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Heating Sector Strategies in Climate-Neutral Societies

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ABSTRACT:

This paper investigates how the heating sector can best support the green transition into climate-neutral societies. In order to do so, the heating sector must be considered and analysed as an integral part of the entire energy system as well as be coordinated with other greenhouse gas emitting sectors. Consequently, in this study with Denmark as a case, we establish the context of a full transition of all sectors into a climate-neutral society. Using such context, we investigate the role of the heating sector with a focus on excess heat potentials, energy savings vs. supply, district heating vs. individual heating as well as the ability to recycle low-temperature excess heat and to provide flexibility and support the integration of variable renewable energy sources also in other subsectors of the energy system. The results of the analyses show (1) a feasible reduction level of around 36% in end-use heat demand in buildings, with higher potential in older buildings and lower in new buildings, (2) expanding district heating to areas with a density of 15-10 kWh/m^2 is feasible, resulting in a district heating share of 63-70% of the heat demand compared to the current level of 51%, (3) a large unexploited potential to use heat sources such as industrial excess heat, geothermal heat, data centres and power-to-X, reducing the need for biomass in the heating sector, and (4) increased use of variable renewable energy and combined heat and power production increasing gas export and thus replacing biomass consumption outside the country.

Keywords

district heating;
energy system analyses;
renewable energy;
climate-neutral.

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1. Introduction

The IPPC's report on Climate Change 2022 [1] states that accelerated action is essential to close the gap between existing climate adaptation and what is needed if global warming should be kept below the 1.5°C limit; in other words, emissions should be halved by 2030 compared to 2019. According to Ritchie et al. [2], energy use in residential and commercial buildings contributed to 17.5% of the global greenhouse gas emissions of 49.4 billion tonnes CO_2eq in 2016. Of the energy use in buildings, a large share is related to heating, depending on the climate conditions, namely for space heating and domestic hot water preparation. Thus, a transformation of the heating sector towards an efficient renewable energy supply is required to reach the global climate targets.

Researchers have been looking into the heating sector and the transformation to renewables for many years, where, e.g., the Heat Roadmap Europe projects [3–7] have been forerunners in identifying potential transition pathways for transitioning the heating sector into renewable energy. According to Lund et al. [8], the heating sector must contribute to the overall energy system, a so-called smart energy system, where technical solutions need to be identified across all energy sectors, gaining the advantage of sector coupling and the flexibility of having more options, e.g., using large-scale heat pumps (HPs) in district heating (DH), using electricity from renewables and storing energy as heat, which is cheaper than storing electricity [9]. The Heat Roadmap Europe studies point at both individual HPs and DH as essential technologies to make the most efficient heat

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Abbreviations

3GDH:	Third Generation District Heating	COP:	Coefficient of performance
4GDH:	Fourth Generation District Heating	DH:	District heating
ATDH:	Ambient temperature district heating	GIS:	Geographic Information Systems
CEEP:	Critical excess heat production	HP:	Heat pump
CHP:	Combined heat and power	O&M:	Operation and maintenance
		PV:	Photovoltaic
		VRE:	Variable renewable energy

supply system as part of future climate-neutral energy systems. The HPs are important as they can utilise electricity from renewable energy, such as wind and solar, and produce heat efficiently compared to electric or fuel boilers. However, individual HPs also require investments in upgrading electricity networks, and in dense urban areas, DH often provides a more feasible option. Basically, DH is a better option when the cost of the DH system is lower than the cost of the individual heating units in an area, typically in dense urban areas with a low-cost heat source available. This strong correlation to heat density was recently examined by Fallahnejad et al. [10], where advanced models to estimate DH investments were applied to find the DH potential in Europe, but has also previously been shown by others [11–13]. In addition to lowering the costs for the area's consumers, DH also benefits the overall energy system, as it allows for utilising more types of renewable energy sources as well as excess heat from different processes and enables better use of large-scale thermal storage as shown in Guelpa and Verda [14].

There is a lot of variation within DH systems; some are old and inefficient, while others are modern, more efficient systems. In general, DH systems need to develop into what has been termed the fourth generation of DH (4GDH) [15,16], where the temperature levels are reduced to approximately 55-60°C/25-30°C from the current third-generation temperature levels of 80°C/45°C. This change in temperature level is required to reduce network heat losses and improve the efficiency of the heat supply. In Sorknæs et al. [17], the benefits of implementing 4GDH in a national context were analysed, where it showed that heat losses could be reduced and a reduction in the overall energy system costs could be achieved. To implement 4GDH, it is important that the efficiency of the current buildings is improved [18,19], as the temperatures cannot be reduced in the network if the buildings still require high temperatures to reach comfortable heating levels. In Volkova et al. [20], the impact of lowering both heat demands in buildings and DH temperature levels was analysed in an Estonian case study, showing how more renewables can be integrated when reducing temperature levels. However, as Meyer et al. [21] showed there are many barriers to implementing energy efficiency measures in buildings, and the right framework conditions are required to ensure that building owners benefit from implementing these measures.

Recent research [22,23] has investigated ambient temperature DH (ATDH). In ATDH systems, the temperatures in the DH network are reduced even further than in 4GDH, and HPs are used in all buildings to raise the temperature levels to the required level of the building. With a lower temperature level and a HP in each building, the network heat losses become less relevant and thus, uninsulated pipes can be used in these systems, reducing the initial investment cost in pipes. Gudmundsson et al. [22] have made an economic comparison of 4GDH and ATDH in a Danish and a United Kingdom case. Their conclusion is that the centralised aspects of 4GDH have clear economic benefits compared to ATDH, which relies on end-use heat generation. They do not examine the competitiveness for different urban densities, and ATDH could be relevant in low-density towns where 4GDH is not feasible. This is especially the case if a low-cost heat source is available that could be distributed in an ATDH grid instead of using traditional air or ground source HPs.

Besides the reduction in temperatures, it is also evident that the heat supply needs to change to decarbonise DH. A review by Werner [24] shows that the global DH supply is dominated by coal and natural gas, while Jodeiri [25] shows that only a few countries, e.g., Sweden and Denmark, have achieved 40-70% renewable energy in the DH supply. In most other countries with DH, the renewable energy share is less than 20%. Therefore, there is still a considerable distance to cover in terms of fully decarbonising the DH sector globally. Ericsson et al. [26] have investigated the Swedish experiences with implementing biomass in the DH sector and have identified investment subsidies, carbon taxes and a successful certificate scheme as some of the main drivers behind this transition.

An important property of DH systems is the ability to integrate different heat suppliers, which is crucial in the transition to a decarbonised energy system. Integrating different heat suppliers enables the DH systems to transition gradually by implementing various new renewable heat sources into the supply mix while phasing out fossil fuel supply options. Thus, in the following, a summary of different options is examined. There are many different decarbonisation supply options for DH, which can generally be divided into solar thermal, geothermal, waste heat, biomass and heat pumps. Solar thermal technology has established itself as a viable option for DH systems and is mainly limited by solar resources and space requirements. The solar resources are also related to variability throughout the year, and e.g., in the Nordic countries, most of the heat from solar thermal is generated in the summer and in the late spring and early autumn. Numerous instances exist of solar thermal integration into DH systems, often incorporating seasonal heat storage mechanisms to prolong the utilisation of solar-generated heat [27]. According to a review of storage options with a focus on solar thermal DH, Dahash et al. [28] show that thermal energy storage tanks or hot water pit storage systems are the most promising technologies for seasonal storage in solar thermal DH systems. Geothermal energy is used for DH supply, but also has a large potential to be used more in future DH systems. Geothermal energy is mainly limited by high investment costs due to drilling and risk related to heat source availability [25], but provides a stable heat source all year round, contrary to solar thermal heating. Utilising waste heat from other processes as heat supply in DH is also an option to decarbonise the heat supply and is one of the main benefits of having DH systems in general. There are many types of waste heat that can be utilised for DH. Traditionally, the waste heat has been from power production, waste incineration or high-temperature industrial processes, as all of these provide heat at the required temperature level for traditional DH systems. With the increasing focus on reducing temperatures in DH and with more renewables in the electricity system, also lower-temperature heat sources are becoming relevant for DH purposes, e.g., metros, data centres, wastewater treatment and service sector buildings [29,30] or electrical transformer stations as examined by Petrović [31]. Biomass comes in many forms and includes, but is not limited to, wood, energy crops, straw and biogas. It can be used as input fuel to combined heat and power plants (CHPs) or boilers and can thus be used in a similar manner as fossil fuels have been used traditionally, producing heat when it is needed. However, as Lund et al. [32] have pointed out, the availability and sustainability concerns associated with biomass must be effectively addressed and managed. Biomass is frequently the sole viable option for certain applications like heavy transport and industry, making it crucial to prioritize its use in a completely decarbonised system. Therefore, the utilisation of biomass in DH, in a fully decarbonised energy system, should be minimized and reserved primarily as a backup system for other heat sources. Finally, large-scale heat pumps[33,34] will also have a significant role in decarbonising the DH systems [33,34]. As individual household heat pumps, the large-scale heat pumps can utilise electricity production from variable renewable energy (VRE) in an efficient manner and be able to use different heat sources such as seawater, groundwater and air as examined by Pieper et al. [35].

The focus of this study is to investigate the role of the heating sector in a future climate-neutral energy system, where the geographical distribution of demands and low-cost energy sources are analysed, as well as the effect of these on the national energy system. This study differs from previous studies, as it is a national study that combines energy efficiency measures in buildings, DH expansions, 4GDH and various heat sources. The heat sources include a spatial mapping of the potentials from traditional high-temperature industries and low-temperature sources while also considering future potentials from geothermal energy, power-to-X plants and data centres. This is all to show how the future heating sector can develop and contribute to the renewable transition of the entire energy system, focusing on the expansion of VRE capacities, the electricity exchange, the power plant operation, the gas exchange, and the energy system costs.

2. Methods

The study applies two well-recognised methods, by combining Geographical Information Systems (GIS) and hourly energy system analyses of national energy systems. GIS has been used to geographically localise heat demands and existing heat sources, as well as investment costs and energy losses of DH grids. As the

GIS analyses do not include the temporal operation of the energy system, this is handled in the national energy system analysis tool, EnergyPLAN, in which the role of the heating sector is analysed in relation to the other energy sectors.

