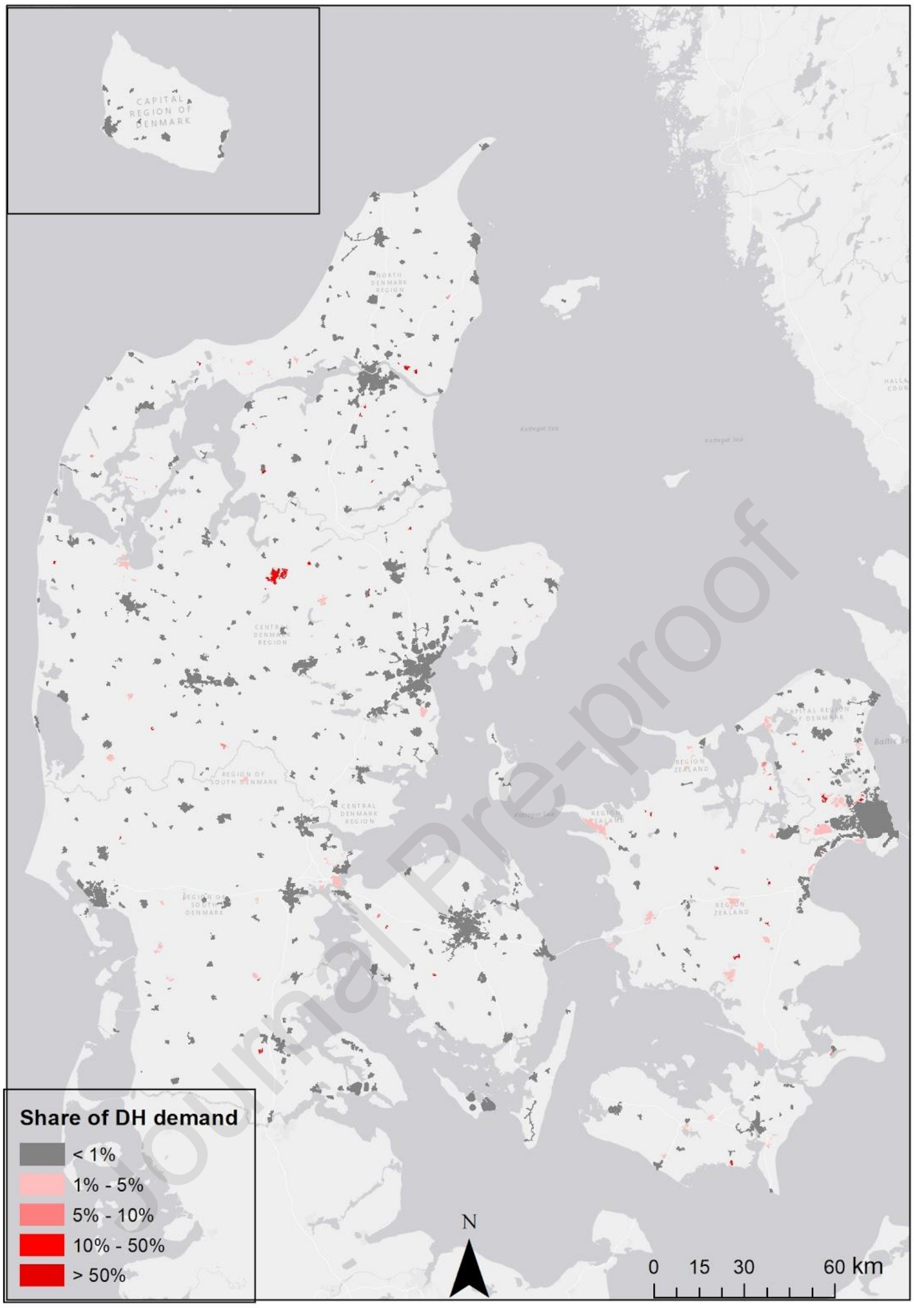


Figure 8. Substitution potential of district heat delivered from the transformers excess heat.

