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Mapping of low temperature heat sources in Denmark

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Abstract:

Low temperature heat sources are available in many applications, ranging from waste heat from industrial processes and buildings to geothermal and solar heat sources. Technical advancements, such as heat pumps with novel cycle design and multi-component working fluids, make the utilisation of many of those heat sources feasible. In this work a mapping of those heat sources is performed to gain an overview of the potential amount of waste heat and natural heat sources in Denmark. The energy potentials are mapped together with the temperature ranges at which the heat is available and the exergy content of the heat. The mapping is based on data and literature primarily published by Statistics Denmark and the Danish Energy Agency, as well as interviews with specialists and engineering estimates. The results indicate that up to 13 % of the energy input to the analysed sectors is available as waste heat. The total accessible waste heat potential is found to be approximately 266 PJ per year with 58 % of it below 100 °C. In the natural heat category, temperatures below 20 °C originate from ambient air, sea water and shallow geothermal energy, and temperatures up to 100 °C are found for solar and deep geothermal energy. The theoretical solar thermal potential alone would be above 500 PJ per year. For the development of advanced thermodynamic cycles for the integration of heat sources in the Danish energy system, several areas of interest are determined. In the maritime transport sector a high potential is found in exhaust gases, where also high temperatures are present. Also the industry sector has a large waste heat recovery potential from refrigeration and cooling processes, however at much lower temperatures.

Keywords:

Waste heat potential, Low temperature heat, Waste heat recovery, Energy mapping, Exergy mapping.

1. Introduction

In the thrive to reduce the energy consumption in Denmark and reach the 2020 goal of a 4 % gross energy consumption reduction with 2006 as a baseline [1], new sources for reductions and technologies have to be found.

Low temperature heat sources are available in many applications, ranging from waste heat from industrial processes and buildings to geothermal and solar heat sources. Technical advancements, such as heat pumps with novel cycle design and multi-component working fluids, make the utilisation of many of those heat sources feasible.

A number of studies have been performed in order to analyse the overall energy and exergy utilisation of countries [2, 3]. They focus on the overall efficiency of the sectors and the efficiency with which the energy inputs are used. With respect to waste heat, a sectorial analysis was conducted by Bonilla et al. [4] for the Basque country and by Maxime and Sapora [5] for France. Both studies show very detailed where waste heat potentials can be found and at what temperature they occur, however they focus solely on the industry sector. For Denmark an investigation [6] was undertaken to show the waste heat and utilisation potential for several industrial sectors.

This study presents an overview of the potential amount of waste heat and natural heat sources in Denmark. The energy potentials are mapped together with the temperature ranges at which the heat is available and the exergy content of the heat. Business sectors as well as other relevant heat energy sources are assessed. The mapping is based on data and literature primarily published by Statistics Denmark [7] and the Danish Energy Agency [8], as well as interviews with specialists and engineering estimates. The results will provide a basis for subsequent energy efficiency and recovery activities in Denmark.

This research is part of a larger research project [9] which aims to devise innovative solutions for utilising low-temperature heat sources at performances superior to state-of-the-art. The overall project goal is to derive solutions that result in the saving of 15% of the energy consumption in the Danish industry and shipping sector. The project results will provide the scientific basis needed for implementation of technologies utilising low-temperature energy sources both for power production and for heat pumps in Denmark. This will contribute to the development of the future society with no use of fossil fuels and with high shares of intermittent, renewable energy sources with electricity being the main energy carrier.

2. Methods

The overall methodology for the assessment of the waste heat potential and its according temperature levels is shown in Fig. 1. The assessment is based on the energy input to the different sectors which is well documented in the case of Denmark by Statistics Denmark [7]. For all sectors relevant processes are determined and for each sector the energy lost as heat, as well as the useful share of this waste heat is estimated. Then the temperature of the useful waste heat is assessed. In the evaluation of the temperatures from the individual processes, it is assumed that the accessible temperature is the same as that of the process from which the waste heat originates. This means that a process stream is assumed to be available for heat recovery before it enters a cooling tower.