Denmark is used as the study area, and thus, the country's national boundary is used as the delimitation. As this study aims to identify the role of the heating sector in a future climate-neutral energy system, it is relevant to apply a future energy system model that includes all energy sectors but does not detail the heating sector as a starting point of the study. Here the energy system model IDA's Climate Response 2045 [36] is used, which is already described in the literature and used in several other studies such as [32,37]. First, the methods involved in the GIS approach are presented, followed by a presentation of the energy system analysis and finally a summarising overview connecting the two parts of the method.

2.1 Geospatial mapping of heat demand and supply

To enable the assessment of DH potentials, it is important to quantify the spatial dimension of the heat demands in buildings. This involves identifying the locations of these demands and estimating their magnitude, as well as determining the types of heat supply currently in use. To provide this, The Danish Heat Atlas [38] was developed using detailed building data from the Danish Building Register and combining this with a heat demand model of estimated specific heat demands, applying building usage, age and size as input parameters. The applied heat demand model is described in Grundahl and Nielsen [39]. Figure 1 displays the heat atlas data, representing each heated building as a circle of a size corresponding to its annual heat demand and a colour indicating the type of existing heat supply. The example in the figure reveals that the majority of buildings utilise DH or natural gas for heat supply, whereas fewer buildings rely on oil, biomass, electricity, or HPs. The map only shows a snippet of the dataset, which covers all heated buildings in Denmark, or around 2 million heated buildings with a total estimated heat demand of 54 TWh/year.

The heat atlas includes an estimate of the heat demand in existing buildings. But it is also vital to include energy renovation of the existing buildings when studying future climate-neutral energy systems. Implementing energy efficiency measures in buildings reduces the heat requirements of the building, which further reduces the required heat supply capacity and improves the efficiency of the heat supply as supply temperatures are typically lower. Reduced supply temperatures in DH lead to reductions in grid losses, improve the efficiency

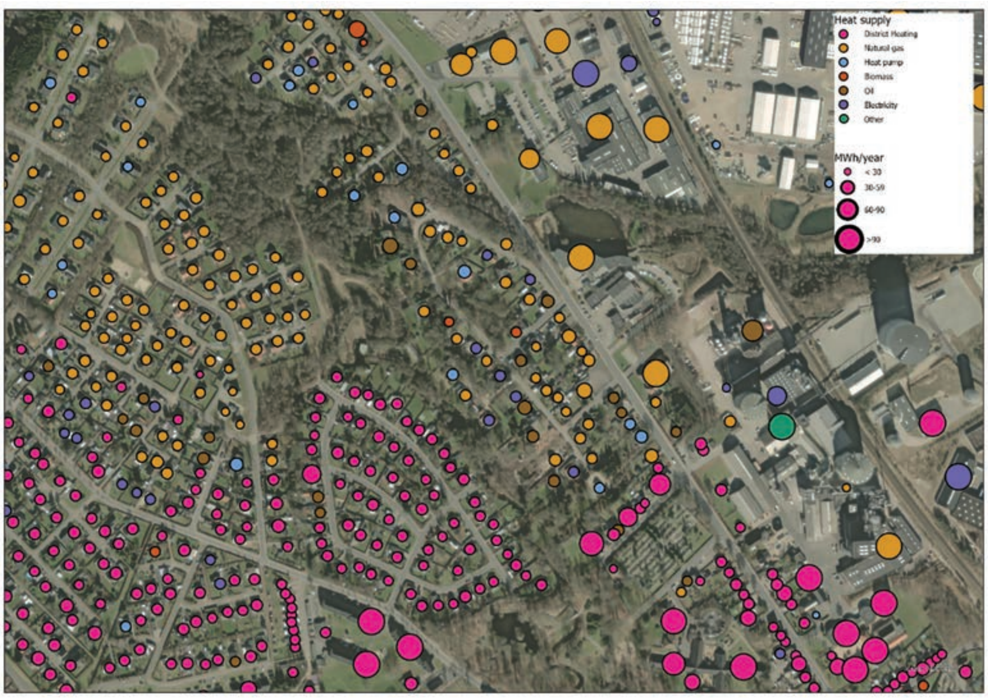

Figure 1: Detailed mapping of heat demand in buildings using the heat atlas method [38].

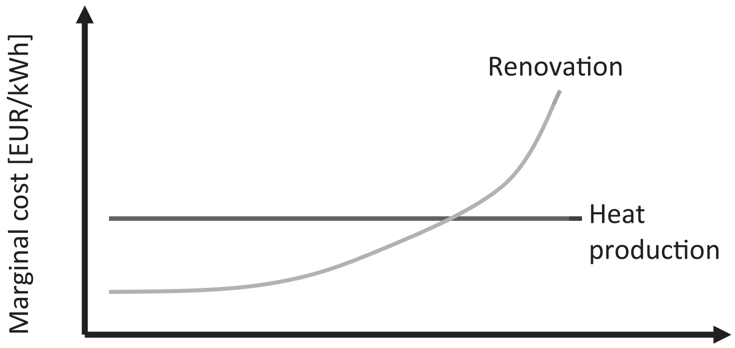

Figure 2: Principal diagram showing that energy renovation investments should be implemented until the point at which the heat production costs are lower than the costs for energy renovation of the building.

and enable more renewable sources. When implementing energy efficiency measures in buildings, it is important to balance the investment in these measures with the costs associated with heat supply. Figure 2 illustrates this strategic approach, where building renovation continues until the point at which it becomes more expensive than the marginal costs of heat production. This evaluation should be done in relation to the costs of the climate-neutral heat supply and not the existing fossil supply system, as this would give a suitable balance for the future system. The heat production cost curves in this article are based on an adjustment of the heat supply from IDA's Climate Response 2045, using the same approach as described in Nielsen et al. [40].

The Danish Heat Atlas has incorporated energy efficiency measure potentials and costs, utilising the same categorization of building usage types and construction periods as the heat demand estimation model. A comprehensive analysis of the energy efficiency potential was conducted in 2017 in a report by the Danish Building Research Institute [41], which included the assessment of savings achievable through seven different levels of energy efficiency measures.

2.2 DH expansion scenarios

DH expansions are modelled using four DH expansion scenarios. The first scenario represents the current heat supply system as it operates today, serving as a baseline for comparison. The second scenario incorporates densification within the existing DH, reflecting ongoing and near-term improvements. Following these two scenarios, the methodology progresses to consider the potential expansion of the DH network into new areas. This expansion prioritizes zones with higher heat density, beginning with regions where the heat demand exceeds 15 kWh/m^2 of land area. Subsequently, the expansion strategy extends to areas with lower heat densities, down to a minimum threshold of 10 kWh/m^2 of land area. This stepwise approach ensures that the most cost-effective and energy-efficient areas are prioritized before transitioning to regions with less favourable heat density characteristics.

As input parameters to the modelling of the DH supply in the new areas, the assumptions in Table 1 are used, showing investment costs, capacity and heat losses for a 4GDH system using temperature levels of 60°C/30°C. The investment costs used for DH pipes are from the Swedish DH association [42], but have been validated with other sources as well. The investment costs encompass expenses related to materials, pipe installations and excavation work specifically within urban areas. The method for estimating the capacity and heat losses is described in Nielsen and Grundahl [43].

In the GIS analysis, the costs of the DH grid extensions and heat losses were determined using a GIS-based model that estimates pipe sizes based on the heat consumption of buildings and calculates pipe network lengths from the road layout. This GIS model serves as a general tool that is more precise than using heat density alone, yet less detailed than the comprehensive planning typically conducted by utility companies, which often includes hydraulic calculations. A key advantage of this method is its consideration of building locations relative to each other, as differences in urban layouts, even with identical heat densities, can significantly impact the design of the distribution network, influencing both heat loss and investment costs. The detailed model was employed in two phases. Initially, it

Table 1: Investment costs, capacities and heat loss for the DH grid using 4GDH temperatures. Investment costs are from the Swedish DH Association [42].

Pipe dimensions [mm]	Investment [EUR/m]	Capacity [MW]	Heat loss [w/m]
48.3	416	0.13	5.9
60.3	474	0.23	6.9
76.1	567	0.44	8.9
88.9	671	0.67	10.9
114.3	805	1.31	13.1
139.7	954	2.24	17.1
168.3	1,054	3.67	21.3
219.1	1,204	7.41	25.2
273	1,442	13.20	31.7
323.9	1,746	21.08	39.6
406.4	2,081	38.25	47.5
508	2,465	68.95	55.4

was applied directly to 3,174 areas, and then its results were generalized through a regression analysis, which was subsequently used to ensure consistent treatment of all areas in the model. The details of this analysis are available in Sorknæs et al. [17].

2.3 Potential heat sources

In relation to DH, the local availability of heat sources is important as these can help to reduce the heat production costs of the DH system. As explained in the introduction, many different types of heat sources can be used for DH purposes. Some heat sources are currently being used, others are available but not used, and others are heat sources that can be expected to be available in the future. In this analysis, the heat sources that are already being used, namely waste incineration and industrial excess heat, are assumed to be available in the future as well; however, waste incineration is assumed to be reduced from 40 PJ to around 13 PJ in 2045 [44], representing a higher degree of recycling and more use of biogenic waste in biogas production. The sources that are available and not used are, in this case, industrial excess heat and geothermal heat, for which the potential is estimated both in terms of quantity and spatial location. The sources that are expected to be available in the future are only estimated in terms of quantity and include mainly data centres and power-to-X plants.

The estimate for geothermal heat sources uses a map made by the private company Innargi, which is an international geothermal company planning, building and operating large geothermal DH plants in the Danish cities Aarhus and Copenhagen as well as the Polish city Łódź. The map from Innargi includes temperature level, coefficient of performance values and economic costs estimated for five areas of Denmark; north, central and south Jutland and north and south Sealand. A map of the areas is presented in the background report for Heat Plan Denmark [45]. In this analysis, it is assumed that only areas inside these five areas have geothermal potential. Based on Innargi's experience, the quantity of heat is assumed to be restricted mainly by the heat demand above ground and the assumption that a geothermal plant needs around 6000-7000 full load hours and a minimum capacity of 10 MW per drilling to be economically feasible. In practice, this means that geothermal heat can only be used in DH areas with a baseload heat demand of at least 80-100 GWh/year.