4. Sensitivity analysis

The share of district heating demand which can be supplied by EHPT is dependent on several factors. First, the temperature of EHPT can change if the operator decides that the benefit of increased electricity transmission (or, in this specific case, increased cooling medium temperature) is greater than the damage caused by the increased temperature of the cooling oil in the PT.

Second, the quantity of EHPT can change because of the electricity demand in the country, i.e. the growth of electricity demand relates to the growth of EHPT supply. For the growth of the electricity demand, an operator can either accept the growth of thermal losses in a PT or install another one in parallel. In the first case, the load losses (no-load losses do not change) grow with the square of the electricity demand (cf. Figure 2) while in the second case the total losses (load + no-load) grow linearly. In case of reduction in electricity demand, the load losses drop with the square of the electricity demand, while no-load losses stay constant.

Finally, the share of DH demand that can be supplied by PTs can change due to changes in the DH demand. The most influential parameters for the utilisation of EHPT for DH are therefore varied to discover the sensitivity of the results.

For each of the four sensitivity scenarios, the following variables are compared with their values calculated in Section 3:

- Theoretical DH potential and electricity needed to run the heat pumps
- Realistic DH potential and the associated electricity needed to run the heat pumps

Within the present section (including Figure 9), the values used for comparison (calculated in Section 3) are denoted as Base. Theoretical and realistic DH potential are expressed as a share of the existing DH demand and DH demand reduced by 30%. The rationale for choosing the reduction of DH demand by 30% is to show the drastic case described as "extra large savings" in "Energy Scenarios towards 2020, 2035 and 2050" published by the Danish Energy Agency [49]. The sensitivity scenarios named OutT, Lin, Const and Red are defined as following and presented in Figure 9:

- **OutT**: Since the average top oil temperature was around 30°C over the seasons (as presented in Section 3), i.e. significantly underloaded, we decided to test the effect of cooling oil temperatures of up to 90°C.
- **Lin**: Doubling of electricity demand accompanied by doubling the number of PTs which is equivalent to installing an additional transformer in parallel with the original one.
- **Const**: Doubling of electricity demand without changing the number of PTs. The load of the PTs doubles.
- **Red**: Reduction of electricity demand by 20% without changing the number of PTs.

OutT scenario resulted in an increased PT outlet temperature. 90°C was roughly adopted as an upper limit, since higher top oil temperatures would certainly result in hot spot temperature (the hottest temperature of the transformer windings) acceding the 98°C, at which relative ageing of regular paper insulation is at unity value. Any further increase would drastically decrease transformer’s lifetime. Since the supply temperature of the DH networks are below 90°C, the actual top oil temperatures can be adjusted to be between 82°C and 88.5°C.

The loading of the individual transformer doesn't change in Lin scenario. In that case, the load of both transformers should be equal to the current load of the transformer. Finally, the power losses and the EH double in this sensitivity measure. The doubling of electricity demand is a drastic assumption coming from potentially high electricity demand from data centres (75% of today's electricity demand in the exponential Scenario defined in [22]) and high cost-effective potential for electrification of industries [50].

In Const scenario, load power losses increase by a factor of four (due to the square dependency of the load losses on the current load, cf. Figure 2) while no-load losses do not change. Just for sake of illustration, if we assume that load and no-load losses are roughly the same before the doubling of electricity demand, then the total thermal losses, i.e. EHPT, should increase by a factor of 2.5 ($50\%\cdot 2^2+50\%\cdot 1=2.5$).

In Red scenario, the load of the PTs reduces by 20%. The power losses, i.e. the Theoretical potential, consequently reduce by 21% of the load losses.

The summary of the sensitivity analysis is presented in Figure 9. The results presented in Section 3 are generally confirmed when the sensitivity analysis is undertaken. Namely, the DH demand which can be supplied by EHPT falls within the range 0.32% to 2.26%, so it represents a small heat source on the national scale, but could be locally important.

