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Power transformers as excess heat sources

Stefan Petrović [a]***, Fabian Bühler*** [b] ***and Uroš Radoman*** [c]

[a] *Technical University of Denmark, Lyngby, Denmark, stpet@dtu.dk*
[b] *Technical University of Denmark, Lyngby, Denmark, fabuhl@mek.dtu.dk*
[c] *Faculty of Electrical Engineering, University of Belgrade, Belgrade, Serbia, uradoman@etf.rs*

Abstract:

The future district heating production is highly uncertain. Large-scale heat pumps, biomass CHPs and excess heat from industries and data centres are seen as promising sources for district heating. A large fraction of the excess heat could be used at competitive costs, as investment and operating costs are relatively low. However, excess heat often remains unused, mostly due to long-term uncertainties. On the contrary, electricity will be an important part of the future energy system. This will unavoidably lead to the use of power transformers. The thermal losses occurring in power transformers can be used for district heating.

The present paper analyses high voltage power transformers in Denmark as sources for district heating. First, we have employed a thermodynamic model of power transformers to determine the amounts of excess heat they produce based on their load. After that, we have applied thermodynamic analysis of a heat exchanger and a heat pump necessary to extract the excess heat and utilise it for district heating. Finally, we have performed spatial analyses in GIS to link the power transformers with the specific district heating networks. The results show that the average top oil temperature of the transformers is relatively constant at around 30°C over the seasons. From the theoretical maximum excess heat potential for district heating of 0.28 TWh per year, 0.12 TWh or 0.5% of district heat can be supplied to the consumers due to the losses in the networks and large distances between power transformers and district heating areas. Entire potential for heat recovery can be utilised through heat pumps, working with an average COP of 4. Therefore, excess heat from power transformers does not have a potential to be an important source of district heating on the national scale, but could be an option on a local scale.

Keywords:

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

1. Introduction

The First Oil Crisis in 1973 triggered large changes in the Danish energy system. The first measures to fight the crisis were heat savings in buildings, conversion of district heating (DH) boilers to combined heat and power (CHP) plants and switching fuels in DH production from oil to coal and natural gas. Later, expansion of DH grids, production of DH in CHPs and extensive use of wind power for electricity production became Danish trademarks. That resulted in growth of DH for domestic heating from 28% in 1972 to 54% in 2015 and growth of share of CHP plants in the DH production from 28% to 67%. Today's goals in front of the Danish energy system emphasize the role of renewable energy - Denmark is one of the signatures of the Paris Agreement and officially aims to have 100% renewable energy system before 2050. Consecutively, 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. Therefore, the 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 [1–3]. Some of the advantages of the future DH is the possibility to integrate low-temperature heat sources, efficiently transmit and distribute heat and offer energy storage in form of thermal storage. In some of these studies [3–7] it is stated that industrial excess heat brings socio-economic benefits, improves energy system efficiency and reduces primary energy demands. However, the potential role of industrial EH for DH production is not emphasised in these studies; the remaining studies do not analyse EH as an alternative.

Bühler et al. [8,9] 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. The analysis of the future Danish energy system [10] showed that data centres can supply around 20% of the DH production after 2040.

The availability of EH from industries and data centres is largely linked to the increase of electrification of the future energy system. Large electrification of industries will reduce the available high temperature EH, while increased demand imposed by data centres will increase available low-temperature EH. 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 will become even greater than today. The purpose of the transformers is to convert voltage levels between two sections of the network in order to optimize conditions of transmission and consumption. During the process of this conversion, relatively small loss occurs [11], but all of them are converted into heat. The present paper analyses the possibility to use EH from power transformers for DH.

We have found very limited work on the utilisation of EH from power transformers for DH, mostly limited to local studies. In the U.K., the EH from a 240-MVA 400/132-kV transformer is used to heat a school [12]. In Austria, another project was done to utilise EH from the transformer for DH [13]. While in [12] the heat is directly recovered from the thermal oil, the Austrian-based system uses the heat rejected to the air from the transformer's radiator. It was argued that such a system is easier to implement.