The industrial and commercial excess heat potential is estimated based on publicly available data from the Danish Central Business Registry. In this article, we present the principles of the method, while a more in-depth description of the methods can be found in Moreno et al. [46]. In the registry, each company is registered with a branch code, and for the excess heat assessment, 46 branches have been selected covering different categories, including manufacture, processing, production, retail, hotels and restaurants, amongst others. The excess heat potentials are then applied in a top-down method where the national energy demand for each branch is distributed to each company depending on the size of the company. The excess heat potential is then estimated as a share of the energy demand and is divided into typical processes for the branch, which include melting, furnaces, boiler losses, other heating, drying, heating/boiling, compression air, distillation, evaporation, cooling/refrigeration, and space heating. In the analysis, the temperature level for each process is estimated to evaluate if the heat can be used directly in the DH system or needs HP boosting.

2.4 EnergyPLAN and IDA's Climate Response 2045

The energy simulations are performed in the tool EnergyPLAN, which is a well-known energy system analysis tool that has been used in many research papers since 2003, as documented in Østergaard et al. [47] and Lund et al. [48]. The tool is typically used for national energy system analyses. It includes all energy sectors and simulates the energy flows of an energy system through a leap year at an hourly resolution. Figure 3 shows a schematic overview of the energy demands, technologies and resources that are included in the tool. The demand sectors included in the tool are electricity, cooling, heating, transport, and process heat in industries, which are shown as orange boxes in the overview. The tool also includes different types of energy streams that are illustrated by a number of coloured arrows. These include electricity, heating, cooling, fuels, CO_2, water, hydrogen, and steam. All these energy streams have different storage options available, and thus the tool can analyse the benefits of storing, e.g., electricity as heat or converting it to fuels. EnergyPLAN is based on the smart energy system approach, as mentioned in the Introduction, and as such, includes energy sector coupling options. As mentioned by Lund [49], the smart energy systems approach is used based on the assumption that one must do so to identify the best solutions. For the same reason, we do not formulate the question of how the heating sector can best decarbonise. Instead, we ask the question of how the heating sector should change to best facilitate the transition of all sectors into a climate-neutral society. The energy inputs are fuels and different types of renewables, but also CO_2 as a source for electro-fuel production in hydrogenation plants. EnergyPLAN can simulate an energy system in two different ways; the technical, where a predefined advanced priority list approach is used to identify a low fuel consumption operation, and a market economic, where the operation is based on the short-term marginal cost of operation of each unit using the current electricity market principles dominant in Europe. In this work, the technical approach is used.

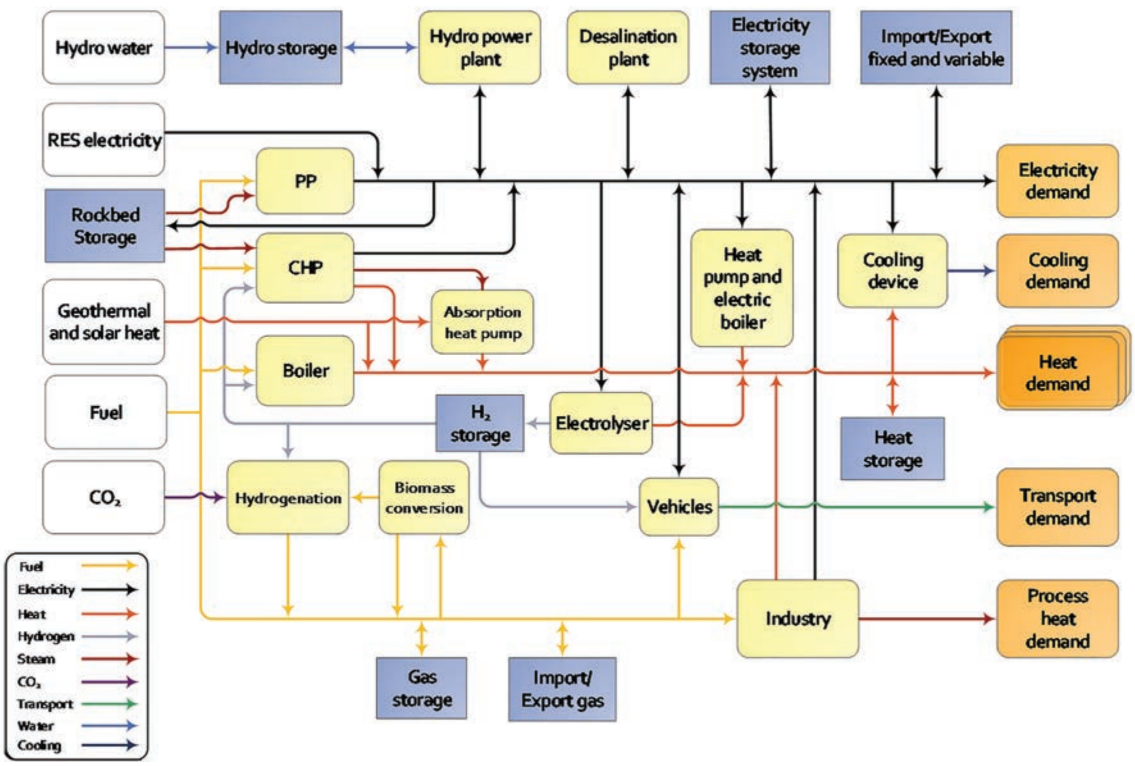

Figure 3: Overview of energy demands, energy conversion technologies, energy storage technologies and energy resources in EnergyPLAN v 16.

The work presented in this paper is based on the pre-existing national energy system model called IDA's Climate Response 2045 [44], which represents a decarbonised energy system for Denmark in 2045 utilising only renewable energy sources and a sustainable amount of biomass. The model is explained in detail in Lund et al.[32], Lund et al. [36], and Kany et al. [37] and includes all energy sectors. Unless stated otherwise, the cost data used in this study are from IDA's Climate Response 2045 as described in Lund et al. [36] and is based on the Danish Energy Agency's Technology Catalogues[50]. In this study, the heating sector is further investigated in relation to how it interacts with the other energy sectors. The model is, as such, used to obtain indications of which development could occur in the other energy sectors. Figure 4 shows a Sankey diagram of the whole energy system in IDA's Climate Response 2045 to give an overview of the context of the heating sector analysis carried out in this article. Focusing on the right side of the diagram, the heat demands are divided into individual heating using HPs supplemented by solar thermal and DH using mainly HPs, geothermal heat, excess heat and CHPs. The energy inputs to the national energy system are mainly wind and biomass. Biomass is mainly used for transport and industry, and due to sustainability criteria, biomass should be kept at a sustainable level; hence it is important not to increase this for DH purposes, as sources indicate that the global sustainable biomass level for energy systems is likely in the range of 10-30 GJ/capita, and the biomass use in the model is 23 GJ/capita [32].

In relation to IDA's Climate Response 2045, this analysis focuses on elaborating aspects related to the heating sector, namely focusing on energy efficiency in buildings, DH share and estimates of potential existing and new excess heat sources. Sorknæs et al. [17] have analysed and argued for the benefits of 4GDH in future decarbonised systems in relation to 3GDH, finding that 4GDH provides lower costs and better energy efficiency. Thus, all the modelling presented in this paper will only include 4GDH systems.

When testing the different DH expansion scenarios, the DH demands and technologies are adjusted accordingly in IDA's Climate Response 2045. First, excess heat from industrial processes is adjusted, as an expansion of DH areas can allow for an increased use of excess heat. Then, the production and storage capacities, not as geographically dependent, are adjusted based on the change

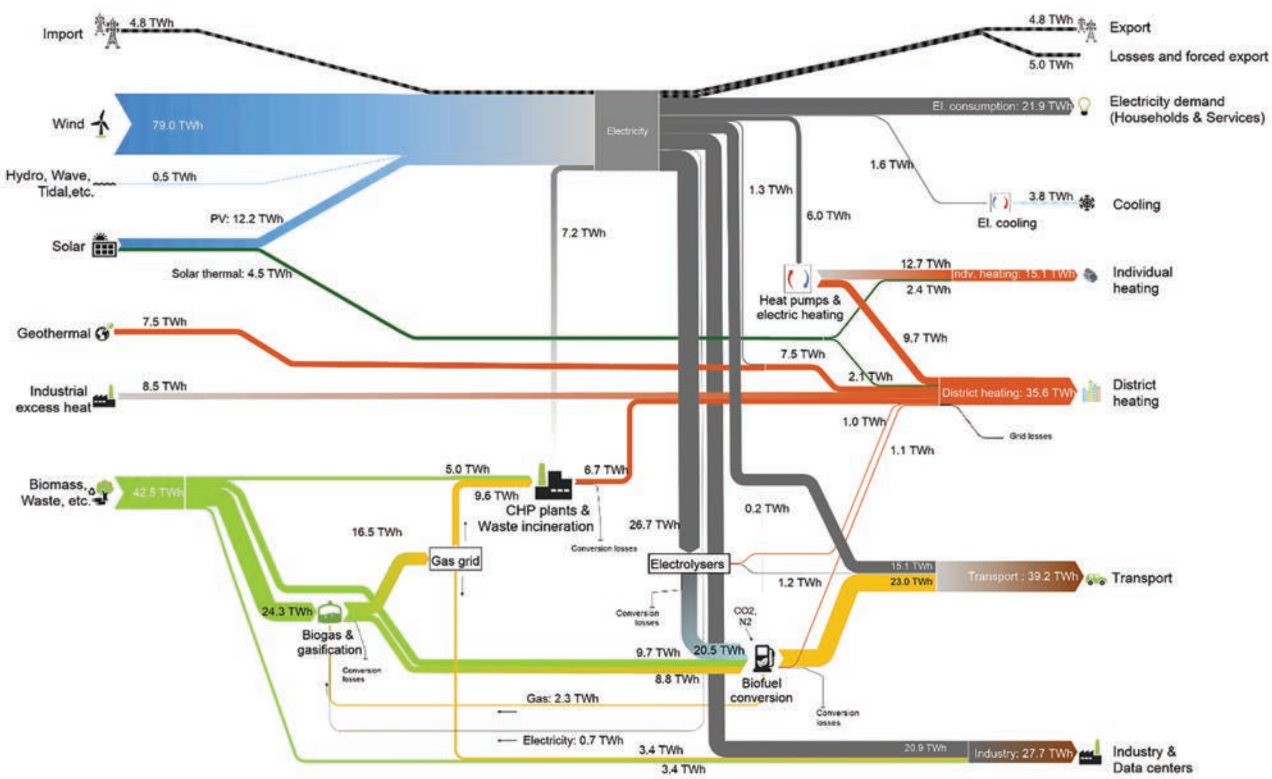

Figure 4: Sankey diagram of IDA's Climate Response 2045 energy system.