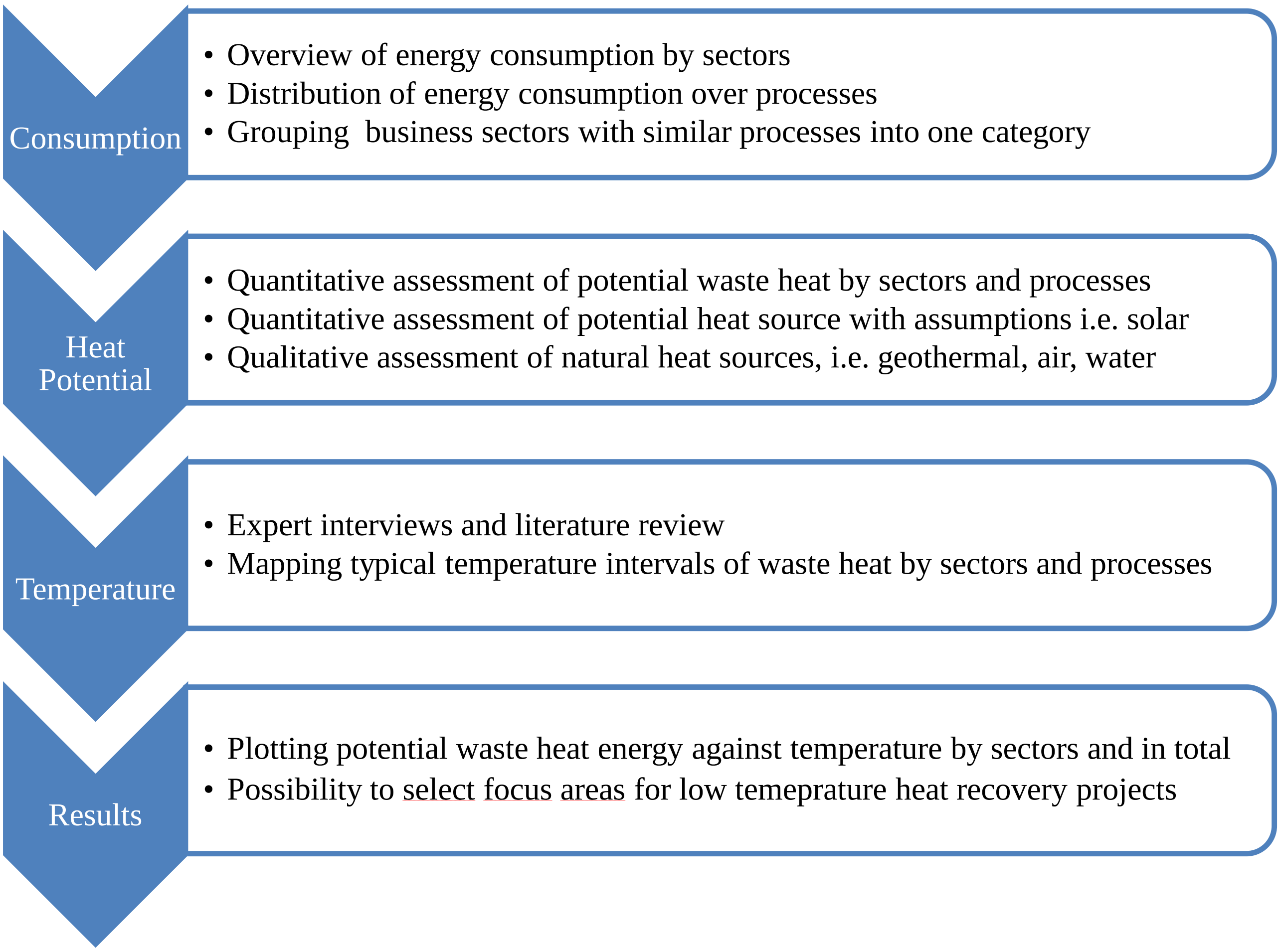

Fig. 1. Overall methodology for identification of waste heat and potential heat energy.

The evaluation of the accessible waste heat potential and the related temperatures are, for a majority of the cases, based on practical experience from the present status of the unit of operations in terms of accessibility and temperatures. Furthermore theoretical considerations and inputs from industrial partners, such as AP Møller Mærsk [10], MAN Diesel & Turbo [11] and Danish Technological Institute [12], are used to refine the evaluation and incorporate more units of operation.

Besides the energy content and temperature, the medium of the heat sources is given. The heating medium differs from one process to another, and therefore the most common ones are shown.

In the case of solar thermal and geothermal heat sources, a review of existing literature on their potential in Denmark is carried out in order to assess the suitable areas for utilising solar thermal and geothermal energy. The potential available solar thermal energy is calculated based on solar thermal collector efficiencies for common collector types and suitable areas available in Denmark, where collectors potentially can be installed.

2.1. Sectors and Categories

The main sectors are defined according to the classifications of Statistics Denmark [13], with the exception of trade and transport which are separated into two sectors. In addition, geothermal, solar thermal, air and water are included to obtain an overview of potential natural heat sources.

The given sectors are merged into eight categories, based on similarities of the energy consuming processes within the sectors. The subsequent categories are Industry, Buildings, Utility Services, Construction, Transport incl. maritime and the three natural categories, solar, geothermal and air/water.

The **industry** category consists of manufacturing, agriculture, forestry, fishing, trade and mining. In the **building** category several sectors are merged as they have similar energy consumption patterns. This includes, amongst others the sectors households, information and communication, financial and insurance and public administration. Within the **utility services** the supply of electricity, natural gas, district heating and water are included. For each of these services the relevant processes are found. For example the supply of electricity is divided into steam power plants, gas turbines, combined cycles and combustion engines.

The **construction** category uses mainly thermal energy for heating and drying [14]. However the waste heat is primarily generated in temporary installations on construction sites. It is therefore difficult to control the flow of waste heat and to distinguish between energy consumption on fixed and temporary installations. For these reasons and due to a lack of data in this category, this is not further evaluated. The **transport** category summarises activities related to passenger and freight transport and associated businesses and facilities. In this category the main focus is on road transport by truck and maritime shipping.

2.2. Exergy

In addition to the energy content and temperature of the waste heat, exergy is also used as an indicator to quantify and assess the value of the heat sources. Exergy is defined as the maximum work, which can be performed by a system by reaching equilibrium with its surroundings. Exergy is destroyed due to irreversibilities and is only conserved in ideal processes, in contrary to energy [15]. In this analysis exergy is a particular interesting indicator as it quantifies the usefulness of the low temperature heat, mainly for power production, but also for heat pumps which utilise two exergy sources – power and low temperature heat. The exergy calculations are simplified and the following assumptions are made.

Only physical exergy, at an atmospheric pressure, is used in this work. All other exergy contributions, such as chemical, kinetic and potential exergy, are neglected. The temperature of the media is taken as the average of the estimated temperature interval. The reference state is defined at atmospheric pressure p_0 and temperature T_0 = 283 K. Furthermore it is assumed that liquids and gases can be cooled down in practice to 10 K and 30 K respectively, above the reference temperature T_0. All liquids are treated as water and all gases are treated as air.

