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The benefits of 4th generation district heating and energy efficient datacentres

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ABSTRACT

This paper identifies the energy system benefits of transitioning district heating infrastructure from current 3rd generation district heating (3GDH) to 4th generation district heating (4GDH) with lower grid temperatures and more integration with other energy sectors. Previous papers have investigated the effect of going from 3GDH to 4GDH on a local perspective. In this paper it is investigated how this transition affects the energy system on a national level, where both the costs and energy effects are evaluated based on national hourly energy systems simulations including all energy sectors in a climate neutral energy system scenario. Moreover, the paper identifies the effects of different cooling solutions in datacentres. The analyses include effects on heat sources as well as the effect on the cost and losses in the district heating grid. This is done for the case of Denmark. In the case of Denmark, it is found that transitioning from 3GDH to 4GDH decreases the system cost by 220 M EUR/year, corresponding to 7 M EUR/TWh delivered heat at the end-user. Increasing the temperature outlet of datacentre waste heat has a value for the system as high as 52–59 M EUR/year, corresponding to 1.7–1.9 M EUR/TWh delivered heating at the end-user.

1. Introduction

A transition towards decarbonised energy systems is ongoing worldwide [1]. For a complete transition, all energy sectors need to be decarbonised, including the heating sector that accounts for the energy used for space heating and domestic hot water consumption. At the same time the heating sector has in previous studies shown to be useful for providing efficient and low-cost sector integration options, allowing for a better integration of variable renewable energy sources (RES) [2]. Especially when it comes to achieving cost-efficient solutions with regard to grid and storage infrastructures, the integration of the heating sector plays an important role [3]. Particularly district heating (DH) has been shown to be relevant in future renewable-based energy systems, as DH both allows for the utilisation of waste heat [4,5], e.g. from industrial processes and production of electrofuels, but also allows for low-cost heat storage options [6] and flexibility in the production by having a mix of energy conversion technologies [4,5,7], such as heat pumps (HP), electric boilers, and combined heat and power plants (CHP).

Integration of energy sectors alongside low-cost storage options is expected to become increasingly important in future decarbonised energy systems, as it is expected that these to a large extent will be based on variable RES to keep the utilisation of biomasses at sustainable levels [8,9]. At the same time, new buildings are built more energy efficient, and existing buildings are in many countries seeing increased energy efficient refurbishment to reduce the end-user energy demand [10]. All these changes raise many questions on how the future of the heating sector, and specifically DH, would look like.

Historically, DH has seen a continued reduction of grid temperatures and increased energy sector integration. This has been defined as a generational development by Lund et al. [10], which defines the current 3rd generation DH (3GDH) as having a supply temperature below 100 °C and a future upcoming 4th generation DH (4GDH) of having one around 50–60 °C. Going towards these lower temperatures in the grid would especially reduce the heat losses in the DH grids, increase the energy efficiency of energy conversion technologies, as well as allow for more efficient utilisation of waste heat. This increased utilisation of waste heat is especially important for low-temperature waste heat sources, such as

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datacentres [11].

Other studies have investigated the effects of a shift from 3GDH to 4GDH [12]. Some studies focus on the individual technologies, such as Averfalk and Werner [13] that investigated the effect of going from 3GDH to 4GDH temperature levels on the production cost of different heat supply technologies without including the rest of the energy system, and Geyer et al. [14] that did energy-economic assessments of nine different heat generation technologies. Other studies focus on individual DH systems such as Nord et al. [15] that investigated a reduction in supply temperature from 80 °C to 55 °C for a DH system in Norway, Romanov et al. [16] that investigated the effects of lowering the grid temperatures in the Moscow DH system, Pakare et al. [17] estimates the length and condition of the current DH network in Latvia to identify what a reduction in grid temperature would mean for national DH grid loss, and Ziemele et al. [18] that investigated the effects of lower grid temperatures and energy savings at consumers for a DH area in Riga. Whereas the previous studies have focused on effects in the DH sector only a few studies include the entire energy system. Sorknæs et al. [19] investigated the effects on all energy sectors of going from 3GDH to 4GDH for a 100% renewable municipal energy system, and Lund et al. [20] made a simplified assessment for a 100% renewable national energy system.

The aim of this paper is to build upon the simplified national assessments that previous studies have made of the energy system effects of going from 3GDH to 4GDH. This is done by including a detailed assessment of the effects on the DH grid through a national analysis using geographical information system (GIS) and a holistic national energy system analysis. A detailed GIS analysis requires a specific case area due to the need for having geolocated data available, and therefore in this study a case is used. The case used is the country of Denmark, more specifically the basis of this analysis is Heat Plan Denmark 2021 [21], that is a national analysis of the role of DH and individual heating in Denmark towards a fully decarbonised energy system.

The advantages of going from 3GDH to 4GDH have shown to be relevant in relation to the effects on the heat supply. Therefore, the effects on low-temperature waste heat sources are further investigated in more detailed by using datacentres as an example. The reason being that besides being a relevant waste heat source, the expected expansion of datacentres globally is posing a huge challenge to the transition of the energy system [22]. Already now, the communication technology sector, including datacentres, generates up to 2% of the global CO_2 emissions and worst-case scenarios indicate that this figure can increase to 23% of the global greenhouse gas emissions in 2030 [23]. Datacentres are estimated to have the fastest growing carbon footprint across the whole communication technology sector [24]. It is therefore important to consider datacentres in relation to the transition of the energy system, especially to the heating sector as large amounts of waste heat are expected from datacentres. The effects of utilisation of different cooling solutions in the datacentres are included, as the cooling solutions partly define the expected temperature level of this waste heat source. A few studies have been made with a focus on utilising datacentres waste heat for DH in a Finnish town [25] and for London [26]. Other studies have analysed the system value of datacentres with a flexible electricity demand [27]. However, no studies for any other country exist that look into the energy system effects of integrating waste heat from datacentres in 3GDH and 4GDH, respectively. Also, no studies have focused on how the development of different cooling solutions will influence such integration.