in yearly DH production: CHP plants, solar thermal, HPs, geothermal heat and heat storages. Geothermal heat is potentially available in most of Denmark and is mostly limited by the local DH demand. HPs are expected to require about 4,000-6,000 full load hours per year to be economically feasible [33], and thereby, they are in competition with geothermal, excess heat and waste incineration for the baseload demand. As such, for HPs the capacity is not adjusted based on the change in total DH production, but instead on the change in residual DH production (the production that is needed after utilising geothermal, excess heat and waste incineration). To make sure that the peak demands can be supplied in DH, the fuel boilers in each DH expansion scenario are set at 120% of the peak DH demand. To make sure that the four scenarios are comparable, it is ensured that these have the same curtailment of renewable energy (also known as critical excess electricity production, CEEP). This is done by adjusting the offshore wind power and PV capacities while keeping the relationship between these unchanged. Having the same level of CEEP in each scenario ensures that the flexibility variations between the different scenarios is reflected in the needed capacities for these two sources, and thereby is reflected in the cost of the different scenarios. The capacities of electric boilers and waste incineration are kept unchanged in all DH expansion scenarios as these units are expected to be dimensioned due to other factors. For waste incineration, the key factor is the need to handle waste, and for the electric boilers, the key factor is their electricity balancing potential, which remains similar regardless of the DH expansion scenario.

Figure 5 illustrates the structure of the analysis and results sections, which are split into four main parts; first focusing on energy efficiency measures in buildings, then DH expansion scenarios, and then future DH production technologies.

3. Analysis and results

The analysis and results are presented in four parts; first, implementing energy efficiency measures in buildings; secondly, analysing the expansion of DH, and finally looking into the future DH supply and showing the chosen final scenario. The discussion is integrated into each part of the analysis and results.

3.1 Implementing energy efficiency measures in buildings

In the analysis, the implementation of energy efficiency measures is divided into two parts: one for buildings connected to DH systems and another for buildings not connected to DH. This division is based on the variation in heat supply costs, which consequently affects the feasibility of energy renovation. In practise, renovation and supply costs differ on an individual building basis. However, for the purpose of a national-scale analysis, this categorization into two groups was adopted to simplify the assessment.

In Figure 5 the impact of implementing energy efficiency measures in buildings is compared to the marginal costs of the heat supply. The graph is divided by buildings connected to DH and buildings not connected. Both have a similar reduction potential as the DH share

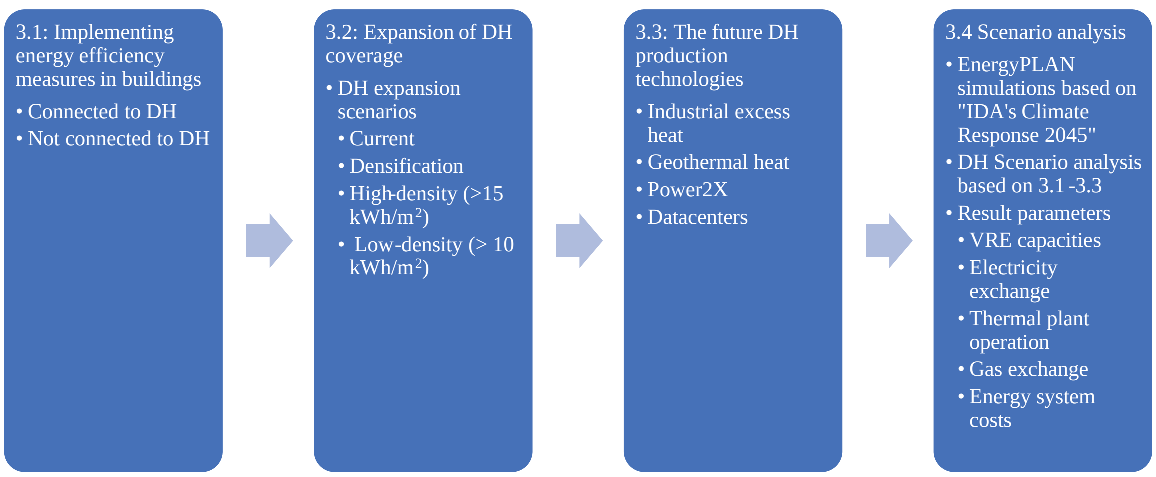

Figure 5: Structure of the analysis and results section.

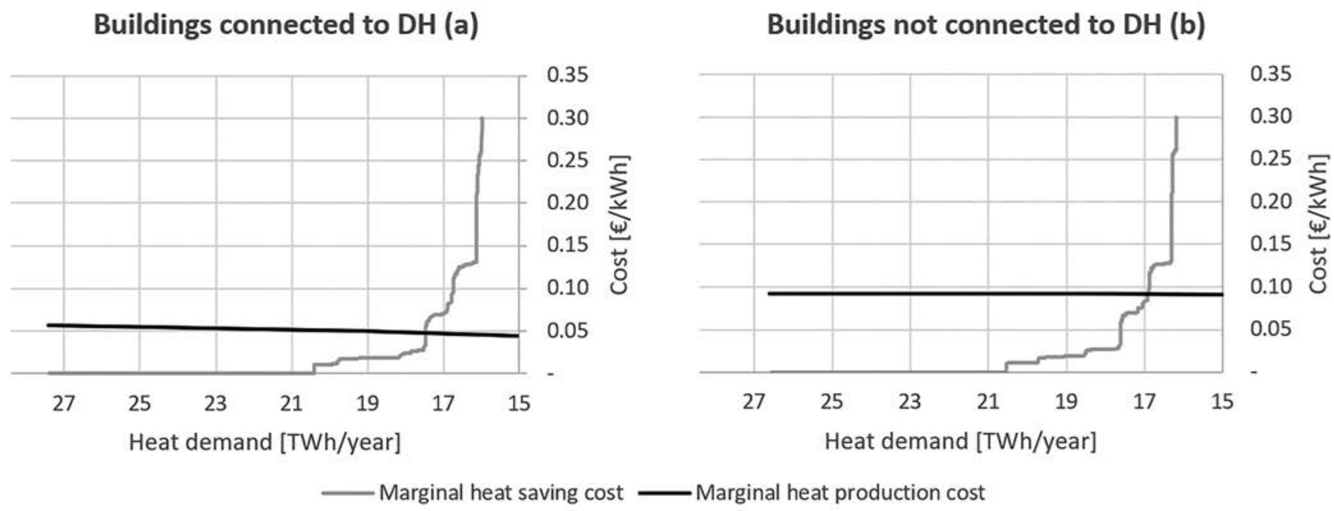

Figure 6: Implementing heat-saving measures compared to marginal heat supply costs for buildings connected to DH systems (a) and buildings not connected to DH systems (b). Please note that the marginal heat production cost in (a) is based on the marginal supply cost in DH, which declines slightly as the demand is lowered. This is because DH depends on the different supply technologies available as supply is lowered. Typically, cheap excess heat is available at low demands, while boilers marginally supply more expensive heat. Thus, cheaper sources can cover the heat demand when heat-saving measures are introduced.

is around 51% in Denmark. For buildings connected to DH, the marginal heat supply cost is around 0.05 €/kWh, while for those not connected to DH the marginal heat supply cost is around 0.9 €/kWh. A closer look at the marginal heat saving cost curve shows that a large share of the cost is assumed to be zero, as these are heat savings that will be implemented due to modern building standards.

Table 2 shows an overview of the results for the buildings connected and not connected to DH, when implementing the heat-saving measures that reach the intersection of the marginal heat saving cost and the marginal heat production cost from the cost curves. The resulting savings for buildings connected to DH are 36.3% and for buildings not connected to DH 35.6%. The combined heat demand reduction in all buildings is 36%, going from 54 TWh/year to around 34.6 TWh/year. The total heat demand includes 98,253 buildings where no savings are carried out, namely industries and sports facilities. When examining the buildings where heat savings are implemented, the total reduction is around 42%, going from 46 TWh/year to 27 TWh/year. Finally, the results also show that the investments in energy renovations to reach these savings are 3.5 billion EUR in total or 155.7 million EUR per year.

Figure 7 illustrates these savings in more detail as a clustered column chart presenting the reductions in heat demand in percentages and categorized by building usage and age. These savings are based on results from the Danish Building Research Institute report coupled with the Danish building register data, as mentioned in Section 2.1. The chart is split into two sections, with buildings connected to DH displayed on the left and buildings not connected to DH on the right. The graph clearly indicates that higher energy savings have been achieved in older buildings than in newer ones. Additionally, variations in reduction levels can be observed among different building usages. When considering the distinction between buildings connected and not connected to DH, Figure 7 shows that buildings not connected to DH have a higher average reduction potential of 41%. This is attributed to the higher marginal heat production costs associated with these buildings. In contrast, buildings connected to DH exhibit a slightly lower average reduction rate of 39%. The reason that the total savings are 42% is that more buildings are in the categories with the higher reduction rate.

Table 2: Overview of energy savings by buildings connected and not connected to DH.