The increase of PT cooling oil temperature in the scenario OutT reduces the theoretical and the realistic EH potential compared to the Base scenario by 19% and 31%, respectively. The temperatures of the cooling oil reach in this scenario similar levels as the DH supply temperature. Since there is no or a relatively low temperature difference between the cooling oil and the DH supply temperature, a HP is not needed to feed the heat into the DH network for most cases. This has twofold consequences. First, the use of electricity is negligible as shown in Figure **9**. That electricity use originates from one DH grid with very high supply temperatures where a heat pump is needed. Second, the absence of HPs means that no electricity is converted to heat, which results in a lower production of DH and a lower need for electricity.

It could be expected that doubling of electricity demand together with the doubling of the number PTs (Lin scenario) would increase the theoretical and realistic potential by 100%. The theoretical potential increases by 100%, but the realistic potential grows by 139%. This happens because more EHPT can be transferred longer distances, which means less EHPT will be excluded as economically infeasible, i.e. having no DH areas located within their cut-off distances. The larger cut-off distances are calculated as in step 4 of the procedure in Section 2.4. The realistic potential for DH from EHPTs reaches 1.08% with the current DH demand and even 1.55% after the reduction of DH demand.

It could also be expected that doubling of electricity demand with a constant number of PTs (Const scenario) would lead to an increase significantly above 100% in theoretical EHPT potential. Similar to the Lin scenario, this is not the case. Only the load losses quadruple, while the no-load losses staying the same. Due to a relatively low loading of Danish power transformers, the load and no-load losses are about equal at present loading regime and equipment capacity. That results in the increase of the total losses by 236%. The theoretical and realistic DH potential are slightly above the Lin scenario; realistic potential reaches 1.58% and 2.26% of the current and reduced DH demand, respectively.

Finally, reducing the electricity demand (Red scenario) by 20% results in only a minor difference compared to the Base scenario.

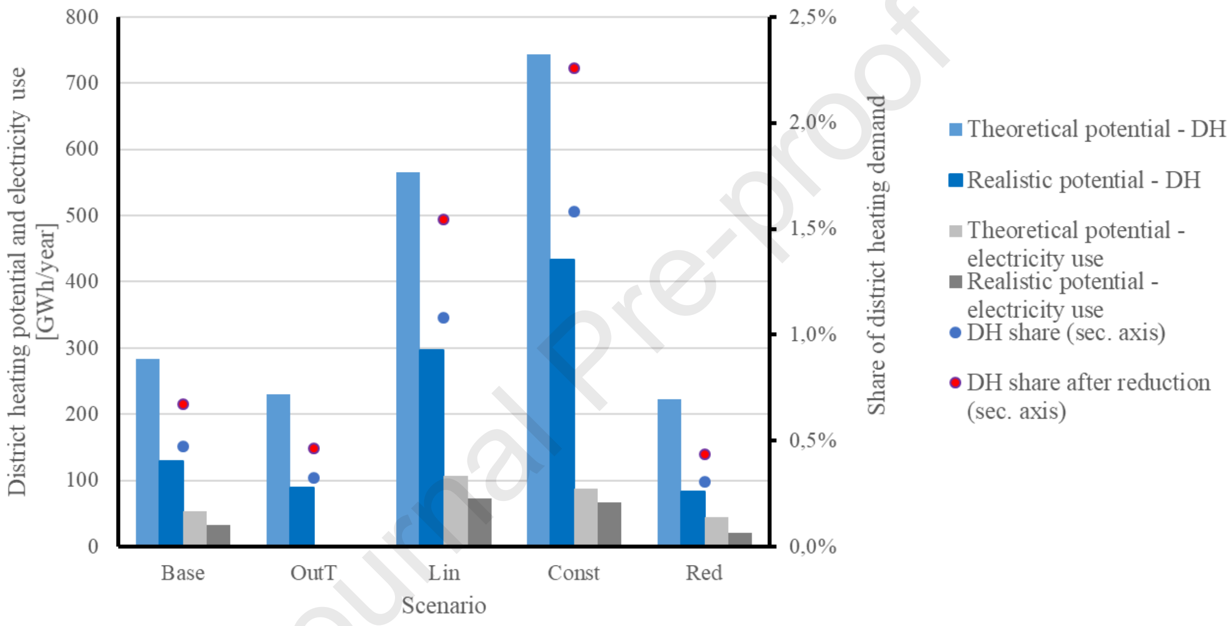


Figure 9. District heating potential for of excess heat from power transformers and the electricity use in the sensitivity scenarios.