2. Methods

The methods used in this paper are based on a combination of GIS analyses and energy system analyses, where the GIS analyses are used to generate some of the input data used for the energy system analyses. The starting point of this work is Heat Plan Denmark 2021 [21] which is a continuation of the work IDAs Climate Response 2045 [28,29], but with a stronger focus on the heating sector in Denmark. The goal of this section is not to explain all aspects of Heat Plan Denmark 2021, but only the parts that are relevant for the comparison between 3GDH and 4GDH. The data used are the same as used in the Heat Plan Denmark 2021 work and for the same year.

2.1. GIS analyses

In Heat Plan Denmark 2021, various GIS analyses were carried out to estimate heat demands of buildings, energy efficiency measures in buildings, DH expansions, industrial waste heat and geothermal heat. The following sections summarizes the method behind each analysis.

2.1.1. Heat demand in buildings and energy efficiency measures

The heat demands of buildings were estimated based on a heat atlas methodology [30,31]. The heat atlas methodology uses data from the Danish Building Register (BBR), where information on all buildings in Denmark is stored and updated regularly by building owners. The annual heat demand for each building is not included in the BBR register but the register includes other detailed information on the buildings, which can be used to estimate the annual heat demand of each building. To estimate the heat demands the buildings' floor area, usage type, and construction year was used as the primary attributes. The Danish Heat Atlas includes 103 building usage types and 9 construction periods. For each combination of these the annual heat demand in kWh/m^2 is estimated. The estimation was done through a statistical analysis that combines the information from BBR with heat sales from the energy suppliers. Finally, the specific heat demand in kWh/m^2 was multiplied with the floor area of each building giving an annual demand in MWh per building. The Danish Heat Atlas includes 1,996,304 buildings in total with a total estimated heat demand of 54 TWh/year.

Energy efficiency in buildings is an important aspect in the energy transition. Energy efficiency measures have been implemented in The Danish Heat Atlas by using the same categorisation of building usage type and construction period as for the heat demand estimate model. The energy efficiency potential has been analysed in a report by the Danish Building Research Institute from 2017 [32], where the saving potential for seven different measures were included. In Ref. [33] a more detailed overview of the specific energy efficiency measures can be found. In Heat Plan Denmark 2021 an energy saving scenario reaching an average saving of 36% was used. All scenarios presented in this paper include this energy saving scenario.

2.1.2. District heating grid expansions

Expansions of DH to new areas were in Heat Plan Denmark 2021 analysed for five different expansion scenarios based on the heat density of the built-up areas in Denmark. For each DH expansion scenario, investment costs and heat losses in the grid were calculated for both 3GDH and 4GDH temperature levels. The cost of the DH grid extensions was calculated based on a GIS model that uses the estimated heat consumption in the buildings to estimate the size of the DH pipes and the road network to find the length of the pipe network. This GIS model should be seen as a general tool that is more detailed than simply applying a cost based on heat density, but less detailed than the specific planning carried out in a utility company, that would typically also include detailed hydraulic calculations. The advantage of the applied method is that it considers the location of the buildings in relation to each other, as even with the same heat density, there can be a big difference in the layout of urban areas, which will affect the design of the distribution network and ultimately affect both heat loss and investment costs. The detailed model was used in two steps, first it was applied directly in 3174 areas and afterwards the detailed model output was generalised in a regression analysis, that was then applied for all areas, as to ensure that all areas were treated equally in the model. The main Heat Plan Denmark 2021 scenario proposes a DH expansion that covers built-up areas with a heat density of at least 10 kWh/m^2, where the m^2

refers to the size of the built-up area. In this paper only this expansion scenario is included. It should be noted that the areas are defined by local municipalities and can vary in size and scope, e.g., an area can be a park area with a few buildings and this area will be found as having a low heat density. Also, the method does not for instance merge two neighbouring areas.

Table 1 shows both the pipe dimensions that are included in the analyses, as well as the associated investment costs. The investment costs include costs for materials as well as pipe and excavation work within urban areas. The method used for identifying pipe dimensions and grid layout is described in Nielsen and Grundahl [34]. The method is used as a general national method, and as such, do not include potential regional differences in for instance labour costs. Capacity and heat loss are calculated based on temperature sets 80 °C/40 °C for 3GDH and 60 °C/30 °C for 4GDH. For all pipes, an average heat loss coefficient for series 2 pipes of 0.335 W/m^{2}K and a ground temperature of 8 °C are used to estimate the heat losses.

As explained earlier, a detailed GIS calculation for all the existing DH areas were not performed in the analysis. The development of DH grids is the result of historic developments which a model would not be able to reconstruct. Furthermore, the details of the existing DH grids in Denmark were not available for this analysis. Therefore, a more generalised approach using a power regression analysis was performed to create a correlation between heat densities and heat losses for all the areas, using the 3174 expansion areas calculated in the detailed GIS model. The power regression analysis was used as it has shown to have the best fit compared to a linear regression.

2.1.3. Geothermal heat

Geothermal heat is subsurface heat that can be utilised for energy purposes. Generally, geothermal heat is typically divided into shallow and deep geothermal sources and in this paper only on the deep geothermal potential for DH is included, which is expected in the depths of 800–3000 m [36]. A screening of the deep geothermal potential in 28 DH areas found that it is the DH demand that sets the limitations for the utilisation of geothermal heat for DH in Denmark [37].

To identify the geothermal energy potential, costs, and electricity consumption of utilising geothermal heat for DH, five geographical areas were identified based on their expected good geothermal potentials, being: the town of Aalborg, Central Denmark Region, northern Zealand, southern Zealand and the town of Sønderborg. For each area, costs and electricity consumption were identified for both 3GDH and 4GDH, and by using GIS a geothermal energy potential was estimated based on the mapped local DH demands and DH expansion potentials within these regions. The geothermal wells were assumed to be at least 10 MW each to be economic feasible. Depending on the scenario for DH demand, e.g., in relation to DH expansions and energy efficiency measures in buildings, the geothermal potential in Denmark was found to be upwards of 20 TWh/year. In the Heat Plan Denmark 2021 main scenario 6.79 TWh geothermal heat are utilised in the DH systems.