	Unit	Connected to DH	Not connected to DH	Sum
Number of buildings	Count	0.8	1.2	2.0
Floor area	Million m2	259.4	210.2	469.6
Heat demand before savings				
- All buildings	TWh/year	27.4	26.6	54.0
- Buildings with savings	TWh/year	24.7	21.4	46.0
- Buildings without savings	TWh/year	2.7	5.2	7.9
Heat demand after savings				
- All buildings	TWh/year	17.6	16.9	34.6
- Buildings with savings	TWh/year	14.9	11.7	26.6
- Buildings without savings	TWh/year	2.7	5.2	7.9
Heat saving percentage				
- All buildings	%	35.6%	36.3%	36.0%
- Buildings with savings	%	39.6%	45.1%	42.2%
- Buildings without savings	%	0.0%	0.0%	0.0%
Investment cost	Billion EUR	1.1	2.4	3.5
Annual investment cost	Million EUR/year	51.2	104.4	155.7

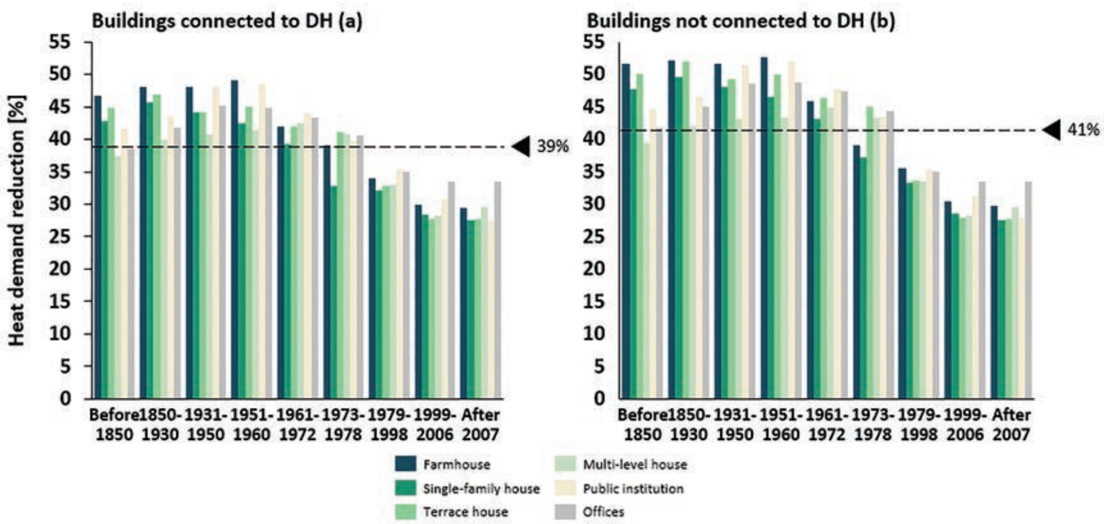

Figure 7: Heat demand reductions by building usage and age divided into buildings connected (a) and not connected to DH (b).

3.2 Expansion of DH coverage

The following part of the analysis examines the four different DH expansion scenarios. The first scenario is the heat supply of today, while the second scenario includes densification within the currently planned DH. These are followed by expanding DH to new areas, starting with the areas with high-density above 15 kWh/m^2 towards low-density areas of at least 10 kWh/m^2, with the m^2 referring to land area. Figure 8 shows all four scenarios, with increasing shares of DH, while Figure 9 illustrates the same expansion scenarios in a map, and a summary of the overall results from the mapping is shown in Table 3. The areas in the map are based on built-up areas, i.e., areas with buildings, which are combined with the heat demands in buildings to estimate the heat density of the area. From the map, it is clear that the existing DH is in dense areas and many of the expansions are adjacent or close to the existing DH areas.

However, there are also low-density areas close to existing DH and high-density areas far away from existing DH areas. Thus, even though expansions are implemented gradually from high to lower densities as shown in Figure 8, the map in Figure 9 shows that this would be a more irregular expansion, as parts of the denser areas are not close to the existing DH. In more local modelling of DH expansions, a more detailed approach could be taken, e.g. including lower-density areas close to existing DH or starting new DH in dense areas far away from existing DH. However, for national modelling, the approach of using the high-density approach is reasonable, as most of the high-density areas are close to existing DH and include the larger towns in the country. The low-density areas are typically more rural areas, where individual HPs would be a less expensive option than DH. As discussed in the introduction, the areas that are not feasible for DH could be potential candidates for ATDH, especially if they are located near a low-cost heat source. ATDH have, however, not been included in this analysis, and thus, this would require further studies. Figure 8 shows that when DH is gradually expanded between scenarios, the other heating supply types are also reduced. It should be noted that the figure shows which existing heat supply types are reduced when the DH scenarios are implemented. In the future climate-neutral heat supply, all the buildings not connected to DH will also convert to HPs; thus Figure 8 does not show the final climate-neutral heat supply, but a first step to achieve it. It should also be noted that here the assumption is that all buildings in the DH areas are connected to DH. This is to show the potential energy system benefits related to the expansion where, from a techno-economic perspective, DH is most cost-effective if all buildings in each area connect. However, in an actual implementation, connection rates are typically lower than 100% [10], which can be due to trust in DH systems and the ability of the building owner to pay for the connection. If fewer buildings connect, the grid cost would theoretically be higher per connected building. However, this is not the case if the distribution pipes are not reduced in dimension accordingly, which they will normally not be due to the potential of the building connecting at a later stage.

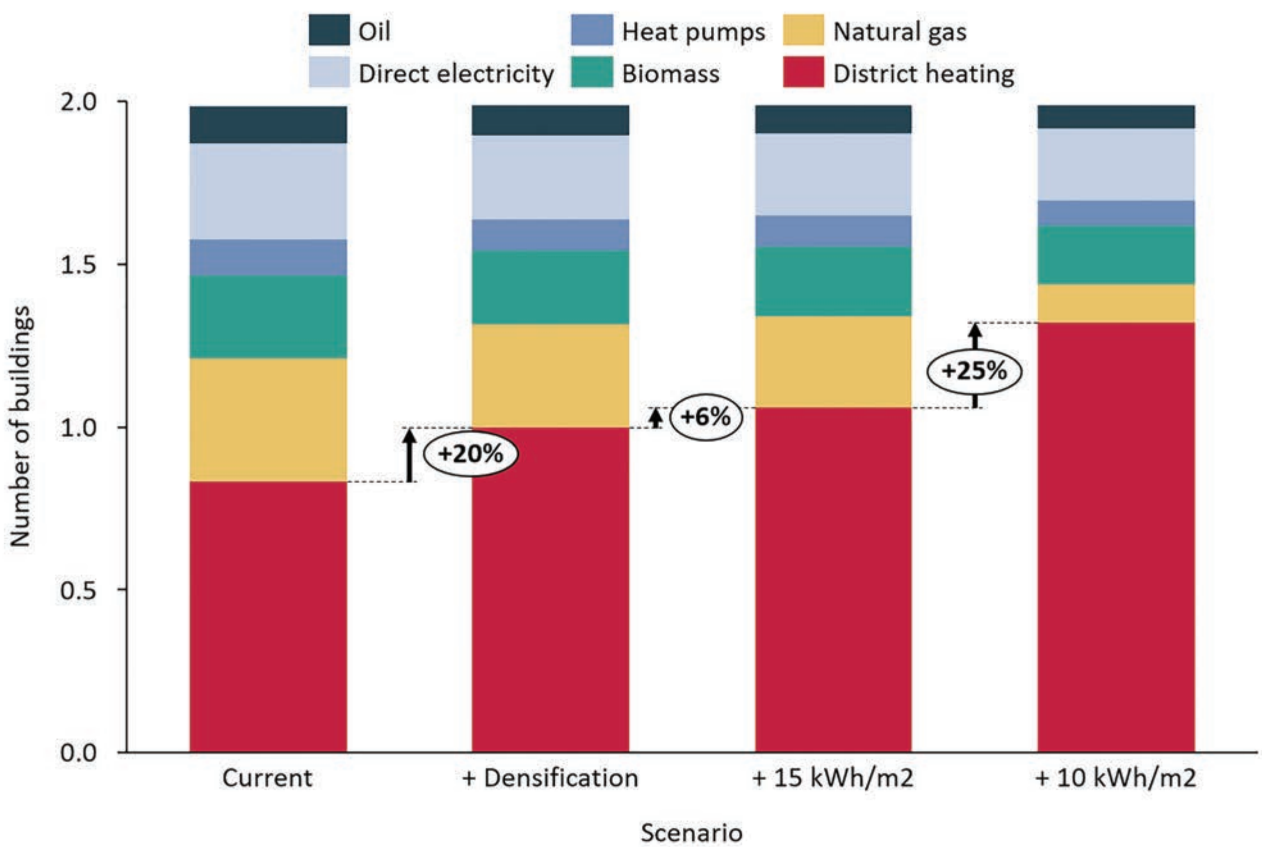

Figure 8: Number of buildings by supply type for four DH expansion scenarios with the current heat supply for remaining buildings