The novelty of the present work lies in:

- Geographic representation of EH from power transformers relative to DH areas.
- The methodology for thermodynamic analysis of EH from power transformers for DH
- Identifying the potential for the utilisation of EH for DH purposes in Denmark

The present paper analyses the possibility to use EH from power transformers for DH. This analysis was based on spatial and thermodynamic considerations for using the EH for DH. Furthermore, the EH from power transformers was determined based on their load profile and type. In the following, the data and methods used in this analysis are introduced in Section 2, followed by the results in Section 3. After that, the results are discussed in Section 4. Finally, the conclusions are drawn in Section 5.

2. Materials and Methods

2.1. Power transformer thermal model

While in operation, power transformers generate heat due to the power losses. A part of these losses is generated in the core (core losses, or no-load losses). The rest 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). Figure 1 shows a schematic drawing of a transformer. The rated power of power transformers is practically determined by the maximum power at which certain temperatures (winding hot-spot and top oil temperature) are exceeding maximum allowed values. These values are usually determined either by the standards (e.g. IEC standard [14]) or, in some cases, by more specific user demands. However, due to the introduction of the safety margins in the design process, a majority of the power transformers are oversized [15], hence the characteristic temperatures at the rated loading conditions are lower than the allowed ones.

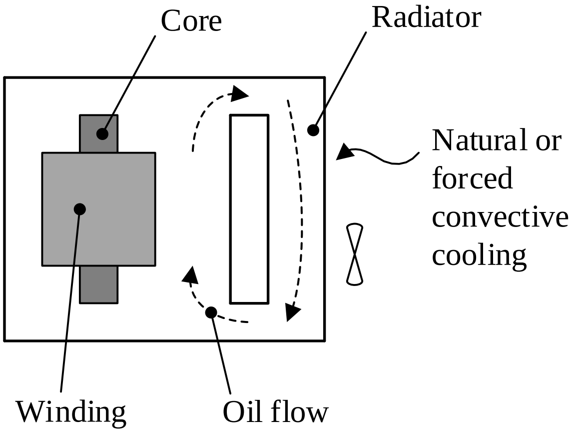

Figure 1. Simplified cooling scheme of the transformer.

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

Publically available data about transmission power transformers in the Danish power grid [16] contain voltage levels, rated power, and split losses (load and no-load). The transformers with missing values were represented by an “average” transformer. To create the "average" transformer, the transformers were distributed in 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). Each “average” transformer was described by the ratio of core losses to rated load. All transformers were considered to be oil-natural air-natural cooled (ONAN) with radiators.

The present study required the 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 [14]:

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

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),

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).

No-load losses are constant over time, while load losses are dependent on the square of the load.

The oversizing of transformer was not considered in this case.

For the calculation of the bottom oil temperature, rated top-to-bottom oil gradient value was assumed to be 22 K [14]. 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 power transformers in the present study were based on averagely loaded power transformer operated by Energinet (Danish TSO). The hourly loads of Energinet's averagely loaded 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 load, and any load oscillation (both daily and periodically during the season) causes the load losses to be higher than in case of constant load.

2.2. Excess heat recovery from transformers

The radiators used in existing transformers to cool the system can be replaced by heat exchangers coupled to the DH network or coupled with a heat pump. Alternatively, the radiators could be kept and an air-to-water heat exchanger used to recover the EH.

As stated in Section 2.1., all the analysed transformers are considered ON ("oil natural") cooled. That means that a pump is not present in the oil circuit. The hypothetical heat exchanger was introduced in outer cooling circuit of the power transformer instead of transformer's radiators. The heat exchanger was assumed not to affect internal distribution of oil flow, and to have the same cooling power as the existing radiators do. In reality, compact heat exchangers tend to be used along with the oil pumps due to the significant pressure drop. In that case the transformer becomes OF ("oil forced") cooled (see Figure 2) assuming construction for directing oil inside the tank does not exist, otherwise, transformer is OD ("oil directed") cooled. For non-ON cooling, the top to bottom oil gradient is usually significantly lower than for ON cooling.

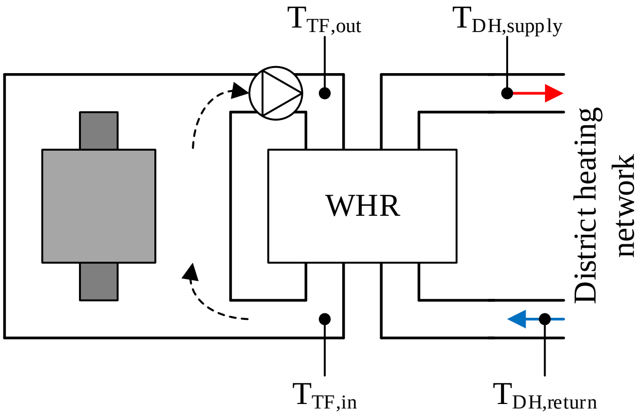

Figure 2. Schematic drawing of excess heat utilisation from the transformer.

2.3. Thermodynamic analysis

The temperature $T_{TF,out}$ and $T_{TF,in}$ at the transformer site and the temperatures $T_{DH,supply}$ and $T_{DH,return}$ on the DH site will determine if a heat pump, a direct heat exchange or a combination of both is required. Furthermore, a minimum temperature difference in the heat exchangers has to be respected which magnitude is typically defined based on economic considerations.

The direct utilisation of the EH is typically possible when the top oil temperature $T_{TF,out}$ is above the supply temperature of the district heating area $T_{DH,supply}$. As the bottom oil temperature is fixed to obtain the necessary cooling effect, a complete direct heat transfer is only possible if the DH return temperature is by the minimum temperature difference below the required bottom oil temperature. If no complete direct heat transfer is possible, a heat pump will be required to provide all the temperature lift or part of the heating or cooling, as shown in Figure 3. This can be beneficial as shown in [17] and [18].

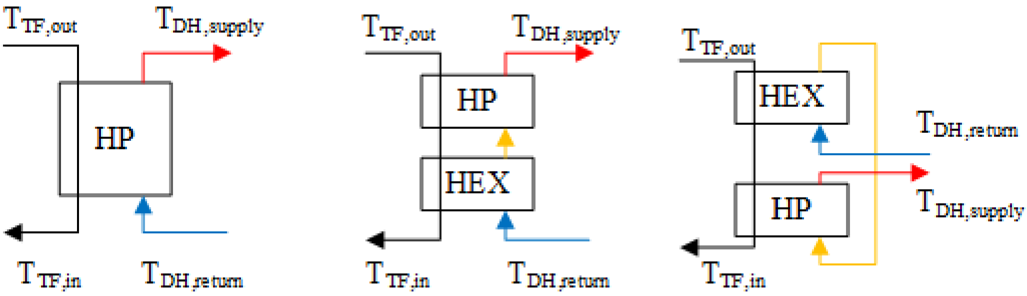

Figure 3. Configurations for the possible waste heat recovery systems of the transformer.

The heat pump was modelled using the Lorenz cycle and was corrected by the Lorenz efficiency η_{Lor} to obtain the real Coefficient of Performance COP. The logarithmic mean temperature of the heat source and heat sink were used to find the theoretical COP. The approach is explained in details in [19]. In this work, a Lorenz efficiency of 0.45 was assumed.

2.4. Spatial analysis

The present paper analysed the amount of EH from high voltage power transformers that can be utilised for DH. This section describes two constraining factors for utilisation of EH for DH:

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

The present methodology was inspired by the methodology applied in [8] for the case of industrial EH; the differences between the methodologies will be highlighted in the following. GIS tools incorporated in ArcGIS 10.6 were applied to find the total heating demand which can be covered by EH from high voltage power transformers. The applied procedure was as follows:

1. High voltage power transformers [16] and official DH areas [20] were projected on top of a background map in ArcGIS 10.6. As in [8], annual district heating statistics published by the Danish District Heating Association [21] 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 [8]. The difference from [8] 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 EH from high voltage power transformers can be greater than existing DH supply.
3. As in [8], for each power transformer, the nearest DH area was identified. It was assumed that the EH is delivered to the nearest DH area.

4. If a high voltage power transformer was located outside of a DH area, the cut-off distance was identified, i.e. the maximum allowed distance from EH source to the nearest DH area. As in [8], the maximum distance was calculated from maximum connection costs per MWh of heat delivered and the costs for transmission pipes as a function of the capacity. The power transformers located within existing DH areas were assumed to be always connectible. The majority (around 85%) of the power transformers had to be within a close distance (between 400 and 500 m) to be considered. For some of the largest EH emitters, larger distances of above 1000 m were feasible.
5. If a power transformer could be connected to a DH area, the deliverable EH amount was reduced for transmission and distribution losses. If no DH area fulfilled the criteria from point 4, the EH was not considered.
6. For each DH area, the heating demand of buildings supplied by DH is summarized. After that, this quantity is compared to the heating demand, which can be supplied from EH from power transformers. If the heating demand of buildings supplied by DH is greater, the entire EH potential could be utilised for DH. Otherwise, only a part of EH potential can be utilised.

3. Results

First, the results of the geographical mapping of excess heat sources are shown, followed by the potential for using these sources for DH.

The analysis of the transformers 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 heat pump will be necessary to exploit the heat in all cases.

3.1. Excess heat from power transformers

The spatial distribution of EH on a national level is shown in Figure 4. The distribution of EH from thermal processes is spatially referenced to the 5 km by 5 km Danish square grid. The EH from power transformers is not uniformly distributed all over the country, with a higher density of transformers' EH around the main cities in Denmark. From the regional perspective, the largest amount of EH, namely around 40% is located in Decentral areas of West Denmark. The rest of EH is almost equally split between Central and Decentral areas of East Denmark and Central areas of west Denmark, namely between 45 and 48 GWh in each of the regions. The Central DH areas have higher heating demands, installed capacities and transmission efficiencies compared to the Decentral DH areas. Two transformer stations are further located on offshore wind parks in the Baltic Sea.

The total EH from power transformers is 229 GWh per year. The majority of EH 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 EH comes from transformers on 110 kV and 232 kV voltage levels.

In 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.

3.2. Excess heat from power transformers for district heating

The potentials for using EH for DH are presented in Figure 5. 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. The electricity needed to run the heat pumps is presented in Figure 6.

The recovery of the accessible EH is reduced by considering network losses and eliminating excess heat sources, which are outside of the cut-off distance. As shown in Figure 5, the losses in DH networks reduce the heat, which can be delivered to DH consumers for 0.06 TWh to 0.22 TWh.

The share of heat which cannot be economically transmitted to DH consumers, due to large distances reduces the annual potential by 0.09 TWh (to 0.12 TWh, third bar in Figure 5). As in [8], to obtain the real potential, we have checked for the EH which cannot be used due to a lack of demand. In the present analysis, lack of demand is not a constraining factor. Therefore, third and fourth bar in Figure 5 are equal and they amount to 0.12 TWh. This means that the DH demand that can be covered from EH from power transformers 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 heat pumps would require 31 GWh 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 EH from power transformers, is shown on the map in Figure 7. Large quantities of EH are located in the vicinity of large cities, such as Copenhagen and Aalborg. However, these cities have large DH demands and resulting share of DH demand, which can be replaced by EH from power transformers, 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 EH from power transformers.

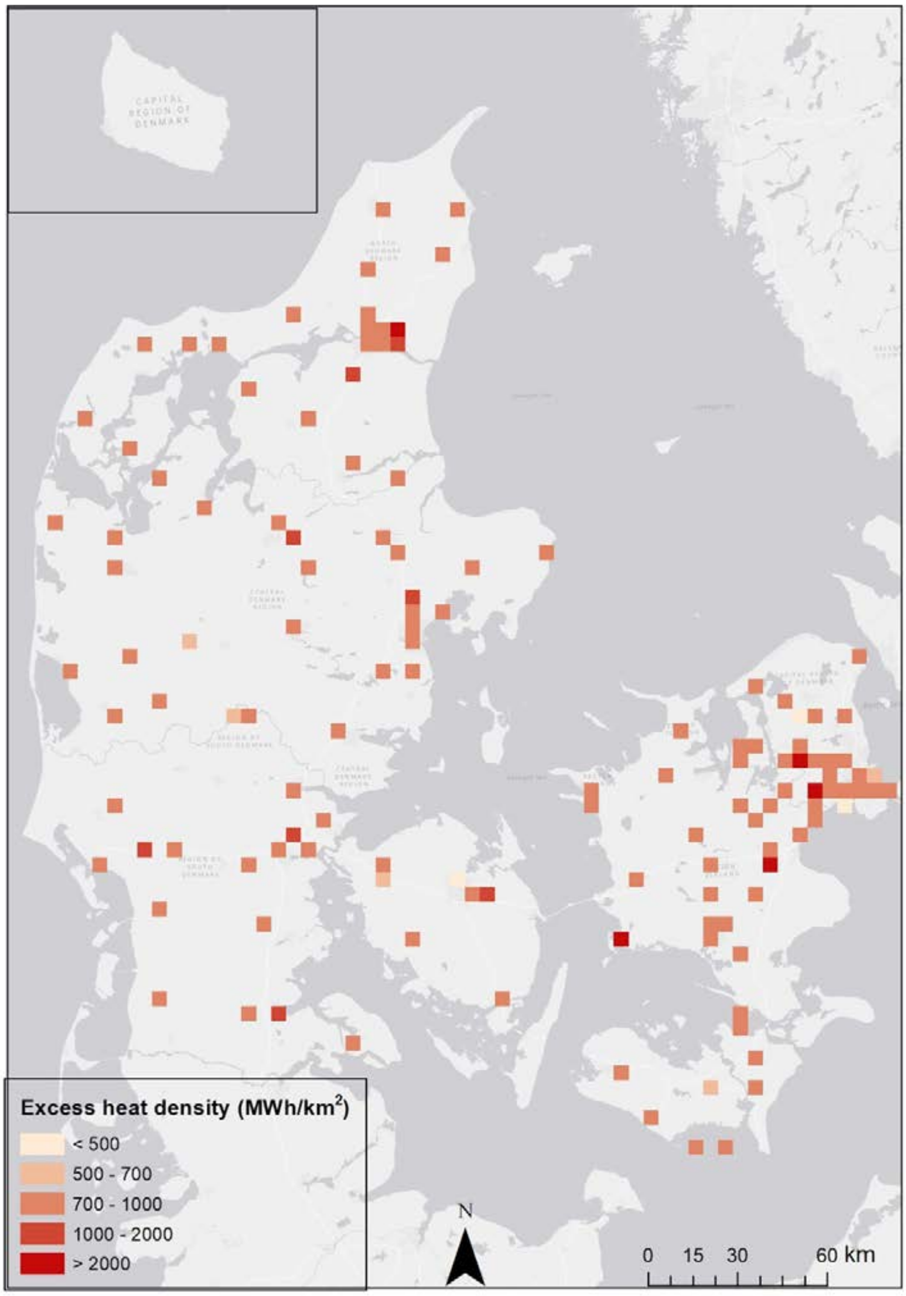

Figure 4. Spatial distribution of excess heat from transformers in Denmark on the 5 km by 5 km square grid.

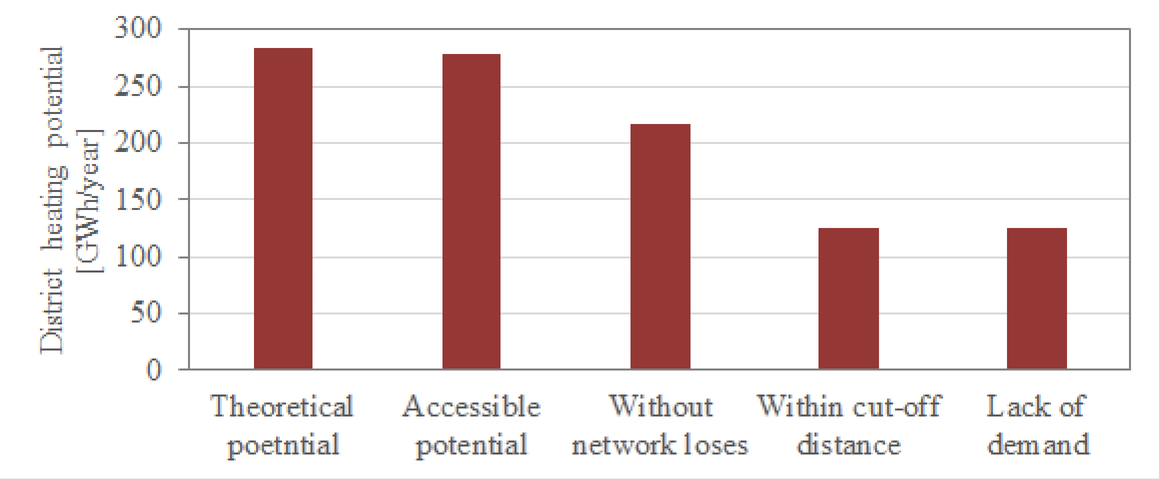

Figure 5. District heating potential of excess heat from transformers.

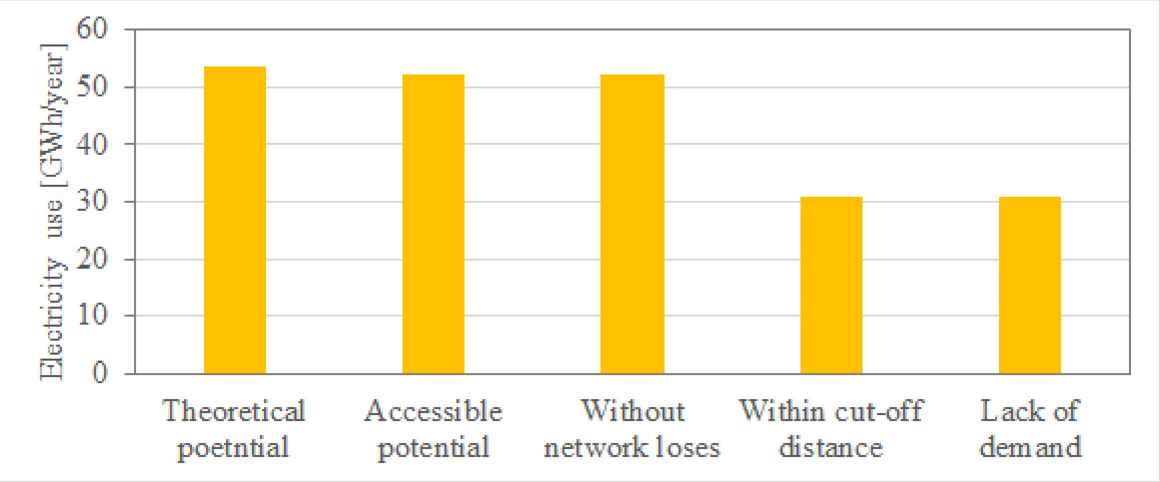

Figure 6. Electricity use for heat pumps.

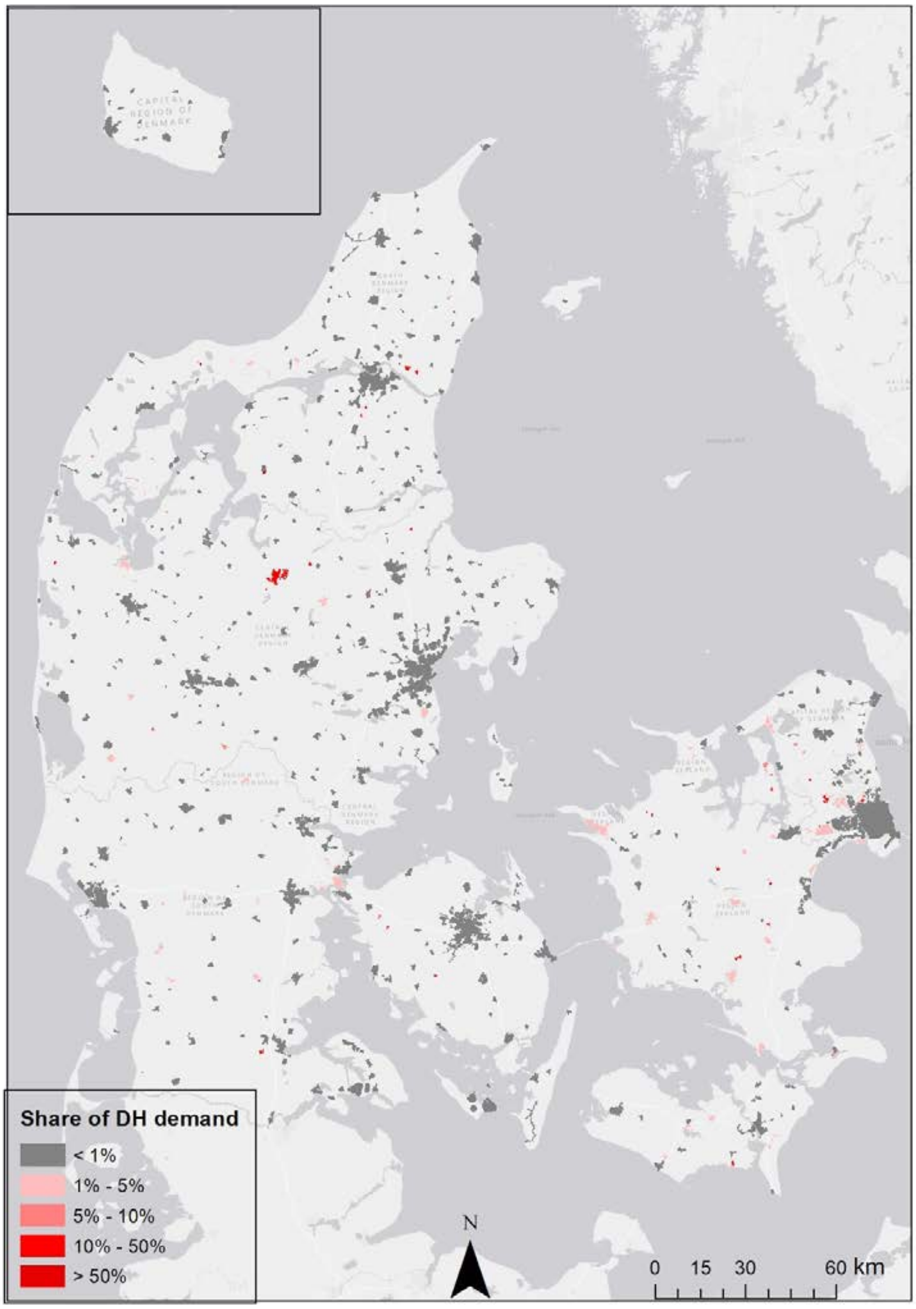

Figure 7. Substitution potential of district heat delivered from the transformers excess heat.

4. Discussion

The systematic approach developed in the present work could also be applicable and beneficial to other regions, even though the data might not be available with such high level of geographical details as in Denmark. The calculated potential for supplying existing DH demand by EH from power transformers should not be discouraging for other regions. Namely, Denmark is characterized by moderate population and heat densities, high DH demands, moderate number of large electricity consumers and moderate loads of power transformers. In regions with higher heat densities, larger number of transformers with higher average loads, the EH from power transformers could supply a much larger share of DH demand.

Even though the present analysis showed that EH from power transformers could not supply a significant share of DH demand on the national scale, they can still be important on the local level.

Large heat consumers such as hospitals, shopping centres and industrial facilities require heat during the whole year. In case a power transformer is located nearby, EH from the power transformer could be a valid option for heat supply. The potential matches will be explored within future work.

The analysis showed that there is an overall potential for utilising EH from transformers for DH. The exploitation of this EH may be connected with 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 [13]. As an alternative, the heat from the indoor air of the transformer house could be used through an air-to-water heat pump. While this system would not require modifications of the transformer, the system's efficiency is expected to be considerably lower.

The installation of the heat pump will further require floor space close to the transformer building. For transformers 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 transformer could be reduced to reach higher top oil temperatures. This would lead to a better performance of the heat pump (increase in COP) but at the same time, the lifetime of the power transformer would be reduced. An analysis of the optimal top oil temperatures with respect to lifetime decrease and lifetime expectations of the operator is thus required.

Another important topic is that the power transformers in Danish power grid are loaded relatively low. Averaged on seasonal level, the load is ca. 25%-30%, causing low load power losses. Although some authors suggest load factor to be targeted at 40%-60% [22], this value differs significantly worldwide, and it usually depends more on the exploitation strategy than on the practical technical aspects.

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 power transformers, 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%.

5. Conclusion

The present paper analyses the possibility to utilise EH from power transformers for DH in Denmark. First, we have determined the amounts of EH produced by power transformers in each of the seasons. After that we have applied a thermodynamic analysis of a heat exchanger and a heat pump necessary to extract the EH and utilise it for DH. Finally, we have geographically represented power transformers and DH areas and performed spatial analyses in GIS to link the power transformers with the specific DH networks. As a result, the present analysis results in a realistic potential for utilisation of EH from power transformers for DH.

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

The EH from power transformers 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. Entire potential for heat recovery can be utilised through heat pumps. The heat pumps would operate at an average COP of 4.

The present analysis showed that EH from power transformers can not be an important source of DH on the national scale. However, they can still be important 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 EH from power transformers.

Acknowledgments

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