The specific physical exergy e^{PH} is then calculated using (1) with the specific enthalpy *h* and entropy *s*,

$$e^{PH} = (h - h_0) - T_0(s - s_0), \qquad (1)$$

which for the given assumptions may be expressed as

$$e^{PH} = c_p(T - T_0) - c_p T_0 \ln\frac{T}{T_0}, \qquad (2)$$

This simplified approach for the determination of the exergy content of the heat sources was chosen as the overall assessment is to give an indication of the magnitude of the overall waste heat rather than precise results for a single process.

3. Results

3.1. Mapping of heat sources

In the following the waste heat energy, exergy potential and temperature ranges for the relevant processes in each category are presented. Additionally the main sources of data and the assumptions made are presented and discussed.

3.2. Industry

The mapping of the waste heat from the industry sector is primarily based on reports from the Danish Energy Agency (Energistyrelsen) [8, 16] and expert consultations. In this category secondary heat, from e.g. ventilation, lighting, and vehicle transport are neglected, as they only provide a small quantity of the total energy input to this sector.

As shown in Fig. 2 the majority of the accessible waste heat is available from distillation and refrigeration operations. Distillation processes are primarily found in the refinery sector, where the heat is available in a temperature interval of 40 °C to 60 °C. Despite the comparably low amount of waste heat from boilers, furnaces and melting processes, the high temperatures make these processes interesting to focus on. This is also expressed in the available exergy, which has a proportional high share of the energy content.

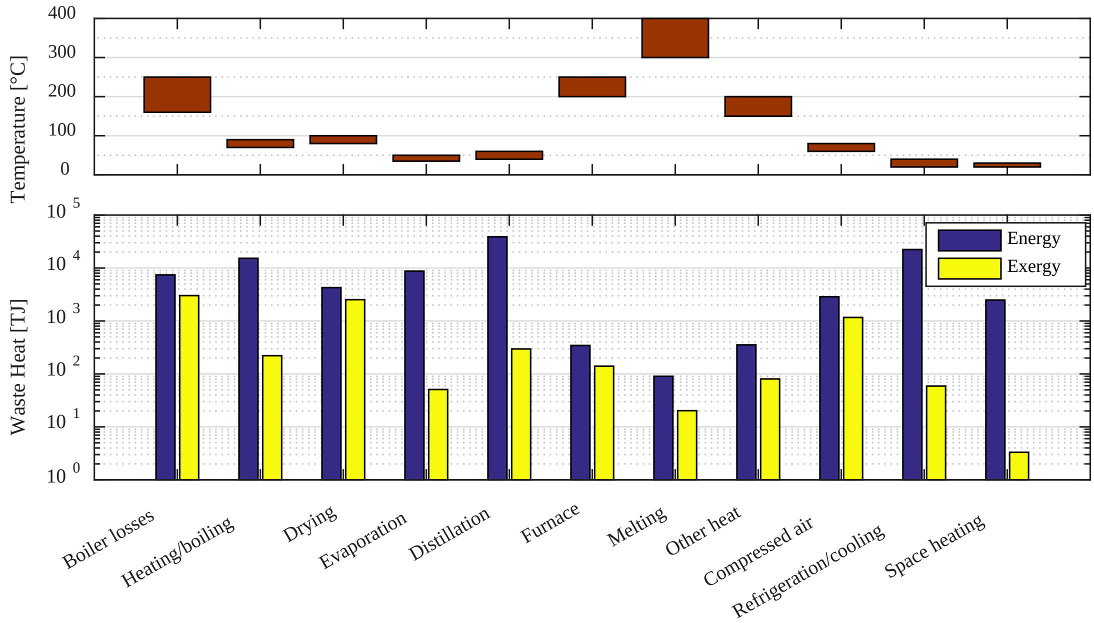

Fig. 2. Waste heat and temperature intervals for the different industrial processes.

3.3. Buildings

The waste heat in the building category is found as the heat loss from the boilers for hot water and space heating, refrigeration/cooling and IT, electronics and electrical. Though space heating itself can account for up to 70 % of the fuel and 80 % of the district heat consumption [17], it is evaluated that there is no accessible waste heat potential. This is based on the assumption that all new buildings are equipped with heat recovery systems and a majority of aged buildings are naturally ventilated.