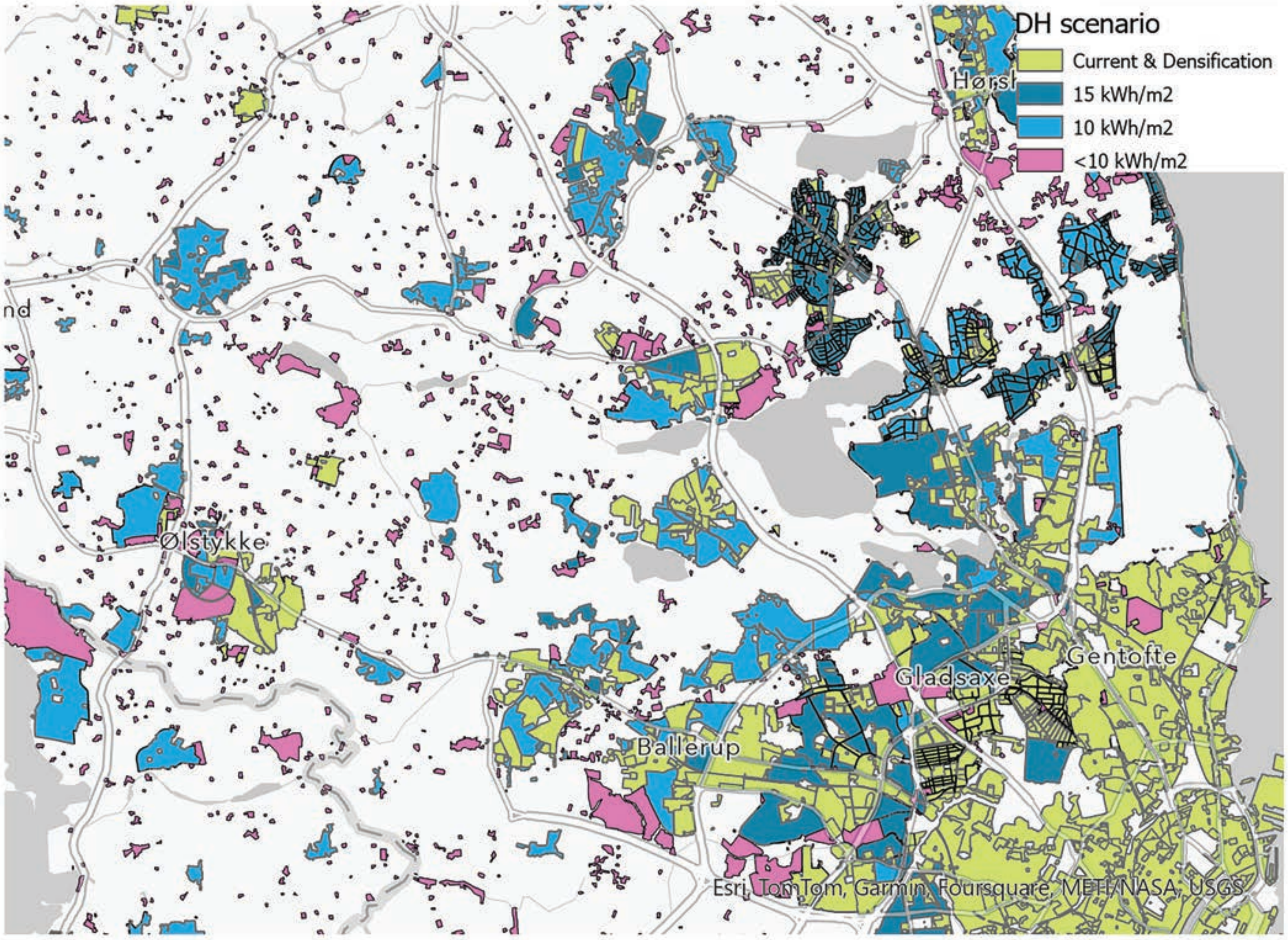

Figure 9: Map of the DH scenarios including areas with lower density than the scenarios. The example shows areas north of Copenhagen

Table 3: Overall summary of the GIS mapping results for the DH scenarios

Technology	Unit	Current	Densification	15 kWh/m^2	10 kWh/m^2
Heat demand all buildings	TWh/year	34.6	34.6	34.6	34.6
Heat demand in DH	TWh/year	17.1	20.5	21.8	24.7
DH share	%	50%	59%	63%	72%
DH heat loss	TWh/year	4.8	5.3	5.4	6.0
DH heat loss percentage	%	22%	20%	20%	20%
Annualised DH investment	MEUR/year	2.6	67.8	310.8	426.0

3.3 The future DH production technologies

The DH supply technologies need to change in the future climate-neutral energy systems, where, e.g., excess heat from new technologies will have a significant role. In Denmark, it is expected that excess heat from different sources, mainly from industries, data centres and power-to-X, can play an important role. Though the utilisation of excess heat sources depends on the proximity to DH areas, geothermal heat can be utilised where excess heat sources are not in abundance, and there is a potential for geothermal heat for DH. These sources can be divided into two groups: sources that can be geographically located using current data and sources that cannot be geographically located as they

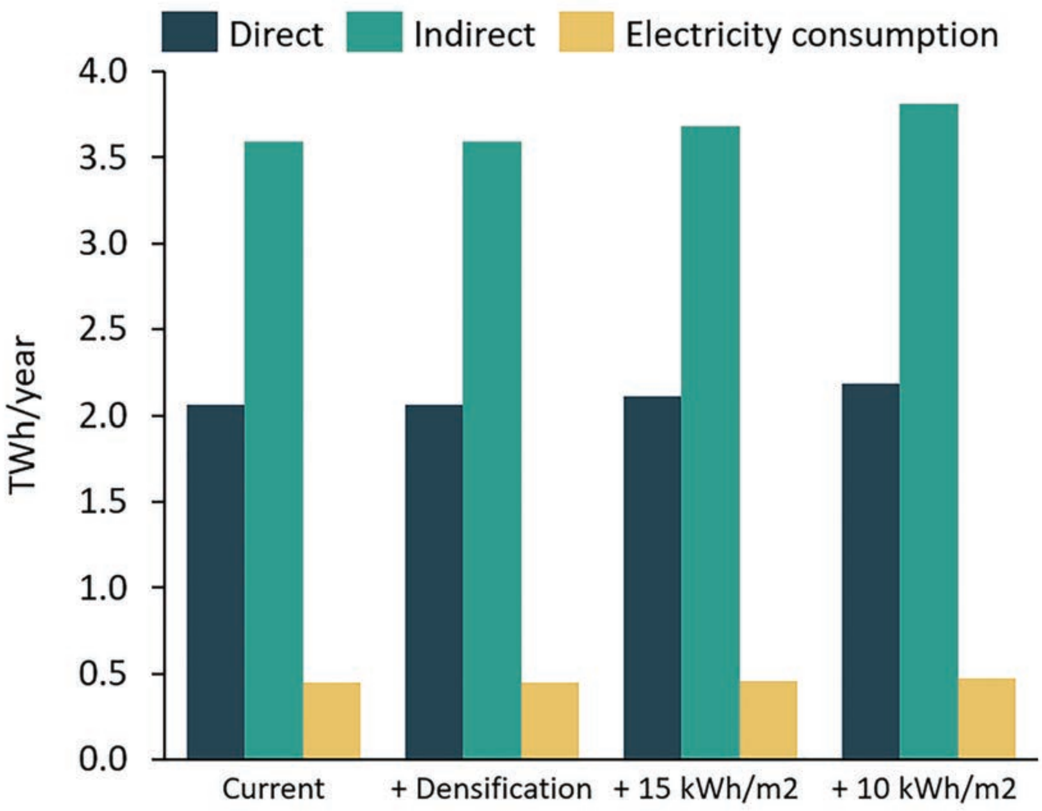

Figure 10: Excess heat from industries and businesses by DH scenario split by direct and indirect (using HP boosting) and associated electricity consumption. Based on 4GDH temperature levels.

have not yet been built, but are expected to be built somewhere in Denmark due to societal development. The sources that can be geographically located using current location data are excess heat from existing industries and geothermal heat based on the expected potentials in the Danish underground. The DH potentials from these sources are estimated for each of the four DH expansion scenarios, as with an expansion of DH, more of these sources could be utilised.

Figure 10 shows the estimated potential excess heat from existing industries and businesses for each DH expansion scenario. It is separated by direct and indirect usage, where indirect usage refers to heat sources that need an HP to increase the temperature level to match the DH supply. The figure shows a potential of around 2 TWh/year for direct use and 3.6 TWh/year for indirect use in the current scenario. These potentials have a modest increase in the DH scenarios, which indicates that most potentials are already within reach of the existing DH.

It is unlikely that all the industrial excess heat would be used for DH, and it is also uncertain how the development of industries will affect this potential. Therefore, only a share of the excess heat is utilised for the energy system analyses. For each scenario, 75% of the potential is utilised, giving first priority to the sources that can be used directly.

Data centres are expected to see a large-scale integration in the Danish energy system. In a report commissioned by the Danish Energy Agency in 2021, the electricity demand for data centres is estimated to increase from 0.88 TWh in 2020 to 7-14 TWh in 2045 [51]. In IDA's Climate Response 2045, the electricity demand consumption for data centres is assumed to be 9.5 TWh in 2045. The amount of excess heat that can be utilised depends especially on the placement of the data centres in relation to the DH areas as well as the cooling technologies used in the data centres, as these affect the temperature of the excess heat. The effect of different cooling technologies is examined more in detail in Sorknæs, et al. [17] and Lund et al. [23]. Here, it is assumed that data centres utilise cooling technologies that enable them to deliver excess heat allowing for direct use of the excess heat without HPs at 4GDH temperature levels in the DH networks. As the location of the data centres is unknown and not all data centres are likely to utilise such a technology, it is assumed that the potential is less than half of the electricity consumption and that this potential is unaffected by the DH expansion scenario. Most likely, the potential would be larger in the scenarios in which DH is expanded the most, and as such, this assumption favours the scenarios with the least DH. In the scenarios, a level of 45% of the electricity consumption is used for excess heat from data centres.

Like data centres, power-to-X technologies are expected to see a large integration into the Danish energy system, as they will be needed for producing fuels for sectors that cannot directly electrify to keep biomass consumption at a sustainable level. Power-to-X facilities are expected to be built in Denmark for domestic purposes, but it is also expected that some will be built for the purpose of exporting products to other countries. IDA's Climate Response 2045 scenario only includes the amount of power-to-X that is needed for providing products that can be considered the Danish share of the global demand, though only for energy demands and not for products needed as part of manufacturing processes. Again, the geographical placement of the facilities is not known, and there are considerations of placing parts of the power-to-X offshore. As such, the placement of power-to-X can limit the utilisation of excess heat significantly. IDA's Climate Response 2045 includes electrolysers that produce 20.5 TWh of hydrogen from 26.7 TWh of electricity. It also includes biogas and biomass gasification that combined produce 8.8 TWh of biogas. The hydrogen, biogas and 9.7 TWh of direct biomass are then synthesised further into 23 TWh of biofuels. All these processes produce excess heat. Based on the technology data catalogue on renewable fuels [50] from the Danish Energy Agency and Energinet, in this analysis, it is assumed that on average excess heat from different power-to-X technologies corresponds to 5-8% of the hydrogen production from electrolysis, 16% of the output from hydrothermal liquefaction, 5% of the biomass input for gasification, 2-5% of the output from CO_2 hydrogenation, 2-4% of the output from N_2 hydrogenation, and 5% of the output from biomass hydrogenation. With the operation of power-to-X technologies in IDA's Climate Response 2045, this means that if all power-to-X facilities were placed where the excess heat could be utilised, the estimated potential would be around 2.96-3.86 TWh/year, depending on the development of the different power-to-X technologies. In this analysis, the lower potential of 2.96 TWh/year is used for all scenarios.