5. Discussion

The systematic approach developed in the present work could also be applicable and beneficial to other regions, even though data might not be available at such high level of geographical detail as in Denmark. The calculated potential for supplying existing DH demand by EHPT should be seen as encouraging for other regions. Namely, Denmark is characterized by moderate population and heat densities, high DH demands, a moderate number of large electricity consumers, and moderate loads of PTs. In regions with higher heat densities, and a larger number of PTs with higher average loads, the EHPT from power transformers could supply a much larger share of DH demand. The examples potentially include industrial areas between Amsterdam and Rotterdam in west Netherlands and between Milano and Monza in North Italy, as well as densely populated service centres such as Paris and Brussels.

Even though the present analysis showed that EHPT could not supply a significant share of DH demand on the national scale, EHPT can still be important on the local level. Large heat consumers such as hospitals, shopping centres and industrial facilities require heat throughout the whole year. With a possible annual heat supply of 800 MWh to 1000 MWh, power transformer can significantly contribute to covering the heating demand of large buildings. In case a power transformer is located nearby, EH from the power transformer could be a valid option for heat supply. The economic analysis showed that between 70 GWh and 211 GWh per year of DH from EHPT can be supplied cheaper than the average DH price. Therefore, EHPT could be a feasible option for consumers in expensive DH areas where the price can be even twice higher than the average.

The potentials calculated in the present paper are under the implicit assumption that EH from power transformers can replace any DH source. In other words, we do not distinguish between the EHPT replacing an old oil boiler or a new solar heating plant. In cases when EH replaces amortized DH producers, this can lead to economic savings. In a similar way, replacing fossil fuel sources lead to environmental benefits. On the other hand, it is difficult to imagine how it would be possible that EHPT replaces a solar heating plant.

The analysis showed that there is an overall potential for utilising EHPT for DH. The exploitation of this EH may relate to several challenges and the EH recovery could be further optimised. The utilisation of EH directly from the thermal oil might be technically challenging as pointed out for the case in Innsbruck [28]. Therefore, the future work should analyse if the hypothetical HEX introduced in the outer cooling circuit of the power transformer instead of the transformer's radiators (Section 2.2) can practically be realised. As an alternative, the heat from the indoor air of the transformer house could be used through an air-to-water HP. While this system would not require modifications of the PT, the systems efficiency is expected to be considerably lower. The installation of the HP will further require floor space close to the transformer building. For PTs located in dense urban areas or in areas where land is not available this may pose another constraint.

To improve the EH recovery, the circulation of the thermal oil within the PT could be reduced to reach higher top oil temperatures. As presented in the sensitivity analysis, this would lead to a better performance of the HP (increase in COP), but at the same time, the lifetime of the PTs would be reduced. An analysis of the optimal top oil temperatures with respect to lifetime reductions and the expectations of the operator is thus required.

Another important topic is that the PTs in Danish power grid are loaded only partially. Averaged on a seasonal level, the load is ca. 25%-30%, causing low load power losses. Although some authors suggest load factors to be targeted at 40%-60% [51], this value differs significantly worldwide, and it usually depends more on the exploitation strategy than on the practical technical aspects. DH supply temperatures are also expected to decrease in the future [52–54] which should lead to higher COPs of HPs and improve attractiveness of low-temperature heat sources such as PTs.

The increasing electrification of the transport, heating and industry sector will increase the electricity demand. The electric power infrastructure will need to be expanded. This will increase the number of PTs, their load and the available EH. In Denmark, the installation of large data centres is planned which will further increase the electricity demand up to 70%. This effect is explored in the Sensitivity analysis and it is shown that power transformers could supply 1.58% of the current DH demand.