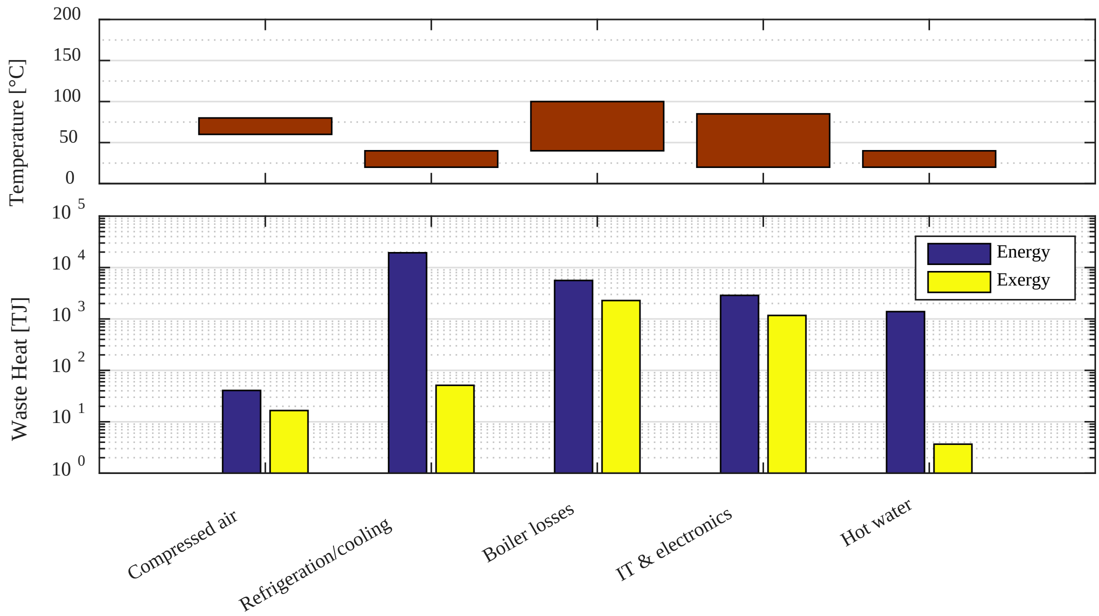

Fig. 3. Waste heat and temperature intervals for the different processes in the building sector.

Figure 3 shows the results of the waste heat mapping for the building category. In this category all temperatures are below 100 °C. The highest potential originates from refrigeration and cooling, where almost 20 PJ is available. However the exergy content is relatively small due to the low temperatures in this process.

3.4. Utility Services

Within the utility services the accessible waste heat for each service is analysed based on the production units [16]. The supply of gas and fresh water is neglected as there are no significant heat sources in their supply chain. For the generation of electricity, steam and hot water, the majority of the waste heat is found in flue gases and water in condensers, for which the temperature and still usable waste heat amount is found [18, 19]. Another important sector in this category is the treatment of waste water [20], where waste heat is available from the treated water [21], biogas production and drying and disposal of sludge.

The highest potential of waste heat in this sector originates from steam power plants, which are a common process within the Danish utility system. The low temperature of the condensate results in a small exergy content, in contrary to the flue gases where temperatures of up to 180 °C are found. In large power plants it is practical to keep the stack temperature at around 180 °C in order to avoid acid formation and to ensure proper dispersion of the flue gases from the stack to the atmosphere [18]. In practise it can therefore be challenging to utilise this waste heat.

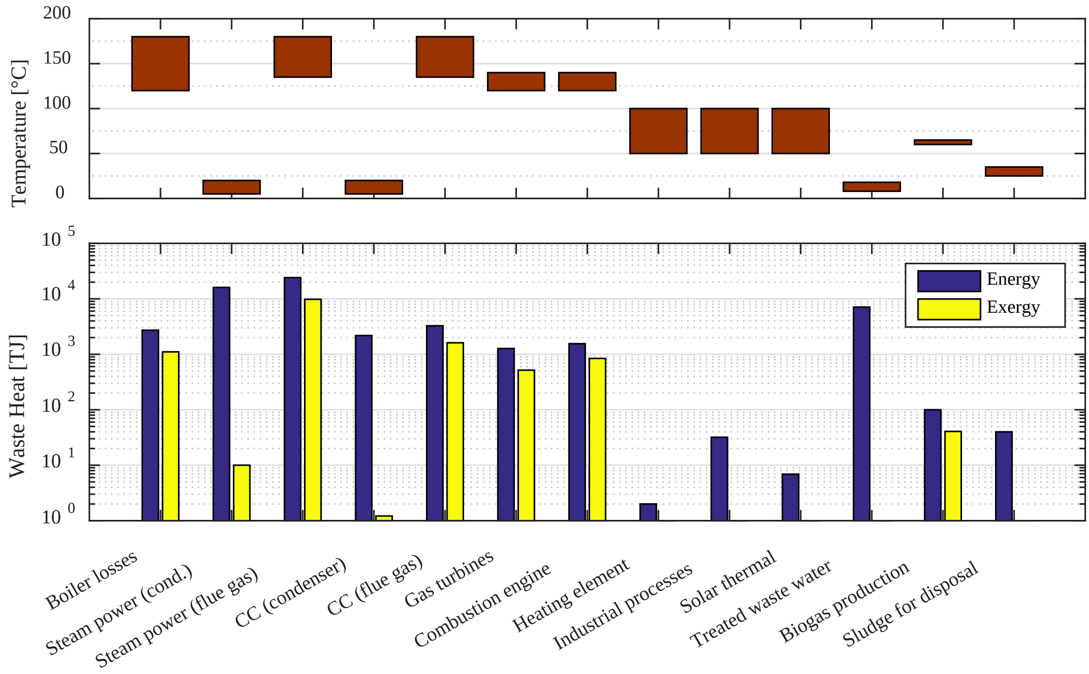

Fig. 4. Waste heat and temperature intervals for the different processes in the utility services.

3.5. Transport incl. maritime

In this analysis the focus in the transport sector lies on shipping and road transport by truck. For both transport modes the main processes, where waste heat is found, are charge air, engine cooling and energy in the exhaust gases. In case of maritime transport the amount of useable waste heat and temperature ranges are based on information from MAN Diesel & Turbo [10] and Maersk [11]. The analysis of road transportation is based on transportation by truck where the fuel distribution [22] and temperatures [23] are taken into account.