Studies in Denmark have found that the technical potential for geothermal heat in Denmark is mostly dependent on the local heat demand in the given area [52,53]. As such, the geothermal potential can be set according to the DH demand profile. Due to high investment costs and relatively low operational costs, geothermal heat generally needs to be operated as a baseload unit, thereby competing with excess heat sources and waste incineration for baseload operation. Due to heat savings in the end-use demand, the heating peak is reduced in IDA's Climate Response 2045 compared with current DH systems. In general, if a heat production unit needs 7,000 full load hours to be profitable, it will be able to produce around 40% of the yearly DH demand, as the heat demand profile over the year sets an upper limit on how much heat is needed. The concept related to the production of baseload units is well explained in Moreno et al. [46]. As part of the DH demand is already covered by excess heat, and this should be given first priority, it is assumed that around 17% of the yearly DH demand can be supplied by geothermal heat in all scenarios. Based on Sorknæs et al. [17], the investment cost is assumed to be 175 M EUR/TWh with a yearly fixed operation and maintenance (O&M) cost of 4.06% of the investment cost. A coefficient of performance (COP) of 4.9 for the electricity consumption used for geothermal heat is assumed to partly cover pumping and partly cover the electricity consumption for HPs for temperature boosting. It is assumed that the electricity consumption for the HPs can be partly flexible.

3.4 Scenario analysis

Based on the findings and the scenario presented in section 2.4, four different energy system scenarios for 2045 are simulated in EnergyPLAN, each showing a different level of DH share. Unless otherwise stated, all demands, capacities, costs, etc., are derived from this energy system scenario.

Table 4 shows that the adjusted capacities for DH production, storage and heat production technologies vary due to changes in the DH production demand, using the method described in section 2.4. As the DH demand increases due to DH expansions, the capacities, storages and heat production from solar thermal, excess heat and geothermal heat are increased as well. The CHP

Table 4: DH production and storage technologies adjusted between the DH scenarios.

Technology	Unit	2020	Current	Densifi-cation	15 kWh/m^2	10 kWh/m^2
HPs in DH	MW_e	65	371	451	477	540
CHP (condensing capacity)	MW_e	5,818	3,915	4,378	4,466	5,006
Fuel boilers in DH	MW_{th}	12,463	10,354	11,581	12,081	13,247
Heat storages in DH	GWh	59	177	198	206	226
Solar thermal in DH	TWh/year	1.00	1.77	2.00	2.10	2.32
Excess heat (industries, data centres and power-to-X)	TWh/year	1.30	11.46	11.46	11.73	12.21
Geothermal heat	TWh/year	0	5.32	5.95	6.20	6.80

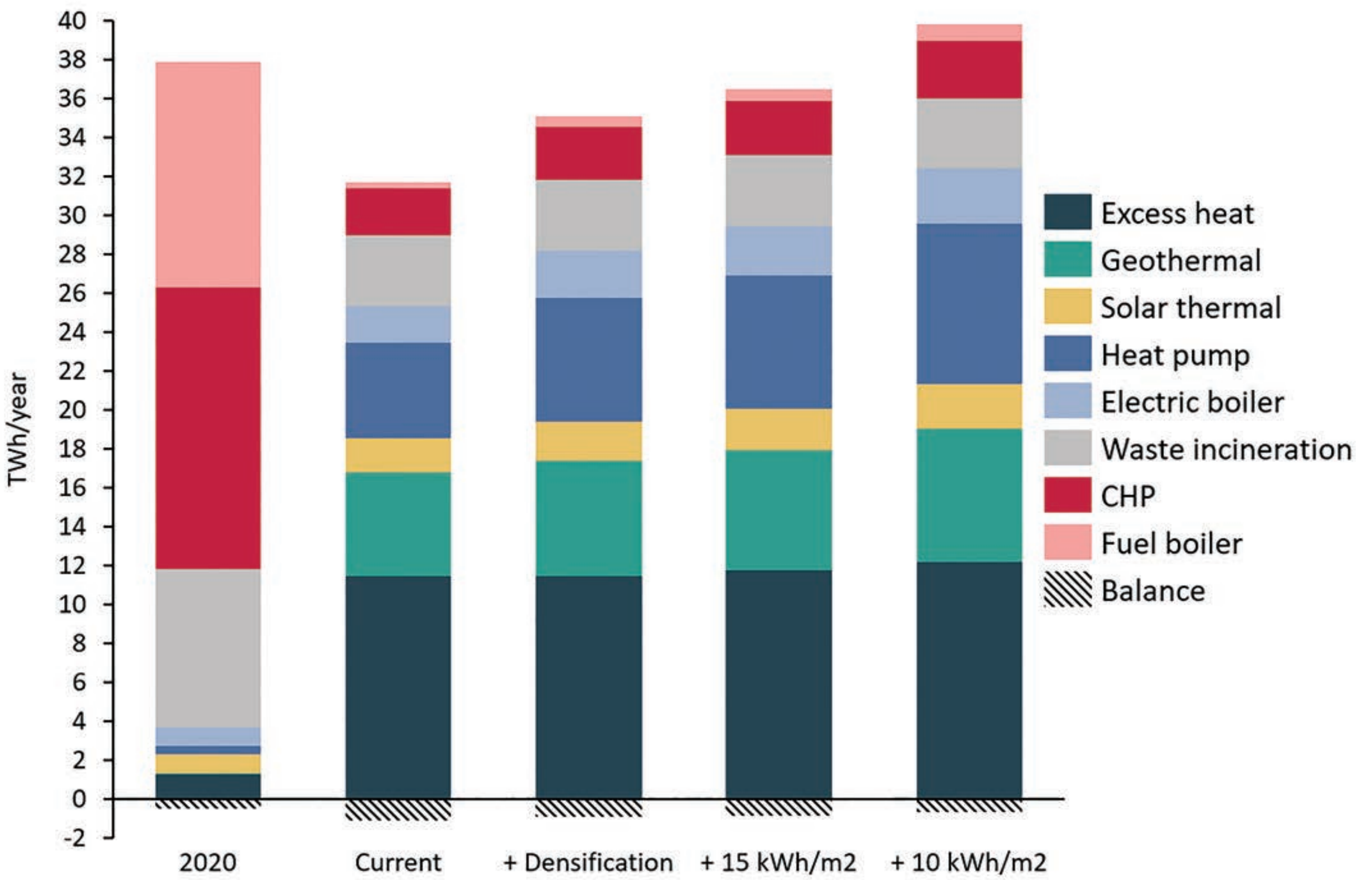

Figure 11: DH production by technology in 2020 and for each DH scenario in 2045.

category does not include waste incineration. It is relevant to have a reference that can be directly compared with the future scenarios, as shown in the 2020 column. In 2020, the Corona pandemic proved to influence the energy consumption [54], which needs to be considered. At the same time, a reference that is simulated by the same energy system model used for the future scenarios makes the results more directly comparable. The 2020 reference shown is an existing energy system model for 2020 modelled in EnergyPLAN from Sorknæs et al. [55], and is based on projections and statistics from 2018 and 2019.

Figure 11 shows the share of DH production by technology for the reference year 2020 and for each of the four DH scenarios for 2045, as they have been simulated in EnergyPLAN. The balance represents the potential overproduction of heat that cannot be utilised or stored, which mostly occurs in the summer period when the DH demand is low. In 2020, the system is primarily fuel boilers, CHPs and waste incineration, with a smaller amount of excess heat, solar thermal and electric boilers. It should be noted that this is the sum for all DH areas. These shares will vary greatly; thus, e.g., excess heat has a much larger share in the specific areas where they are present. In the 2045 systems, the heat production from fuel boilers is almost zero, the CHPs are reduced to around 8%, and waste incineration is also reduced from 22% to 9-12%. These are then replaced by HPs producing 16-21%, geothermal heat producing 17%, and excess heat from industries, data centres and power-to-X plants delivering 31-37% of the yearly DH production.

The scenarios are analysed based on their effect on the overall energy system. Specifically, focus is on the need for VRE capacities, electricity exchange, power plant operation, gas exchange and energy system costs. These are shown in Table 5. Total system costs are the sum of the variable costs, i.e., fuels costs and variable operation and maintenance (O&M) costs, fixed O&M costs and annualised investment costs.

The table shows that as DH is being expanded, the VRE capacity is slightly increased to keep the same level of curtailment. For comparison, the offshore wind power capacity was 1,7 GW and the PV capacity was 1,1 GW in 2020. This is because DH offers an increased flexibility option compared to individual HPs, and thereby allows for more VRE in the energy system at the same level of curtailment. This can be seen as even though the VRE capacities are increased, the yearly exchange of electricity is reduced with higher amounts of DH. In the modelling, the import and export of electricity on a yearly basis are kept at the same level with a transmission capacity of 6,000 MW. Though the yearly exchange is reduced, the peak import of electricity is slightly increased with increased DH amounts. This is due to the reduced use of power plants and increased use of CHP plants, which are utilised more with increased

Table 5: Main result parameters for each DH scenario

	Unit	**Current**	**Densifi-cation**	**15 kWh/m²**	**10 kWh/m²**
DH					
DH share	**%**	**51**	**59**	**63**	**70**
VRE capacities					
Offshore wind	MW	14,642	14,675	14,683	14,690
PV	MW	9,967	9,990	9,995	10,000
Electricity exchange					
Import/export electricity	TWh/year	4.4	4.24	4.22	4.17
Peak export of electricity	MW	6,000	6,000	6,000	6,000
Peak import of electricity	MW	5,806	5,875	6,000	6,000
Thermal plant operation					
CHP electricity production	TWh/year	3.19	3.54	3.6	3.78
Power plant production	TWh/year	1.58	1.07	0.91	0.61
Power plant peak production	MW	2,416	2,016	1,869	1,815
CHP and power plant peak	MW	5,939	5,960	5,971	6,023
Gas exchange					
Gas export	TWh/year	3,51	3,59	3,69	3,74
Gas exchange income	M€/year	98	101	104	105
Energy system costs					
Variable costs	M€/year	948	947	944	943
Fixed O&M costs	M€/year	4,372	4,357	4,351	4,311
Annual investment costs	M€/year	15,074	14,991	15,051	15,117
Total system costs	M€/year	20,394	20,295	20,346	20,371
Total system costs excl. gas	M€/year	20,492	20,396	20,450	20,476

implementation of DH. This can be seen in the yearly electricity production, but also in the yearly electricity production peak of power plants and the combined yearly peak of power plants and CHP plants. The increased use of CHP plants instead of power plants results in a reduced use of gas in the energy system, and thereby there is an increase in gas export as DH expands. At lower levels of DH, power plants are needed to a higher degree to balance the electricity demand from individual HPs in periods with low production of VRE. This effect on the gas balance is important in relation to the use of sustainable biomass, as the production of gas in the energy system is biogas, and by being able to export a larger amount of biogas, biomass consumption in connected energy systems can be reduced. From an energy system cost perspective, the lowest costs are found in the Densification and 15 kWh/m^2 scenarios, though the cost differences are only 0.1-0.5% of the total energy system costs in the Current scenario.