Finally, the present work calculated the theoretical and realistic EHPT potentials as well as an estimate of cost of DH produced from PT. The role of EHPT within the transition of the whole Danish energy system, i.e. its effect on the investment and operation costs, fuel use, and environmental emissions is not quantified within this work. However, based on the results presented in Section 3.3, DH based on EHPT seems to be competitive only with small-scale air-source and ground-source HPs and too expensive compared to other alternatives. Therefore, it is hard to imagine DH based on EHPT could have a significant role in the future energy system. The results from economic analysis entail several uncertainties – future investment, operation and maintenance and electricity prices are uncertain and will change in future, the capacity factors will depend on the production mix in every DH grid, while the cost of DH from competing technologies comes from a different source.

All issues mentioned in this section deserve to be addressed in further work.

6. Conclusion

The present paper analysed the possibility to utilise EHPT for DH in Denmark. First, we have determined the amounts of EH produced by PTs in each of the seasons. After that we applied thermodynamic analysis of a HEX and a HP necessary to extract the EH and utilise it for DH. Finally, we geographically represented PTs and DH areas and performed spatial analyses in GIS to link the PTs with specific DH networks and assigned costs to them. As a result, the present analysis resulted in a realistic potential for utilisation of EHPTs for DH.

The analysis of the PTs showed that the average top oil temperatures were relatively constant at around 30°C over the seasons, as only minor load variations were observed.

The EHPT is not uniformly distributed all over the country, with a higher density of transformers' EH around the main cities in Denmark. The largest amount of EH, namely around 40% is located in decentral areas of West Denmark while the rest is almost equally split between remaining DH areas.

From the theoretical maximum EH potential for DH of 0.28 TWh per year, 0.12 TWh of DH can be supplied to the consumers due to the losses in DH networks and large distances between power transformers and DH areas. The lack of demand is not a constraining factor. The entire potential for heat recovery can be utilised through heat pumps, with an average COP of 4.

From the economic analysis, between 70 GWh and 211 GWh of DH from EHPT can be supplied to consumers at prices lower than the average DH price in 2016. Since the maximum DH prices can be even double as high as the average, DH from EHPT could be an alternative in some local cases. However, economic analysis also showed that HPs are often a cheaper solution.

From the sensitivity analysis, we have found out that the increased top oil temperature at almost 90°C will result in direct heat transfer, i.e. no HPs would be needed. In that case, the amount of DH to be supplied to the consumers would be reduced to 0.32%. On the negative side, this will decrease the lifetime of the insulation and thus the PT. Doubling the electricity demand without changing the number of PTs has the highest effect out of all sensitivity measures - PTs can supply 1.58% of the existing DH demand.

The present analysis showed that EHPTs is a small and relatively expensive resource on the national scale but could be an important source on the local level or regional level. The city of Viborg as well as DH areas northeast of Aalborg and northwest of Copenhagen could have around 20% of their DH demand covered by EHPTs. The present research should develop in two most important directions – selection and analysis of local cases in Denmark and (geographical) extension to other countries and regions with higher heating demands, larger population densities and larger electricity demands.

Acknowledgments

The work presented in this paper is a result of the research activities of the HEAT 4.0 project, which has received funding from Innovation Fund Denmark (Project number 8090-00046). The authors would like to acknowledge the contribution of Kim Boe Jensen from Energinet for supplying locations of power transformers and data about representative, averagely loaded transformer. The usual disclaimer applies.

Appendix A. Cost figures and COPs

The key assumptions of the economic analysis are presented in Table 1, Table 2 and Table 3.