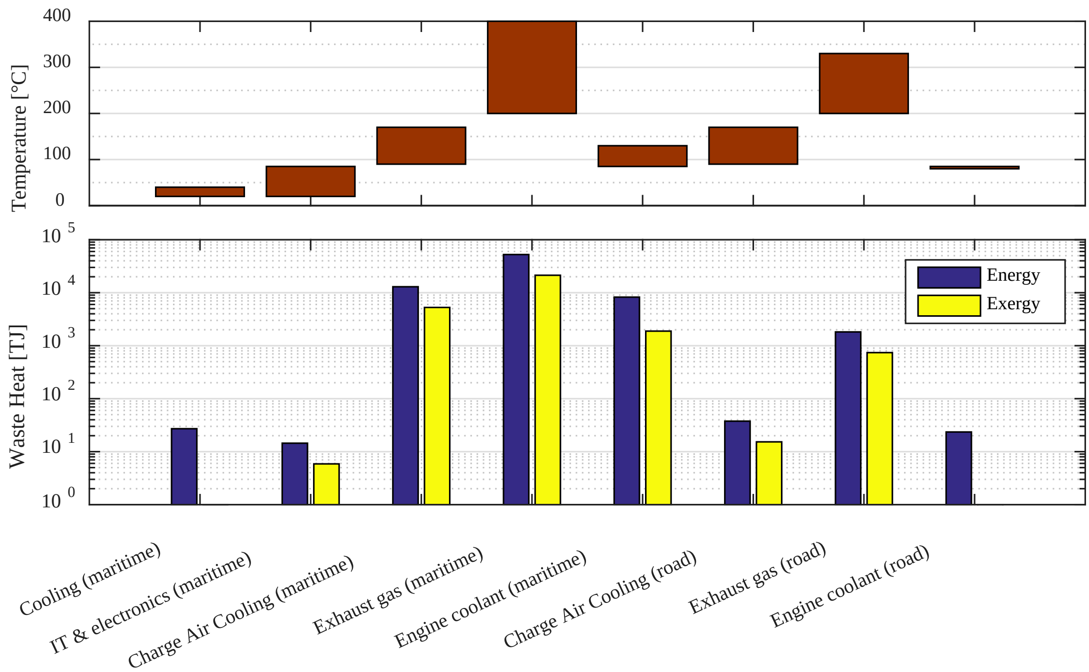

Fig. 5. Waste heat and temperature intervals for the different processes in the transport category.

The transport sector has a large potential of waste heat. As can be seen in Fig. 5 the highest potential is found in the exhaust gases of the shipping sector, where also high temperatures of up to 400 °C are present. Also for road transport by truck a large potential with high temperatures is available in the exhaust gases. The influence of these high temperatures on the exergy content is also noticeable. The charge air cooling has a larger waste heat potential and a higher temperature range than the engine cooling. However the medium of engine cooling is water instead of gases, which could be easier exploited in limited space.

3.6. Natural Sources

This section presents the main natural heat sources found in Denmark, namely geothermal, solar thermal and air and water.

3.6.1. Solar thermal

The assessment of the solar thermal potential in Denmark is based on suitable areas and technologies to harvest the solar irradiance. Areas suitable for the installation of solar thermal collectors are divided into residential, agricultural, industrial, commercial and public. The suitable area for the first four sections is only for installation on buildings [24], where the suitable area is defined as an area with a minimum annual irradiance of 80 % of the country's maximum. The public sector is assumed to primarily consist of open land, where solar installations could provide district heating [25].

For each sector an applicable solar collector type is selected based on the required temperature range [26]. The conversion efficiency of the solar collector is then found as a function of the collector type and temperature [27]. For residential and public installation standard flat plate collectors were chosen and evacuated tube collectors for agricultural, industrial and commercial installations. The achievable temperatures depend to a high degree on the collector technologies, which is in practice decided by economic factors and application area. Assuming an average ambient temperature of 15 °C, a solar collector efficiency of 28 % is retrieved for evacuated tube collectors, delivering heat at 100 °C. For flat plate collectors, an efficiency of up to 40 % at a delivery temperature of 70 °C is used.

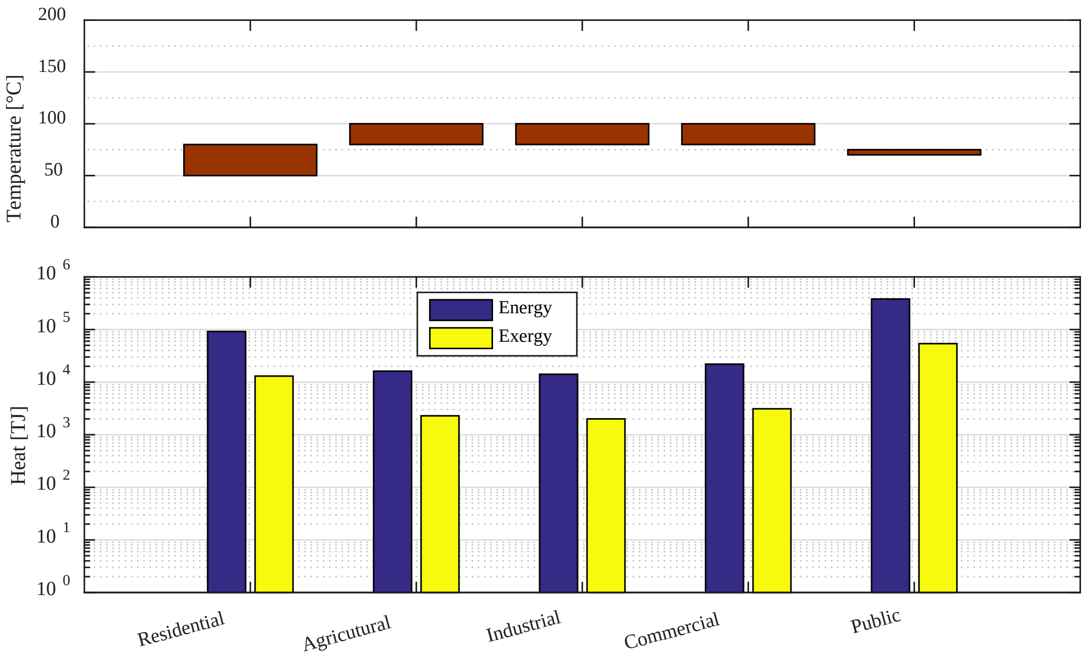

Fig. 6. Solar thermal heat potential and temperature intervals for different application areas.