4. Conclusion

This paper studies how the heating sector on a national scale can develop as part of a future climate-neutral energy system. The focus is on using technological options that are feasible in terms of both economic and environmental impacts as part of the whole energy system. The methods applied are well known, using detailed geographic analysis in combination with hourly energy system simulations. The study uses Denmark as a case as the country has many years of experience with planning both renewable energy and heating systems. The specific results will differ for other countries, but here the focus is on the general learning outcomes in the form of both methods and technological options and their impact on the overall energy system.

First, the study examined how to implement energy efficiency measures in buildings to reduce the energy use and capacity needs of the whole supply system. The heat demand of the existing buildings was estimated by using the heat atlas method, mapping the annual heat demand of every single building in Denmark. This was combined with a cost model for energy efficiency measures that consider the building usage, age and size to estimate the cost of different levels of energy savings for each building. The marginal costs of heat savings were then compared to the marginal costs of heat production. The results showed a feasible level of around 36% reduction in the total heat demand, with higher potential in old buildings and lower in new buildings. Implementing energy efficiency measures in the existing buildings is a crucial part of the transition to carbon-neutral societies, as this reduces the requirements to the rest of the energy system. It reduces resource use and enables the use of technologies such as 4th generation DH and heat pumps. However, the implementation of energy efficiency measures also requires that the incentive structure and framework conditions for building owners are in place, as energy renovation needs to be attractive to happen. In this analysis, the focus is only on the socioeconomic aspects of implementing these measures, which are not necessarily in line with the private economy of a building owner.

The second part of the study examines the expansion potential for DH areas. Potential expansions were examined by summarizing the buildings by built-up areas and estimating the heat density and costs of deploying a DH network in the areas. Four DH scenarios were then developed; current DH, densification, 15 kWh/m^2 and 10 kWh/m^2, where the m^2 refers to the built-up land areas. The results show that expanding DH to areas with a density of 15-10 kWh/m^2 is feasible, resulting in a DH share of 63-70% of the heat demand compared to the current 51%. These results will vary from country to country as they depend on the urban structure of a country; in countries with a more urban structure, the potential would be higher, while it would be lower in countries with a more rural structure. DH is feasible at this level in the analysis because it reduces the need for investments in heat pumps and renewable energy by enabling the use of more efficient heat supply options, industrial excess heat, geothermal heat, large-scale heat pumps and potentially excess heat from power-to-X and data centres. Expanding DH can, however, be a challenge in many countries, especially the ones with no history of DH systems, but also in countries that have a lot of DH, like Denmark. Among the key enablers to make DH economically viable in an area are a high heat density and access to low-cost heat supply. However, it is not enough that the heat density is high in an area, a high connection rate is also needed. Thus, in practice, DH companies need to secure a high connection rate before a DH project can be implemented. The proposed scenarios in this analysis also include a shift to 4th generation DH systems, which also have many barriers, such as upgrading existing DH systems or ensuring that buildings are well insulated and suitable for low-temperature supply.

The third part of the analysis looks at the future DH production technologies. These heat sources can be divided into two groups: sources that can be geographically located using current data and sources that cannot be geographically located as they have not yet been built, but are expected to be built somewhere in Denmark due to societal development.

Excess heat from existing industries and geothermal heat, based on the expected potentials in the Danish underground, can be geographically located using current location data. The DH potentials from these sources are estimated for each of the four DH expansion scenarios, as an expansion of DH could utilise more of these sources. The results show a modest increase of industrial excess heat potentials in the DH scenarios, which indicates that most potentials are already within reach of the existing DH. It should be noted that around 2 TWh/year of industrial excess heat can be utilised directly, while around 3.5 TWh/year needs a heat pump to boost the temperature level to the DH temperature. For the energy system analysis, only a 75% share of the excess heat is utilised. Due to high investment costs and relatively low operational costs, geothermal heat generally needs to be operated as a baseload unit, thereby competing with excess heat sources and waste incineration for baseload operation. Due to heat savings in the end-use demand, the heating peak is reduced in IDA's Climate Response 2045 compared with current DH systems. As part of the DH demand is already covered by excess heat, and this should be given first priority, it is assumed that around 17% of the yearly DH demand can be supplied by geothermal heat in all scenarios.

For the unlocated heat sources, a large-scale integration of data centres into the Danish energy system is expected. In IDA's Climate Response 2045, the electricity consumption for data centres is assumed to be 9.5 TWh in 2045. The amount of excess heat that can be utilised depends especially on the placement of the data centres in relation to the DH areas as well as on the cooling technologies used in the data centres. The potential for data centre excess heat is, in theory, 100% of the electricity consumption, but not to overestimate in the analysis, 45% or around 4.3 TWh/year is used. Finally, like data centres, power-to-X technologies are expected to see a large integration into the Danish energy system, as they will be needed for producing fuels for sectors that cannot directly electrify, while keeping biomass consumption at a sustainable level. With the operation of power-to-X technologies in IDA's Climate Response 2045, this means that if all power-to-X facilities were placed where the excess heat could be utilised, the estimated potential would be around 2.96-3.86 TWh/year, depending on the development of the different power-to-X technologies. In this analysis, the lower potential of 2.96 TWh/year is used for all scenarios, giving again a relatively conservative estimate of the potential.

The third analysis shows that there are benefits to implanting these various sources in DH systems; however, there are also many uncertainties related to utilising these potentials. Some uncertainties are addressed by including a large variety of different sources and not utilising the full potential. The excess heat potential from existing industries is very beneficial, especially high-temperature sources; however, in the long term, some of these are relatively uncertain as the industries might not be there in the future. Geothermal heat has high investment costs and uncertainty in relation to the availability of the quantity of heat required. Data centres and power-to-x facilities might not be placed close to DH systems, and thus, these potentials can also be uncertain. Most of these heat sources are not owned by the DH companies, and thus, DH companies need to make agreements with providers of excess heat to ensure the heat production capacity.

Finally, the last part of the analysis examined the share of DH production by technology for 2020 and for each of the four DH scenarios for 2045. These shares will vary greatly; thus, e.g., excess heat has a much larger share in the specific areas where they are present. In the 2045 systems, the heat production from fuel boilers is almost zero, CHP is reduced to around 8%, and waste incineration is also reduced from 22% to 9-12%. These are then replaced by HPs producing 16-21%, geothermal heat producing 17%, and excess heat from industries, data centres and power-to-X plants delivering 31-37% of the yearly DH production. The analysis also shows the effect on the overall energy system. When DH is expanded, the VRE capacity is slightly increased to keep the same level of curtailment. The reason for this is that DH offers an increased flexibility option compared to individual HPs, and thereby allows for more VRE in the energy system at the same level of curtailment. Furthermore, the DH expansion also increases the use of CHP plants instead of power plants, resulting in reduced use of gas in the energy system, and thereby, an increase in gas export. This effect on the gas balance is important in relation to the use of sustainable biomass, as the production of gas in the energy system is biogas. With the ability to export a larger amount of biogas, this can replace biomass outside the country. In terms of costs, the lowest costs are found in the Densification and 15 kWh/m^2 scenarios, however, this is very similar in all scenarios, as the cost difference is less than 0.5% of the total energy system costs in the Current scenario.

While the focus of this research is on technical aspects, addressing other aspects, such as human factors, regulations, and feasibility, is crucial. Public acceptance and behavioural changes are key to adopting technologies like heat pumps and DH systems, as well as implementing energy renovations in buildings. To achieve these changes, engagement is required from homeowners, businesses, and communities. Additionally, upskilling the workforce through training is vital for successful implementation. Policies must align with climate goals. Financial incentives like subsidies and tax breaks can encourage adoption. Energy-efficient building codes and performance standards are essential. The scenarios depend on infrastructure readiness, requiring significant investments. Technological maturity must address local conditions, necessitating ongoing research and development. Governments should, therefore, set targets, fund projects, and create favourable regulations for the required changes. Private-sector innovation and partnerships are crucial, as is academic research to optimize technologies and assess impacts. Consumer participation, supported by awareness campaigns and affordability measures, is necessary. Achieving a renewable heating transition is technically feasible but demands collaboration and robust policies. Hence, policymakers should focus on long-term planning and proactive engagement to ensure a sustainable outcome.

Author contribution

Steffen Nielsen: Conceptualization, Methodology, Validation, Formal analysis, Data curation, Writing – original draft, Writing – review & editing. Peter Sorknæs: Conceptualization, Methodology, Validation, Formal analysis, Data curation, Writing – original draft, Writing – review & editing. Henrik Lund: Conceptualization, Methodology, Writing – review & editing. Brian Vad Mathiesen: Conceptualization, Funding acquisition. Diana Carolina Moreno Saltos: Methodology, Formal analysis. Jakob Zinck Thellufsen: Conceptualization.

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