The investment cost for geothermal with 4GDH was found to be 175 M EUR/TWh with a yearly fixed operation and maintenance (O&M) of 4.06% of the investment cost. The costs are found based on an assumption of 7500 full load hours per year. The electricity consumption for operating the geothermal was found to be corresponding to an average coefficient of performance (COP) of 4.9. With 3GDH the geothermal heat was found to have a higher costs and lower COP, as it needs to provide a higher supply temperature for the DH grid. The cost for geothermal at 3GDH was found to be 180 M EUR/TWh with a yearly fixed O&M of 4.01% of the investment cost and an average COP of 3.8.

Table 1
Investment costs, capacities, and heat loss for the DH grid with 3GDH and 4GDH. Investment costs from [35].

Pipe dimensions		3GDH		4DGH	
[mm]	Investment [EUR/m]	Capacity [MW]	Heat loss [w/m]	Capacity [MW]	Heat loss [w/m]
48.3	416	0.17	8.3	0.13	5.9
60.3	474	0.31	9.7	0.23	6.9
76.1	567	0.59	12.5	0.44	8.9
88.9	671	0.90	15.3	0.67	10.9
114.3	805	1.74	18.4	1.31	13.1
139.7	954	2.99	24.0	2.24	17.1
168.3	1054	4.90	29.9	3.67	21.3
219.1	1204	9.88	35.5	7.41	25.2
273	1442	17.60	44.5	13.20	31.7
323.9	1746	28.10	55.6	21.08	39.6
406.4	2081	50.99	66.8	38.25	47.5
508	2465	91.94	77.9	68.95	55.4

2.1.4. Industrial waste heat

Generally, waste heat comes in two forms; direct and indirect. Direct waste heat is waste heat that can be delivered without the need for temperature boosting, and indirect waste heat is waste heat that is at a so low temperature that boosting is needed, most commonly via a HP, to utilise it. Here it is assumed that all indirect waste heat needs an electric-driven HP to be utilised. Cost-wise it is assumed that direct waste heat has an investment cost of 30 M EUR/year [38]. Indirect waste heat is assumed to have an investment cost of 109 M EUR/TWh, assuming an investment cost of 0.76 M EUR/MW$_{th}$ [39] and assumed 7000 full load hours per year for the installation. In this, waste heat is seen as coming from three different sources, being; existing industries, Power-to-X (PtX), and datacentres.

The method for mapping industrial waste heat from existing industries is described in detail in Moreno and Nielsen [40]. Existing industries were mapped based on data from the Danish Central Business Register (CVR), combined with a top-down model that distributes energy consumption by NACE2 classifications and company size. The waste heat potential was estimated by using typical processes for each NACE2 classification [41,42]. The CVR data includes the specific location of all the companies, and thus it was possible to link this to the DH areas and DH expansion scenarios. The estimated waste heat potential from industries was added to the waste heat that is already being utilised from industries. The industrial waste heat has been categorised into three different temperature ranges, being; <60 °C, 60–80 °C, and >80 °C. This categorisation is made due to the different forward temperature levels with 3GDH and 4GDH. It is assumed that for 3GDH HPs are needed for temperatures <80 °C, and for 4GDH it is needed for temperatures <60 °C. This is a simplification, as it would be possible to utilise e.g., 70 °C waste heat in 3GDH if another unit can deliver at a higher temperature thereby making up for the lower temperatures from 3GDH. Thereby, this simplification can be seen as resulting in a conservative high level of HPs for utilising waste heat from industries. For the Heat Plan Denmark 2021 scenario it is found that 0.9 TWh more industrial waste heat could be utilised at temperatures higher than 80 °C, 0.65 TWh are between 60 and 80 °C, and 3.81 TWh are <60 °C. Due to uncertainties in the method utilised, it was for the Heat Plan Denmark 2021 scenario chosen to only use around 75% of this waste heat, assuming that first the high temperatures will be utilised. For calculating the COP of the HPs required for temperature boosting, it is assumed that the average temperature for the <60 °C category is 30 °C that via the HPs are reduced to 20 °C in average, and for the 60–80 °C category it is assumed to be 65 °C in average and that it is reduced to 35 °C in the HPs. The HPs are assumed to have a Lorentz efficiency of 50% [39]. This means that with 3GDH, the average HP COP in the <60 °C category is 4.5 and, in the 60–80 °C category, it is 13.7, resulting in an average COP for both categories with 3GDH of 6.73. With 4GDH the average COP for the <60 °C category is found to be 8.

PtX and datacentres are currently not widely implemented in Denmark, but are both expected to see a large expansion in the near future, though the location of these are not know, and therefore cannot be evaluated based on their geographical locations. In the Heat Plan Denmark 2021 scenario, the utilised waste heat from PtX is 2.1 TWh/

year, out of an estimated potential of 2.96–3.86 TWh/year. In this it is assumed that the waste heat from PtX is unchanged between the 3GDH and 4GDH scenarios, and that the higher forward temperatures in 3GDH do not result in the need for HPs for utilising the waste heat from PtX. This assumption is a simplification due to the uncertainties related to the development of PtX. This simplification likely favours the 3GDH scenario.

For datacentres it is assumed that 50% of the electricity demand results in waste heat that can be used for DH. It is estimated that the electricity demand for datacentres will increase significantly in Denmark, from around 0.88 TWh in 2020 to around 7–14 TWh in 2045 [43]. In Heat Plan Denmark 2021 it is assumed that the electricity demand for datacentres increases to 9.5 TWh, resulting in 4.8 TWh waste heat being potential to utilise for DH. It is assumed that the datacentres will use direct water-cooling, allowing the waste heat to be delivered to the DH at 60 °C [43]. The effect of this assumption is tested as a sensitivity analysis, where the energy system effects of instead using air-cooling is tested. At 60 °C this waste heat can be utilised directly in 4GDH, and indirectly with a HP in 3GDH. Assuming that the waste heat is cooled from 60 °C to 35 °C in the HP and that the HP has a Lorentz efficiency of 50% the COP is found to be 11.4.

2.2. Energy system analyses

The energy system analyses are done in the energy system analysis tool, EnergyPLAN. EnergyPLAN has been used for several national energy system analyses [44] and was used for developing the Heat Plan Denmark 2021 scenario for Denmark. EnergyPLAN chronologically simulates hourly energy balances of the modelled energy system including all energy sectors for one leap-year. The simulation includes energy conversion technologies, storages and import and export of electricity and gas [45].

An overview of the included elements and their connections can be seen in Fig. 1.

The result of the simulation is hourly energy balances incl. fuel consumption, as well as yearly costs of the energy system, including annualised investment costs. The investment costs are here annualised using an interest rate of 3%. The Danish state recommends socio-economic calculations to use 3.5% for the first 35 years of a project and 2.5% for following 35 years [47]. This means that the used interest rate is 0.5%-points lower than that recommended by the Danish state, however, as some of the investments have a longer lifetime than 35 years this lower discount rate has been used. EnergyPLAN has two general simulation strategies for choosing how to operate the different technologies, being; technical simulation strategy and market economic strategy [45]. In this study the technical simulation strategy is used, as it is independent of existing energy market structures, and aims at reducing the fuel consumption of the energy system. In this work EnergyPLAN version 16 is used.

2.2.1. Inputs for the energy system analyses in EnergyPLAN

The Heat Plan Denmark 2021 scenario has been described in Ref. [21]. The scenario is built using 4GDH, and as such, it is important to define how 3GDH differs from 4GDH. Other sources have identified differences in efficiencies and costs between 3GDH and 4GDH. The differences used in this are based on previous analyses, where Table 2 shows the expected differences between 3GDH and 4GDH for production and storage technologies. The 4GDH values are taken from the Heat Plan Denmark 2021 scenario, and the 3GDH figures are calculated via the differences found between the previous analyses between 3GDH and

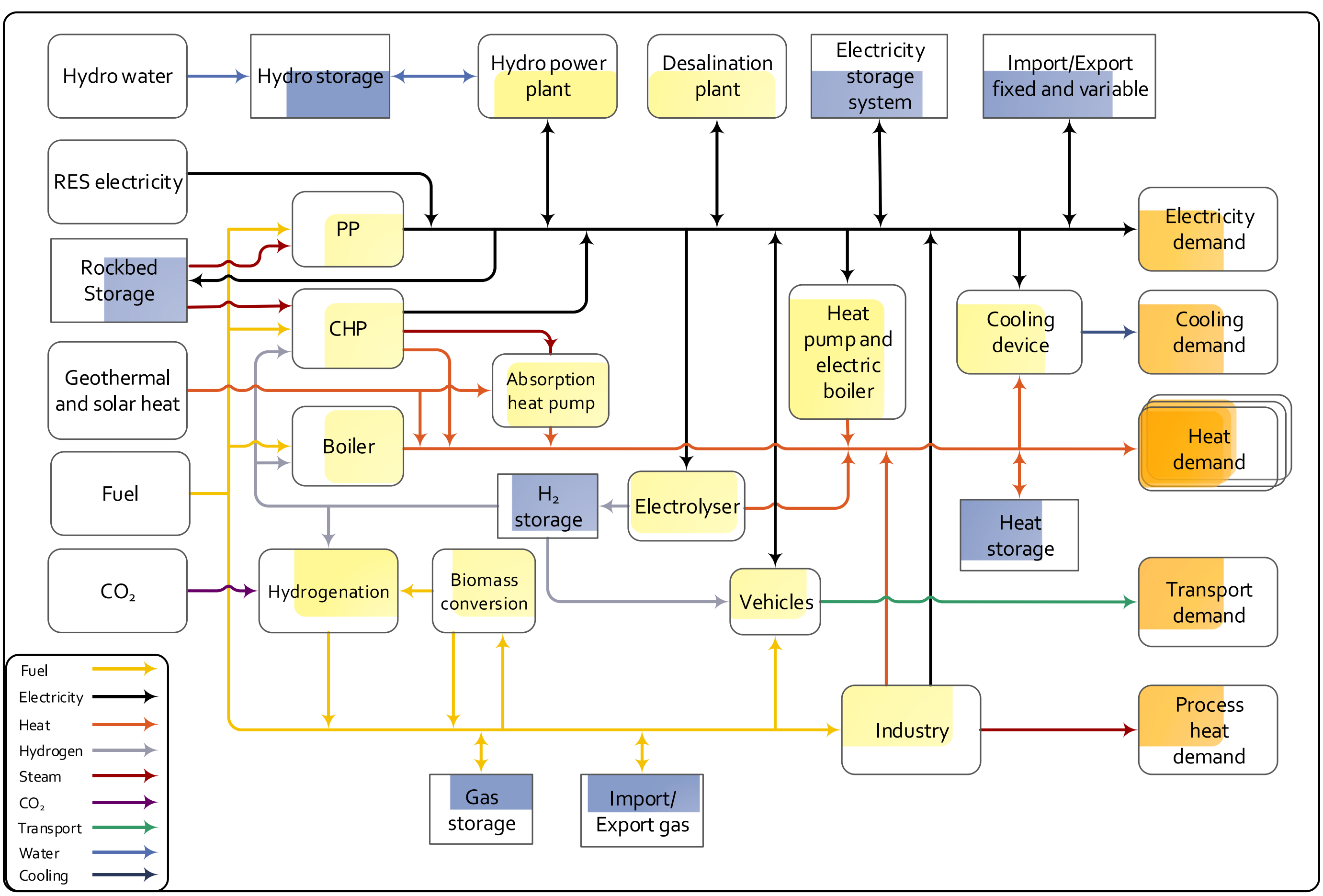

Fig. 1. Overview of energy demands, energy conversion technologies, energy storage technologies and energy resources included in EnergyPLAN v 16 [46].