The evaluation shows that the solar thermal potential is by far the highest in the public sector, due to the large areas found there. Because temperatures of below 75 °C were assumed for this sector, the largest solar thermal potential lies below this temperature. However temperatures of up to 100 °C are possible by using, for example, evacuated tube collectors, but this reduces the accessible amount of heat.

3.6.2. Air and Water

Air and water is an abundant source of low temperature heat and its exploitation is only limited by technical and economic constraints. Therefore, as for geothermal energy, only a discussion of the possible temperatures is undertaken.

The monthly average temperature in Denmark varies from 1.2 °C in February to 17.4 °C in July, with average variations between day and night from 4.12 °C to 9.2 °C [28].

The temperature potential of water focuses on the sea, where the temperature at the coast of Copenhagen is found to be representative for the rest of the country with a 2 °C difference at some areas. The temperature of the water is between 0 °C and 17 °C throughout the year with the highest potential in July and August [29].

By definition the exergy content of the ambient source with the lowest temperature at the given time has zero exergy content.

3.6.3. Geothermal

In the case of geothermal energy a number of studies have been undertaken in Denmark. However these studies were performed locally and thus an overview of the total Danish potential cannot be given. For this reason a literature study was undertaken to give an indication of the geothermal heat and its possible temperatures, without including specific values for the heat amounts in the final results.

The geothermal temperature can vary between 8 °C and 90 °C, depending on a number of local conditions. For deep geothermal drillings a temperature gradient of 30 °C per 1000 m from the surface was found by Mathiesen et al. [30]. However the investigated reservoirs showed a large local variations and a maximum drilling depth of 3 km.

Based on the summation of geothermal resources over the Danish area, heat potentials as high as 20 GJ/m² can be found with strong local variations. The summarised heat mapping of resources is based on several sub maps of different geological formations [31].

3.7. Overall Mapping

The accumulated results of the heat mapping for Denmark are presented in Figs 7 and 9 for energy and Figs 8 and 10 for exergy. When solar thermal is included a heat energy potential of 800 PJ is found, of which 86 % is available below 100 °C. Considering only the business sectors in Denmark the total waste heat potential is 266 PJ. Here, only 58 % of the heat is found at temperatures below 100 °C.

In terms of exergy a total potential of 128 PJ is found of which 74 PJ originate from solar thermal. In contrast to energy, only 17 % of the exergy, when excluding solar thermal, is available at temperatures below 100 °C. With solar thermal energy the exergy potential below 100 °C is 65 %. A large exergy potential lies further at temperatures between 130 °C and 175 °C, where 25 % of the total exergy is allocated, originating primarily from the utility and transport sector.

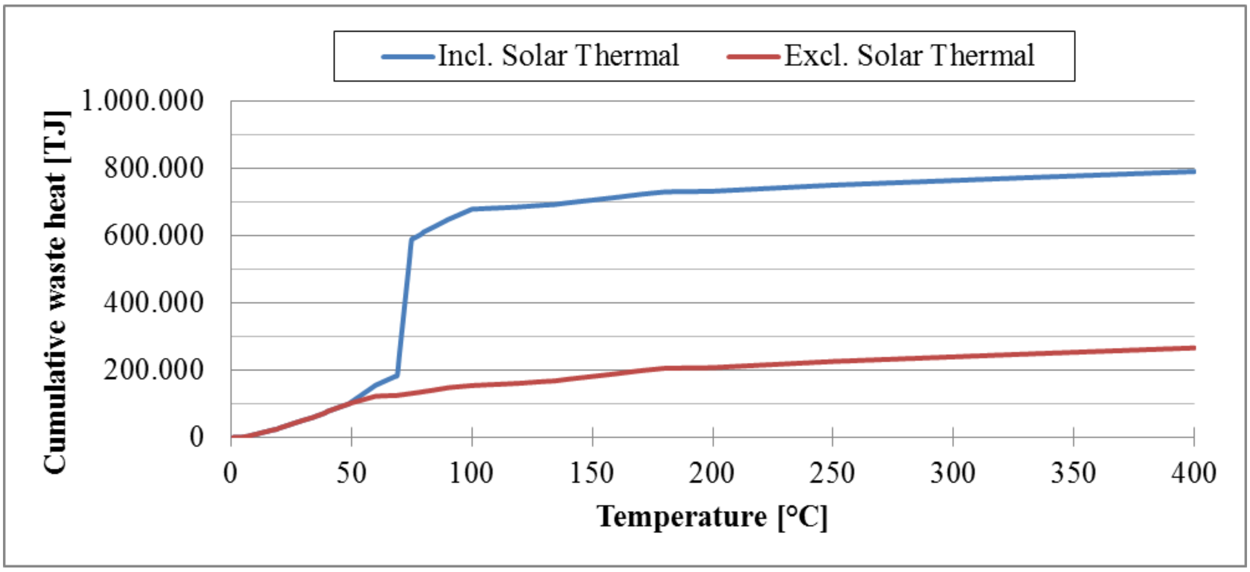

Fig. 7. Cumulative waste heat of the processes with and without solar thermal energy.