Table 1. Economic data about heat pumps needed to utilize excess heat from power transformers

Range [MW]	Electricity cost [EUR/MWh]	Investment cost [MEUR/MW]	Fixed O&M costs [ME/MW]	VAR O&M [EUR/MWh]
0.2-1	69	1,24	0,002	2,70
1-5		0,86		2,20
>5		0,67		1,70

Table 2. Economic data about alternative heat pumps

Range [MW]	Investment costs [MEUR/MW]						Electricity cost [EUR/MWh]			Fixed O&M costs [ME/MW]		
	Flue gas		Ground water		Air-source		Flue gas	Ground water	Air-source	Flue gas	Ground water	Air-source
	Min	Max	Min	Max	Min	Max						
0.5-1	0,53	0,63	1,18	1,72	0,9	1,12	69			0,002		
1-4	0,46	0,53	0,77	1,18	0,73	0,9						
4-10	0,44	0,46	0,69	0,77	0,7	0,73						

Table 3. COPs of alternative heat pumps

Range [MW]	Investemnt costs [MEUR/MW]		
	Flue gas	Ground water	Air-source
0.5-1	4,1	3	2,9
1-4	4,6	3,3	3,1
4-10	5,1	3,9	3,8

References

[1] Danish Energy Agency - Energistyrelsen. Energistatistik 2018. 2019.

[2] Regeringen (Danish Goverment). Aftale om klimalov (Agreement on climate law). Copenhagen: 2019.

[3] Mathiesen BV, Lund H, Connolly D. Limiting biomass consumption for heating in 100% renewable energy systems. Energy 2012;48:160–8. https://doi.org/10.1016/j.energy.2012.07.063.

[4] Münster M, Morthorst PE, Larsen H V., Bregnbæk L, Werling J, Lindboe HH, et al. The role of district heating in the future Danish energy system. Energy 2012;48:47–55. https://doi.org/10.1016/j.energy.2012.06.011.

[5] Mathiesen BV, Lund H, Karlsson K. 100% Renewable energy systems, climate mitigation and economic growth. Appl Energy 2011;88:488–501. https://doi.org/10.1016/j.apenergy.2010.03.001.

[6] Danish Energy Agency. Denmarks energy and climate projection 2014 [In Danish: Danmarks Energi- og Klimafremskrivning 2014]. Copenhagen: 2014.

[7] Lund H, Möller B, Mathiesen B V., Dyrelund A. The role of district heating in future renewable energy systems. Energy 2010;35:1381–90. https://doi.org/10.1016/j.energy.2009.11.023.

[8] Möller B, Lund H. Conversion of individual natural gas to district heating: Geographical studies of supply costs and consequences for the Danish energy system. Appl Energy 2010;87:1846–57. https://doi.org/10.1016/j.apenergy.2009.12.001.

[9] Mathiesen BV, Lund H, Connolly D. Limiting biomass consumption for heating in 100% renewable energy systems. Energy 2012;48:160–8. https://doi.org/10.1016/j.energy.2012.07.063.

[10] Karlsson KB, Petrović SN, Næraa R. Heat supply planning for the ecological housing community Munksøgård. Energy 2016. https://doi.org/10.1016/j.energy.2016.08.064.

[11] Jensen IG, Wiese F, Bramstoft R, Münster M. Potential role of renewable gas in the transition of electricity and district heating systems. Energy Strateg Rev 2020;27:100446. https://doi.org/10.1016/j.esr.2019.100446.

[12] Lester MS, Bramstoft R, Münster M. Analysis on Electrofuels in Future Energy Systems: A 2050 Case Study. Energy 2020;199:117408. https://doi.org/10.1016/j.energy.2020.117408.

[13] Bramstoft R, Pizarro-Alonso A, Jensen IG, Ravn H, Münster M. Modelling of renewable gas and renewable liquid fuels in future integrated energy systems. Appl Energy 2020;268:114869. https://doi.org/10.1016/j.apenergy.2020.114869.

[14] Venturini G, Pizarro-Alonso A, Münster M. How to maximise the value of residual biomass resources: The case of straw in Denmark. Appl Energy 2019;250:369–88. https://doi.org/10.1016/j.apenergy.2019.04.166.

[15] Bühler F, Petrović S, Karlsson K, Elmegaard B. Industrial excess heat for district heating in Denmark. Appl Energy 2017;205. https://doi.org/10.1016/j.apenergy.2017.08.032.