Table 2
Changes in efficiencies, COP, and investment costs in 3GDH and 4GDH, excl. DH grid, buildings, geothermal and waste heat.

	3GDH	4GDH	*Source for 3GDH*
Efficiencies and COP			
DH-based HPs – COP	2.9	3.9	[19]
Gas engines – heat eff	43%	48%	[19]
Waste incineration – heat eff	70%	80%	[20]
Combined cycle gas turbine – heat eff	22%	27%	[20]
Single cycle gas turbine – heat eff	43%	45%	[19]
Investment costs			
Solar thermal [M EUR/TWh]	505	355	[20]
Short-term DH storage [M EUR/GWh]	2.5	3.0	[19]

4GDH. Therefore, only the sources used to find this difference are given in the table.

In addition to the differences shown in Table 2, it is also expected that there will be an additional cost for retrofitting buildings to prepare them for 4GDH, due to the lower temperature levels compared to 3GDH. The costs for this are based on [20]. It is assumed that the buildings have an average distribution of the heat demand of 80% for space heating and 20% for hot water. The cost of retrofitting buildings for 4GDH is expected to be 0.65 EUR/MWh space heating for radiators and 2 EUR/MWh hot water. In addition, it is assumed that 20% of the buildings will need extra Legionella treatment at a cost of 13.4 EUR/MWh hot water. These costs are expected to be averages, and potentially can vary from building to building depending on existing heating system.

2.2.2. Making comparable energy system scenarios

When shifting from 3GDH to 4GDH the total DH production is expected to change due to reduced heat loss in the DH grid with 4GDH. To make comparable scenarios, adjustments are made to the DH production and storage units, so that they reflect this lower production need with 4GDH. The different DH technologies handle different tasks in the DH system, which is why they are varied differently. In the scenario, the role of fuel boilers is first and foremost to function as peak and reserve load, which is why their capacity is changed only in relation to the change in peak load DH production. The role of CHP plants, HPs, solar thermal collectors and heat storages is more aligned with the annual need for DH production, whereby their heat capacities are changed in relation to relative changes in the annual DH production including grid losses. The input to waste incineration plants is not expected to be related to a change in the DH demand, and therefore this is kept unchanged when the DH demand including grid loss is changed. Likewise, the capacity of electric boilers is not changed, as their role must be seen more in the context of balancing the electricity system.

Similarly, to adjusting the DH production capacities due to changes in DH production needs, it is also important to ensure comparable energy system scenarios for the overall energy system. The energy system models are set so that the yearly net electricity exchange is always zero, and the biomass consumption in the energy system is kept constant, as the power plants (PP) and DH production units utilise upgraded biogas. The biogas production is limited by the available resources in Denmark, and will be assumed to be unchanged. Instead, the energy system scenarios are made comparable by ensuring the same yearly export of upgraded biogas to the surrounding Europe and the yearly critical waste electricity production (CEEP). CEEP is electricity produced that cannot be used, stored or exported at the time of production, meaning that in a real-world application it would result in e.g. curtailment of wind power. In the Heat Plan Denmark 2021 scenario the net biogas export is 3.74 TWh/year and the CEEP is 4.97 TWh/year. These two are ensured balanced by adjusting the marginal variable RES capacity and direct electrification of DH.

The marginal variable RES is here seen as a combination of offshore wind power and photovoltaics (PV). The potential for offshore wind power in Danish waters has been estimated to be 40 GW [48], and in Heat Plan Denmark 2021 14.69 GW is installed. The PV potential has been estimated to be 20 TWh/year on large roof-tops alone [49], and in Heat Plan Denmark 2021 12.16 TWh/year are installed. Therefore, both these can be expanded as needed for the analyses, and a combination of these will provide a better integration of variable RES in the electricity system, due to their different variability through the year. Adjustments to the marginal RES will be done so that their relative interrelation is unchanged.

For direct electrification of DH, HPs are used in connection with heat storages. HPs and heat storages allow for an efficient and flexible connection between the marginal variable RES, and as in Heat Plan Denmark 2021 around 87% of the gas consumption is used for CHP and DH based fuel boilers, this connection can be used to affect the gas consumption in the system. When adjusting the HP capacity in DH the heat storage capacity is adjusted by the same percentage. In Heat Plan Denmark 2021, 540 MW_e HP are installed alongside 177 GWh of heat storages. The DH HPs here are excluding the HPs required for temperature boosting at industries. All other technologies are kept unchanged between the scenarios.

3. Results and discussions

The results are first shown for the GIS analyses, and then for the energy system analyses.

3.1. GIS assessment of district heating grid losses and network costs

The map in Fig. 2 illustrates an example of a result for an urban area, where the detailed GIS grid expansion model is used to create a DH distribution network that can supply all buildings in the area. The example shows the resulting network for both 3GDH and 4GDH temperature levels, respectively. Here it is seen that the model connects all buildings to a hub (the blue dots on the map in Fig. 2). The hub is chosen as a random central location for each urban area. In a specific planning, there will be several considerations in relation to the context for each city, but since the model is run on 3174 built-up areas, a deep individual assessment has not been possible. To find the distribution network, the model uses the shortest routes between each building and the hub. The routes where there is overlap between several buildings share a distribution line and therefore it is seen that towards the junction there is a need for larger distribution lines up to 219.1 mm in thickness, where the branch lines close to the buildings are typically 48.3 mm used. At the 4GDH temperature levels some connections need slightly larger pipes, in the example the largest pipe is 219.1 mm with 4GDH while it is 168.3 mm with 3GDH. This means that the investment for each area will be slightly higher in a 4GDH situation.

As described in the methods section, the detailed DH expansion model was applied as a first step to serve as input for a more generalised regression model, that was applied to all areas. The regression model is established based on the estimated grid loss and the heat density from the detailed DH expansion model. The regression analysis is carried out for 3GDH and 4GDH, respectively. Fig. 3 shows the formulas found from the regression model for 3GDH and 4GDH, respectively. It must be emphasized that the loss is stated as a percentage of the final demand in the buildings, i.e., that it would be lower if it were stated as a percentage of the delivered DH demand incl. grid loss. Fig. 3 shows that heat loss decreases with high heat densities and that 4GDH is lower than the corresponding scenario with 3GDH. It should also be noted that the R^2 only shows to be approx. 0.877 for both cases, meaning that the relation is not significant but is assumed to be acceptable in a general model like this. The formulas found in Fig. 3 are used on all areas to estimate the grid loss of each of these based on the calculated heat density of these DH areas.

In Heat Plan Denmark 2021 it was found feasible to go to all built-up areas with a heat density of at least 10 kWh/m^2. With this expansion, 493,099 buildings, corresponding to an end-user heat demand of 7.6

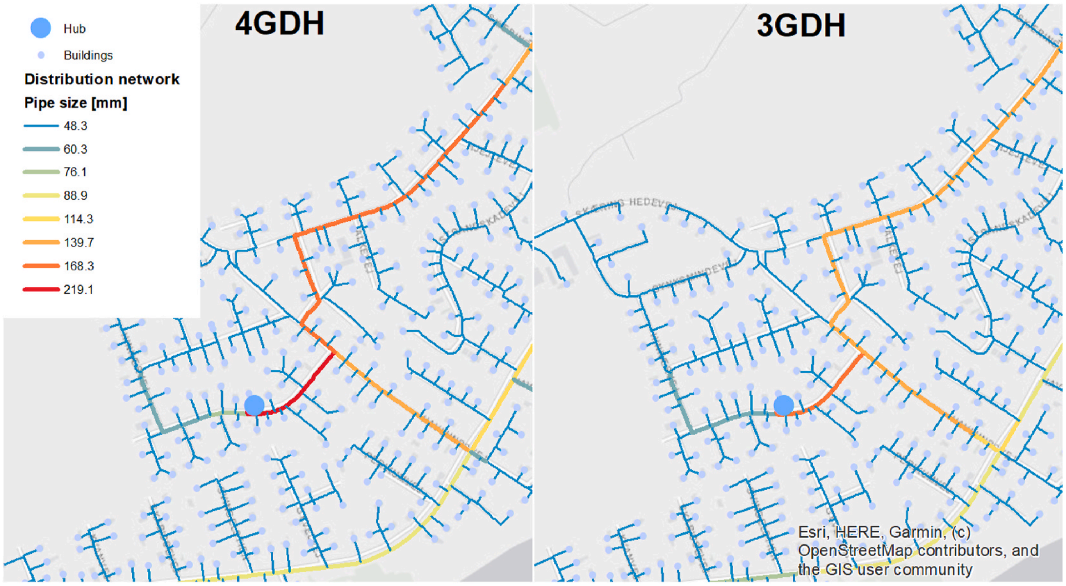

Fig. 2. Example of output of the distribution model for 3GDH and 4GDH incl. Heat savings in buildings.

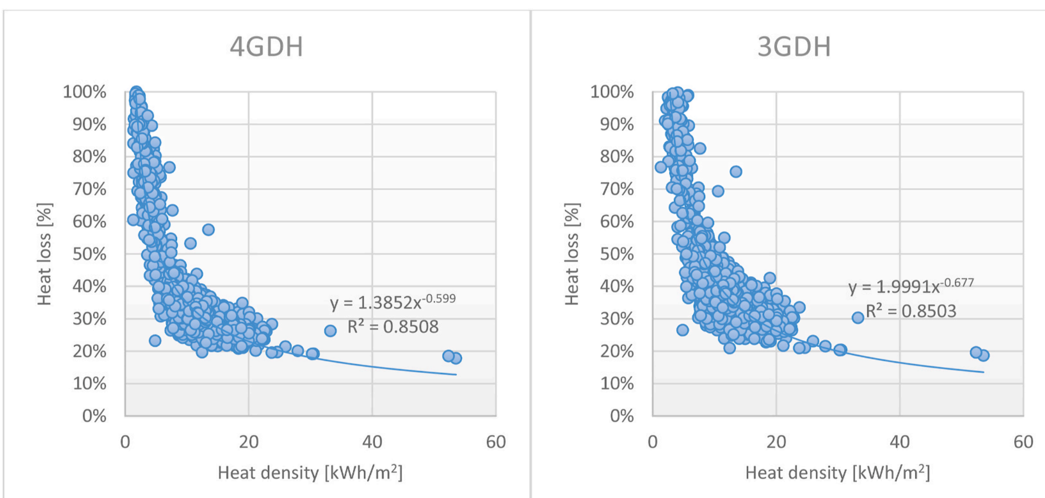

Fig. 3. Regression analysis to estimate grid loss in DH areas in relation to heat density.

TWh/year, are moved from individual heating solutions to DH. This means that in Heat Plan Denmark 2021 DH covers about 70% of the heat demand in Denmark, with the rest being delivered by individual HPs. Using the regression model the heat loss, incl. losses in the substations, in these DH expansion areas is found to be approx. 0.95 TWh/year with 3GDH and 0.76 TWh/year with 4GDH, corresponding to an average heat loss for these areas of 18.3% and 15.1%, respectively. For the existing DH areas, the grid loss is found to be approx. 6.12 TWh/year with 3GDH and 5.26 TWh/year with 4GDH, corresponding to an average heat loss for these areas of 23.0% and 20.4%, respectively.