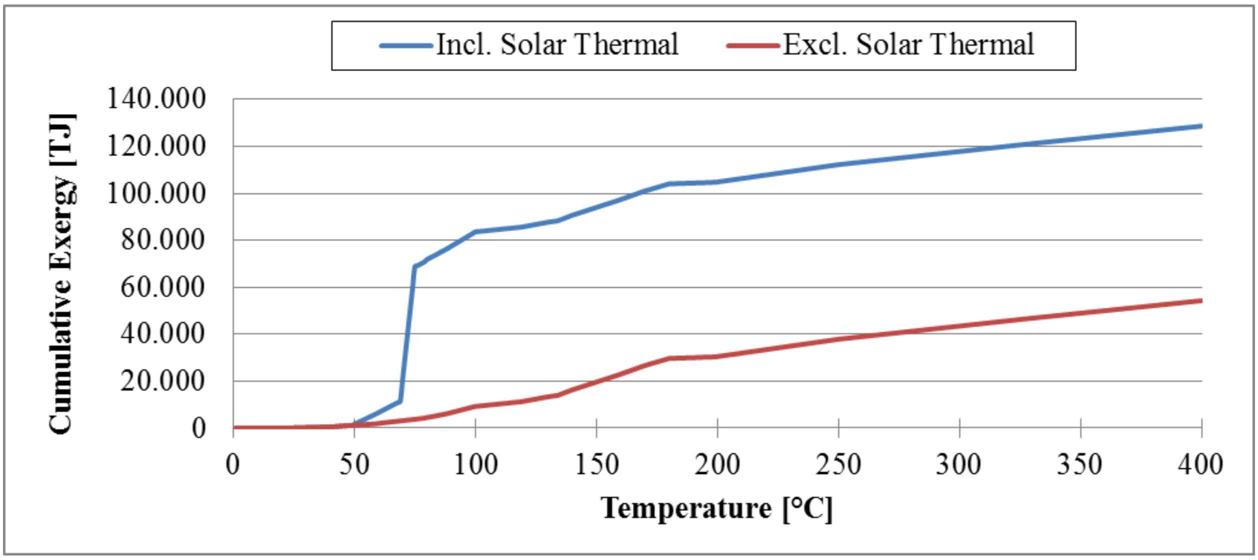

Fig. 8. Cumulative waste heat exergy of the processes with and without solar thermal exergy.

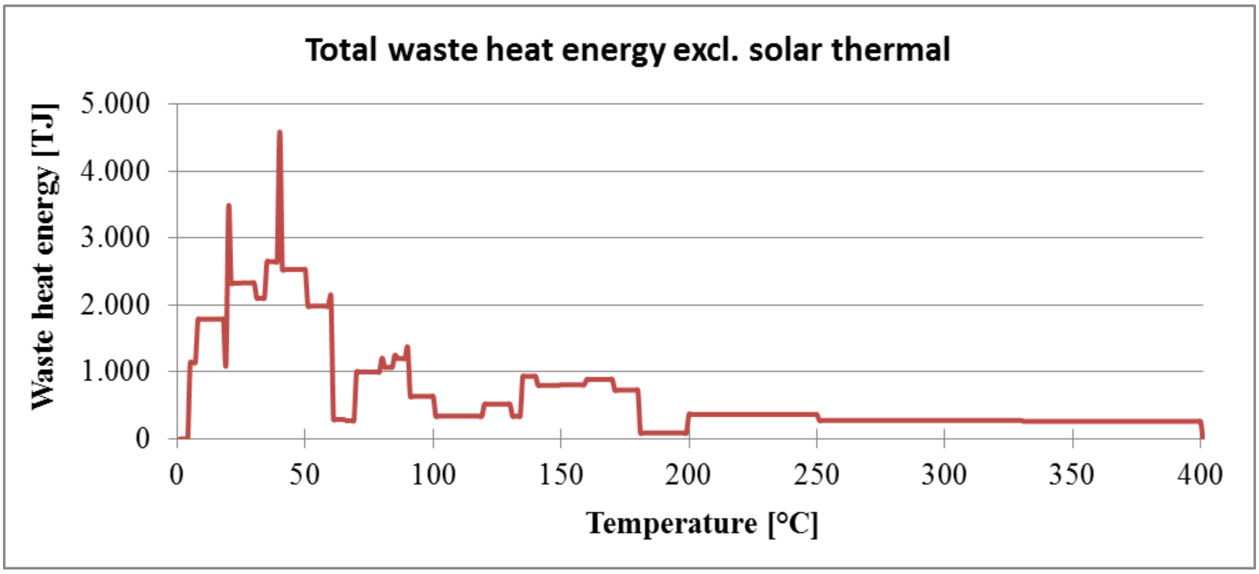

Fig. 9. Waste heat of the processes with temperature excluding solar thermal energy.

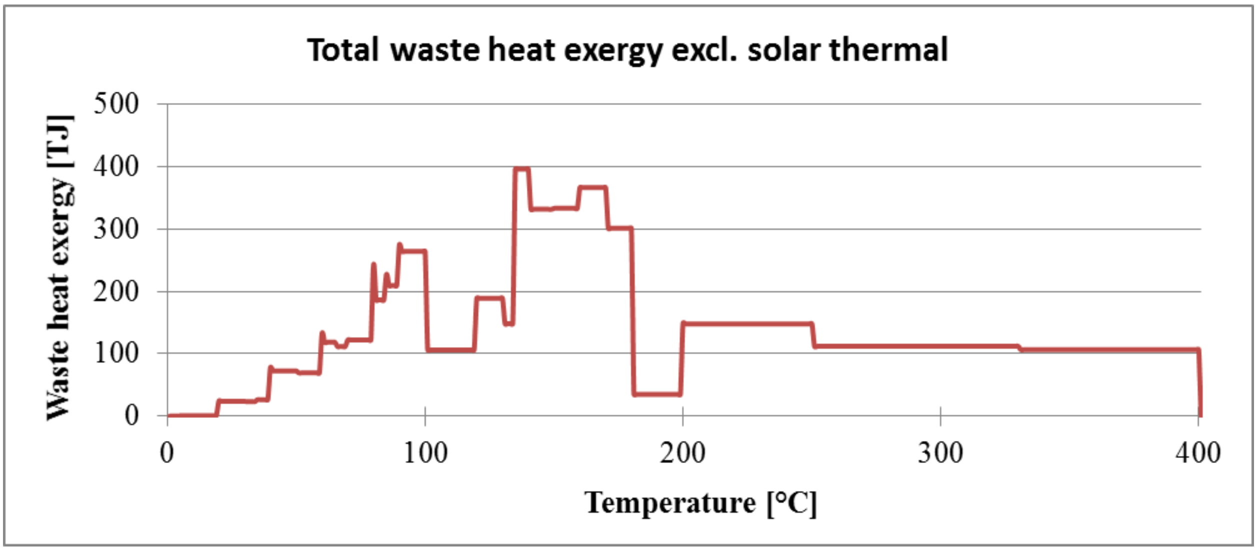

Fig. 10. Waste heat exergy of the processes with temperature excluding solar thermal exergy.

On a sectorial level the largest potentials were found for the manufacturing sector (77.8 PJ) where 16% of the energy input is available as waste heat and transport (75.6 PJ) with 14% of the inputs. The sectors with the lowest energy efficiencies are mining & quarrying and trade, where 33 % and 32 % respectively of the energy consumption are available as waste heat.

When analysing the sources of the waste heat, the highest potentials are found in the exhaust gases of the transport sector where 22 % of the total heat is found. This source is followed by distillation (15.7 %), flue gas from steam power plants (9.8 %) and refrigeration/cooling (9.1 %).

In terms of exergy, the largest potential is also found in the exhaust gases of the transport sector, representing more than 40 % of the total exergy, followed by flue gases from steam power plants. Boiler losses in the industry and buildings have the third largest exergy potential with a share of almost 12 %, while they only account for less than 7 % of the waste heat energy.

5. Discussion

The accessible heat of 266 PJ in the analysed Danish sectors corresponds to 13 % of the energy used by the utility and end use sectors. The total energy consumption of 2,020 PJ estimated in this study includes producers where an energy conversion takes place (production of heat and power) and therefore some of the energy input is accounted for twice. The Danish net energy input is with 791 PJ in 2012 [16] significantly lower than the energy consumption found in the present analysis, as the net energy input only uses primary energy and does not include the energy for maritime shipping. The results for the mapping of the natural heat sources are based on theoretical considerations with respect to land use and thus only give an indication for the accessible heat potential. Also the waste heat found in the transport sector is, in practice, only exploitable in some cases, as there is a large quantity of mobile sources. In particular for road transport, a possible utilisation of the waste heat is not given.

The large potential of waste heat below 50 °C will make the use of e.g. heat pumps necessary if process integration is targeted. The feasibility of recovering the low temperature heat sources also depends on the potential users and their location and temporal variations in relation to the source. As Denmark has a large district heating network, many sources in most of the sectors, could be used to supply heat to the network. In the shipping sector waste heat could be used to generate power to replace commonly used diesel generators. However for each source an individual and detailed analysis has to be undertaken to locate and assess possible users of the recovered heat.

The simplifications, assumptions and sectorial calculations cause uncertainties of the quantified waste heat amounts in this analysis. However the aim of this work is to identify processes and sectors which are suitable to analyse further with respect to new technologies being developed as part of the

THERMCYC project. These technologies will still be viable, even if the total potential in a sector is lower in reality, as the first targets are the more easily accessible sources.

In the shipping sector 16 % of the energy used is available as waste heat, and most of this heat has high temperature levels. The waste heat in the industry sector is available at lower temperatures, however the unused and accessible waste heat represents more than 17 % of the total energy input. To reach the THERMCYC project aim of a 15 % reduction in energy consumption within these sectors, the accessible waste heat potential can contribute to a large extend.

6. Conclusions

The energy mapping of the available waste heat energy in Denmark is based on the consumption in the five Danish sectors and from three natural energy sources. The largest potential for waste heat is within the industrial sector, where a total of 103 PJ are estimated as recoverable. The second largest potential is found with more than 76 PJ in the transport sector, followed by the utility and building sectors where the potential is 58 PJ and 25 PJ, respectively.

The results show that despite great efforts in industrial energy efficiency, a large potential in optimising processes and reusing waste heat still exists. It is expected that large quantities of the waste heat could be reused within the industrial sectors.

Considering the accessible waste heat from all sectors, there are two major potentials. First, low temperature waste heat in the form of water from cooling/refrigeration, condensate and various industrial processes all below 60 °C. Secondly there is high temperature waste heat in the form of exhaust gas from various combustion and heating processes.

The large amount of low temperature waste heat calls for innovative methods to utilise these sources. For temperatures below 60 °C heat pumps can be used to upgrade the waste heat or it could be directly used in ultra-low temperature district heating. For high temperatures, power cycles like the organic Rankine cycle and the Kalina cycle can be used to utilise the heat for production of electrical power.

Acknowledgment

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