[16] Bühler F, Petrović S, Holm FM, Karlsson K, Elmegaard B. Spatiotemporal and economic analysis of industrial excess heat as a resource for district heating. Energy 2018;151:715–28. https://doi.org/10.1016/j.energy.2018.03.059.

[17] DTU Management Engineering. Energy agreement [In Danish: Energiaftalen] 2018.

[18] Bühler F, Holm FM, Elmegaard B. Potentials for the electrification of industrial processes in Denmark. ECOS 2019 - Proc 32nd Int Conf Effic Cost, Optim Simul Environ Impact Energy Syst 2019:2137–52.

[19] Bühler F;, Zühlsdorf B; M, Müller Holm F, Elmegaard B. The potential of heat pumps in the electrification of the Danish industry. 2nd Symp High-Temperature Heat Pumps SINTEF

2019:51–67.

[20] Bühler F, Zühlsdorf B, Nguyen T Van, Elmegaard B. A comparative assessment of electrification strategies for industrial sites: Case of milk powder production. Appl Energy 2019;250:1383–401. https://doi.org/10.1016/j.apenergy.2019.05.071.

[21] Bühler F, Holm FM, Zühlsdorf B, Elmegaard B. Energy integration and electrification opportunities in industrial laundries. ECOS 2020 - Proc 33rd Int Conf Effic Cost, Optim Simul Environ Impact Energy Syst 2020:2109–21.

[22] COWI. Temaanalyse om store datacentre (Thematic analysis on large data centers). 2018.

[23] Petrović S, Colangelo A, Balyk O, Delmastro C, Gargiulo M, Simonsen MB, et al. The role of data centres in the future Danish energy system. Energy 2020;194. https://doi.org/10.1016/j.energy.2020.116928.

[24] Del Vecchio R, Poulin B, Feghali P, Shah D, Ahuja R. Transformer Design Principles: With Applications to Core-Form Power Transformers. London: CRC Press; 2010. https://doi.org/10.1201/EBK1439805824.

[25] Giampieri A, Ma Z, Ling Chin J, Smallbone A, Lyons P, Khan I, et al. Techno-economic analysis of the thermal energy saving options for high-voltage direct current interconnectors. Appl Energy 2019;247:60–77. https://doi.org/10.1016/j.apenergy.2019.04.003.

[26] Rauch E. Transformers to heat a London school. 2015.

[27] Paul Jarman, Kevin Hampton, Mark Lashbrooke GJP. Reliable , optimised power transformers with heat recovery for urban areas. Transform Mag 2017;4.

[28] Sinfonia Smartcities. New twist in power transformer’s use to heat buildings in Innsbruck 2017.

[29] Chien ZJ, Cho HP, Jwo CS, Chen SL, Lin YL. A study of waste-heat recovery unit for power transformer. Adv Mater Res 2014;875–877:1661–5. https://doi.org/10.4028/www.scientific.net/AMR.875-877.1661.

[30] Kulkarni SV, Khaparde SA. Transformer Engineering Design, Technology, and Diagnostics. vol. 53. CRC Press; 2013. https://doi.org/10.1017/CBO9781107415324.004.

[31] International Electrotechnical Commission. Standard 60076-14 Power transformers –Part 14: Liquid-immersed power transformers using high-temperature insulation materials. vol. 2014. 2013.

[32] Electrotechnical Commission. Geneva I. Power transformers: Part 7: loading guide for oil-immersed power transformers 2005.

[33] IEC. Power transformers. Temperature rise for liquid-immersed transformers. 60076-2 2011.

[34] Radakovic Z, Sorgic M. Wirtschaftliche Betrachtung der thermischen Auslegung von olgekuhlten Leistungstransformatoren-Berechnungsmethode zur Kostenermittlung. Elektrizitätswirtschaft 2008;107:32–8.

[35] Energinet. Access to network data [In Danish: ADGANG TIL NETDATA] 2019. https://energinet.dk/El/Data-om-energisystemet/Netdata (accessed January 8, 2020).

[36] Personal communication with Kim Boe Jensen from Energinet 2019.