Besides the heat loss, transitioning from 3GDH to 4GDH can affect the cost of the DH grid, due to the lower ΔT with 4GDH. For the new areas, the grid costs are found to be 304 M EUR/year with 3GDH and 314 M EUR/year with 4GDH, based on the detailed GIS model. However, for the existing DH areas, the cost difference is hard to estimate without the detailed network model. Alternatively, a regression analysis could be used, however, where a reasonable correlation can be found with respect to grid loss and heat density to estimate losses in all areas, the same correlation cannot be found for the cost of the grid. This is due to the non-linear effect of the different pipes used shown in Table 1. Here a minor increase or decrease in needed capacity can either mean that the existing pipe is sufficient or that a different pipe size is needed, resulting in non-linear connection between increase or decrease in energy flows and cost. Instead, the potential increase in cost with 4GDH for the existing grid is discussed using findings from other works. The increase in cost was in Lund et al. [20] estimated to be 0–10 M EUR/year for the existing DH grids in Denmark with a total yearly cost of the existing DH grids of 932 M EUR in 4GDH. Lund et al. [20] assumes a change in ΔT for the design temperatures of the grid of 5 K, whereas in this work it is assumed to be 10 K. With a change in ΔT of 10 K, the DH grid expansion costs with 4GDH are here found to be around 3% more expensive when a new grid has to be made for an area, due to increased pipe sizing in some areas. With the total grid costs from Lund et al. [20] this result in an increase in costs for existing grids of 27 M EUR/year. As such, the cost is expected to be in the range of 0–27 M EUR/year. However, it should be noted that these costs include significant uncertainties as the layout of the existing DH grids are not known, and these are likely to be more complex than those modelled due to being developed and expanded over many years.

3.2. Energy system analysis of 3GDH and 4GDH

The results from the GIS analyses are used as input to the energy system analyses, as described in the methods section. To keep the yearly net gas exchange and CEEP balanced there are added extra 383 MW offshore wind power, 261 MW PV, 610 MW_e DH HP and 200 GWh heat storages to the 3GDH scenario compared with the 4GDH scenario. The increase in offshore wind power and PV means that the primary energy consumption of the 3GDH scenario is 2.1 TWh/year larger than for the 4GDH scenario.

The DH production of the two scenarios is shown in Fig. 4. Here it can be seen that the DH production is 1.33 TWh/year larger with 3GDH due to increased grid losses. Due to the less efficient CHP technologies in the 3GDH scenario the DH HPs need to produce more as to reduce the fuel consumption of these, both to make up for the less heat produced by waste incineration and to ensure the same net yearly gas exchange in the two scenarios, where the gas consumption for CHP is 0.66 TWh/year larger in the 3GDH scenario, and the PP and boiler consumption is 0.66 TWh/year larger in the 4GDH scenario. This larger DH HP production also reduces the utilisation of the electric boilers in the 3GDH scenario.

Cost-wise, 4GDH provides a reduction in energy system costs of 220 M EUR/year, excl. potential costs for upgrading the existing DH grids, compared with 3GDH. The potential additional cost for existing grids with 4GDH is expected to be 0–27 M EUR/year. This reduction corresponds to 7 M EUR/TWh DH delivered at the end-user. The reduction in costs stems from a reduction in investment costs of 166 M EUR/year, a reduction of 52 M EUR/year in fixed O&M costs, and a reduction of 2 M EUR/year in variable costs. The variable cost difference is due to a small reduction in variable O&M costs in 4GDH. An overview of the reductions in investment and fixed O&M per type of technology is shown in Fig. 5. Here it is shown that the reductions for 4GDH mainly come from a reduction in DH HPs and offshore wind power, which are the technologies used in the method for ensuring similar CEEP and yearly net gas export balances. If the DH HP and offshore wind power capacities at 4GDH were used instead in the 3GDH scenario then the total cost reduction of 4GDH would instead be 132 M EUR/year, however, the yearly net gas export from the Danish energy system to the rest of Europe would also decrease from 3.7 TWh/year to 1.0 TWh/year, meaning it is less likely that the system adheres to a sustainable amount of biomass, as the Danish energy system has relatively large potentials for biomass compared with EU in general, and therefore is expected to export biomass products.

As the effects are largest on the investment cost the results are also somewhat sensitive to a variation in the interest rate. If the interest rate was instead 1% then the reduction in energy system costs would instead be 180 M EUR/year, and if it was 5% it would be 266 M EUR/year.

3.2.1. Waste heat from datacentres

In the previous analyses it is assumed that waste heat from datacentres can be used directly for 4GDH without HP for boosting. However, for this assumption to stand, the datacentres must be built with direct water-cooling as this allows for an output temperature of 60 °C to DH. Currently, many datacentres are build using air cooling, which has shown to provide temperatures around 25 °C for DH, meaning that HPs are needed for temperature boosting. As the datacentres make up a large share of the waste heat utilised for DH in the scenario used, it is here analysed what the effects of using air cooling instead are on the 3GDH and 4GDH energy system scenarios.

The waste heat output from the datacentres is assumed to be 4.79 TWh/year, which corresponds to approx. 50% of the electricity input for all datacentres. It is assumed that with air cooling the heat output from the datacentres are 25 °C and this will be cooled to 15 °C in the HP. The HP is assumed to have a Lorentz efficiency of 50%. With 4GDH the DH return is 30 °C and the DH supply needs an output of 60 °C, which gives a COP of 6.4. With 3GDH the DH return is 40 °C and assuming a DH supply of 85 °C the COP becomes 4.0.

For 4GDH this means that an extra electricity demand is added to the energy system of 0.75 TWh/year, which is assumed to be relatively constant distributed through the year. The investment cost for this waste heat is assumed to change from 30 M EUR/TWh to 109 M EUR/TWh. Again, the marginal RES and direct electrification capacities are used to balance the yearly net gas exchange and CEEP. This results in an increase of the offshore wind power capacity of 113 MW, an increase in PV of 77 MW, an increase in DH HP capacity of 50 MW_e, and an increase in heat storages of 16 GWh. The primary energy supply is increased by 0.6 TWh/year due to the increased marginal RES capacities. Cost-wise, this result in an increase of the total energy system cost of 52 M EUR/year corresponding to 10.9 M EUR/TWh utilised waste heat and to 1.7 M EUR/TWh delivered heating at the end-user, when compared with the datacentres using direct water-cooling. If the energy system scenario would not be balanced, the cost increase would instead be 33 M EUR/year.

Using the same method for 3GDH, the offshore wind power capacity is increased by 70 MW, the PV is increased by 48 MW, the DH HP is increased by 270 MW_e, and the heat storage capacity is increased by 89 GWh. Compared with the direct water-cooled datacentres. The primary energy supply is increased by 0.37 TWh/year due to the increased marginal RES capacities. Cost-wise, this result in an increase of the total energy system cost of 59 M EUR/year corresponding to 12.3 M EUR/TWh utilised waste heat and to 1.9 M EUR/TWh delivered heating at the end-user. If the energy system scenario would not be balanced in relation to the gas exchange and CEEP the cost increase would instead be 33 M EUR/year.

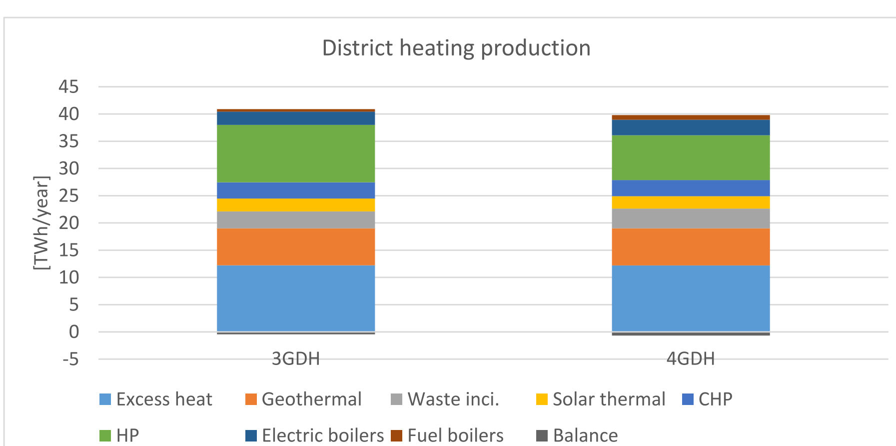

Fig. 4. DH production for the 3GDH and 4GDH scenarios, respectively.

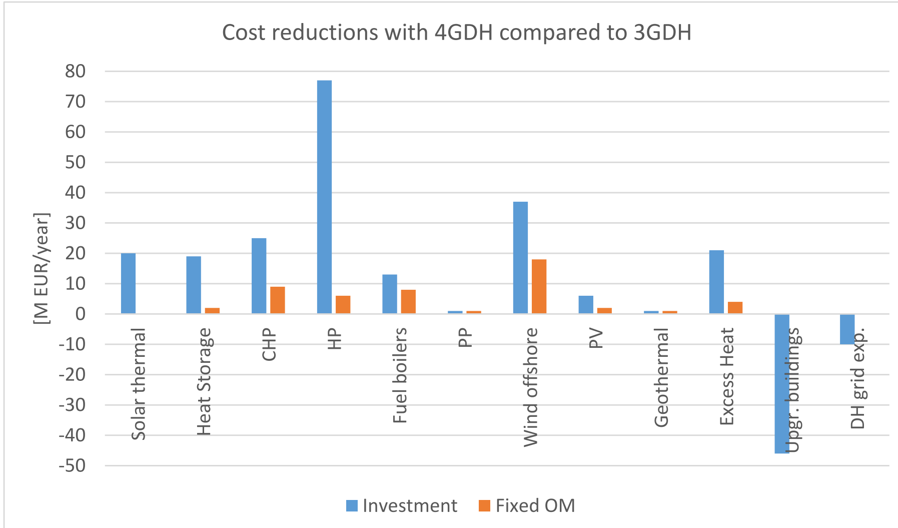

Fig. 5. Cost reductions with 4GDH compared to 3GDH, excl. potential cost for the existing DH grid. Positive values reflect cost reduction while negative values are increased costs.

4. Conclusion

In this paper the energy system benefits of transitioning district heating infrastructure from current 3GDH to 4GDH are analysed. 4GDH utilises lower grid temperatures and allow for a better integration with other energy sectors. This is analysed for the case of Denmark, where a future climate-neutral national energy system scenario is used. The analysis includes both GIS analyses and energy system analyses. The GIS analyses are used to estimate the DH network costs and heat losses, DH potential and heat sources from industrial waste heat and geothermal heat. The energy system analysis is used to estimate the effects on the national system energy system in terms of primary energy and costs. The energy system analyses include an analysis of the energy system effects of using different cooling solutions in datacentres.

The GIS analysis showed that transitioning from 3GDH to 4GDH reduces the DH grid loss from 7.07 TWh/year to 6.02 TWh/year due to lower grid temperatures. However, due to a lower ΔT, 4GDH do result in an increased grid investment costs of around 10–37 M EUR/year. However, despite the increase in grid investment cost, it is through the energy system analysis found, that transitioning from 3GDH to 4GDH decreases the energy system cost by 220 M EUR/year, corresponding to 7 M EUR/TWh delivered heat at the end-user. The reduction is especially due to reduced costs of energy conversion units, due to these being able to operate more efficiently with 4GDH and the lower DH production need with 4GDH as a result of the lower grid loss. This result supports previous findings in the field and highlights the relevance of policies enabling this transition e.g., by making sure that the building code allow for this transition to lower supply temperatures.

For the waste heat output from the datacentres, it is found that using direct water-cooling instead of air cooling reduces the energy system costs by around 52–59 M EUR/year, corresponding to 1.7–1.9 M EUR/TWh delivered heating at the end-user.

Author contribution

Peter Sorknæs: Conceptualization, Methodology, Validation, Formal analysis, Data curation, Writing – original draft, Writing – review & editing. Steffen Nielsen: 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.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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