[37] Commission IE. Power transformers – Part 7: Loading guide for oil-immersed power transformers. Order A J Theory Ordered Sets Its Appl 2002;2002:1–4.

[38] Orosz Á, Friedler F. Multiple-solution heat exchanger network synthesis for enabling the best industrial implementation. Energy 2020;208. https://doi.org/10.1016/j.energy.2020.118330.

[39] Jensen JK, Ommen T, Markussen WB, Elmegaard B. Design of serially connected ammonia-water hybrid absorption-compression heat pumps for district heating with the utilisation of a geothermal heat source. 29 th Int. Conf. Effic. Cost, Optimisation, Simul. Environ. Impact Energy Syst., 2016.

[40] Ommen T, Markussen WB, Elmegaard B. Heat pumps in combined heat and power systems. Energy 2014;76:989–1000. https://doi.org/10.1016/j.energy.2014.09.016.

[41] Reinholdt L, Kristófersson J, Zühlsdorf B, Elmegaard B, Jensen J, Ommen T, et al. Heat pump COP, part 1: Generalized method for screening of system integration potentials. Refrig Sci Technol 2018;2018-June:1207–13. https://doi.org/10.18462/iir.gl.2018.1380.

[42] Bühler F, Petrović S, Ommen T, Holm FM, Pieper H, Elmegaard B. Identification and evaluation of cases for excess heat utilisation using GIS. Energies 2018;11. https://doi.org/10.3390/en11040762.

[43] Danish Business Authority. Collective heating supply 2017 [in Danish] 2017.

[44] Danish District Heating Association. Dansk Fjernvarmes årsstatistik 2015/2016 [Annual district heating statistics 2015/2016] 2016.

[45] Danish Energy Agency. Technology Data 2020:5–6.

[46] Pieper H, Ommen T, Buhler F, Lava Paaske B, Elmegaard B, Brix Markussen W. Allocation of investment costs for large-scale heat pumps supplying district heating. Energy Procedia 2018;147:358–67. https://doi.org/10.1016/j.egypro.2018.07.104.

[47] Masatin V, Latõšev E, Volkova A. Evaluation Factor for District Heating Network Heat Loss with Respect to Network Geometry. Energy Procedia, vol. 95, Elsevier Ltd; 2016, p. 279–85. https://doi.org/10.1016/j.egypro.2016.09.069.

[48] Bühler F, Petrović S, Karlsson K, Elmegaard B. Industrial excess heat for district heating in Denmark. Appl Energy 2017;205:991–1001. https://doi.org/10.1016/j.apenergy.2017.08.032.

[49] Danish Energy Agency. Energiscenarier frem mod 2020, 2035 og 2050 (Energy scenarios towards 2020, 2035, and 2050) 2014:5. https://doi.org/ISBN: 978-87-93071-64-3.

[50] Bühler F, Müller Holm F, Elmegaard B. Potentials for the electrification of industrial processes in Denmark. 32nd ECOS Conf., Wroclaw, Poland: 2019.

[51] Short TA. Electric Power Distribution Handbook. Boca Raton FL: CRC PRess; 2004.

[52] Lund H, Werner S, Wiltshire R, Svendsen S, Thorsen JE, Hvelplund F, et al. 4th Generation District Heating (4GDH). Energy 2014;68:1–11. https://doi.org/10.1016/j.energy.2014.02.089.

[53] Lund H, Duic N, Østergaard PA, Mathiesen BV. Future district heating systems and technologies: On the role of smart energy systems and 4th generation district heating. Energy 2018;165:614–9. https://doi.org/10.1016/j.energy.2018.09.115.

[54] Lund H, Østergaard PA, Chang M, Werner S, Svendsen S, Sorknæs P, et al. The status of 4th generation district heating: Research and results. Energy 2018;164:147–59. https://doi.org/10.1016/j.energy.2018.08.206.

[55] Energinet DEA and. Technology Data for heating installations. Danish Energy Agency and Energinet; 2016.

Declaration of interests

☒ 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.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: