# The competitiveness of district heating compared to individual heating

## When is district heating the cheapest source of heating?

GRØN ENERGI

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**Description:** This analysis compares the competitiveness of newly established district heating and individual heating by doing calculations on a Danish case. In the analysis it is explained which parameters affect the price of district heating and individual heating as well as what kind of influence the heat demand has regarding costs. The competitiveness between individual heating and district heating is very relevant to examine regarding newly established district heating systems outside of Denmark and because of this, the results from this analysis are relevant concerning an export perspective.

**Members of Green Energy Association:**

# Abstract

Green Energy Association has analyzed which heat price can be obtained for a household by establishing a new district heating system in an area. The resulting heat price is compared to the cost of establishing an individual heating system. The costs of heating a house with the two system types are compared. The calculations in the analysis are done under the assumption that there is no existing heat supply in the area (neither district heating nor individual). This can also be viewed as a case where the existing heat supply in the area has reached its technical lifetime and is in need of replacement. The purpose of the analysis is therefore to examine under which circumstances district heating is cost-effective compared to individual heating solutions and therefore under which circumstances it is preferable/beneficial to establish a new district heating system.

This section summarizes the results for the competitive conditions of district heating for heating demands which is assumed normal today as well as for future low-energy buildings. Furthermore, the significance of taxes on the district heating price is discussed, the competitive conditions of district heating compared to individual heating solutions is shown and the export potential of district heating is indicated.

The analysis builds upon prices, technologies and efficiencies from the Danish system and the cost calculations include Danish taxes and tariffs. The taxes and tariffs are further shown specifically to simplify comparison between countries.

The overall outcome of the analysis is that a new district heating system is highly competitive with respect to heating price when compared to individual heating solutions, when the district heating system is established in cities and towns. This is the case for both the state of buildings as of today and for new areas with low-energy buildings. Even if the taxes on electricity for space heating is lowered or even completely removed, new district heating systems will be able to compete with individual heating solutions, such as individual heat pumps.

**District heating and individual heating:** At a heat demand of 13 800 kWh/year, which corresponds to an energy renovated building, a new district heating system is the most cost-effective source of heating. This is the case when the district heating is produced with either a wood chip boiler or an electrical compression heat pump. In this scenario the yearly price of heating is approximately 430 € cheaper for district heating compared to an individual natural gas boiler. Compared to an individual biomass boiler and individual air-to-water heat pump, district heating is approximately 805 € cheaper. In percentages, the annual cost of district heating is approximately 19 % lower than an individual natural gas boiler and approximately 30-31 % cheaper than an individual biomass boiler and an individual air-to-water heat pump.

**District heating and low-energy:** In a scenario where the buildings in an area are converted to meet the energy limit of the Danish building regulations for 2015 (BR15), a new district heating system is the most cost-effective source of heating when compared to individual heating solutions. For a 130 $m^2$ building this is equivalent to a heat demand of 4900 kWh/year. In this scenario the yearly price of heating is approximately 270 € cheaper than individual electric heating (19 %) and an individual natural gas boiler (22 %). Compared to an individual air-to-water heat pump, the yearly price of heating for a new district heating system is approximately 940 € cheaper (47 %).

**District heating and taxes:** When comparing a new district heating system to individual heating solutions it will under Danish conditions be of particular interest to compare district heating to individual heat pumps when taxes are lowered or completely removed. The results from the analysis show that a new district heating system is the most cost-effective source of heating when compared to individual heating solutions even if the taxes on electricity for space heating is lowered or completely removed.

**District heating and export potential:** In order to even consider establishing district heating in a new area it must first be determined whether a district heating system can deliver more cost-effective heating or environmentally friendly compared to individual heating solutions. This analysis has showed that this is indeed possible for new district heating systems in Denmark. There is even room for considerable uncertainties regarding the costs of establishing the district heating network. Outside Denmark, it is likely that the heat in a district heating system will not be produced with the same technologies as in Denmark, as in the cases of a wood chip boiler and an electrical compression heat pump that are shown in the analysis. The results depends on fuel prices, tariffs and taxes and as these vary from country to country the results may change. These factors decide which heat producing technology is the cheapest in each country. The advantages of district heating (high fuel efficiency, lower heat production capacity requirement and cheaper fuels) will most often make district heating cost efficient and environmentally friendly. This is especially the case in densely populated areas where the heat loss will be low. Densely populated areas will therefore be the natural starting point for establishment of new district heating systems outside of Denmark.

# Contents

# Introduction

The purpose of this analysis, is to investigate whether you will achieve the lowest price of heat by using a newly established district heating system or individual heating. The analysis does not cover the competitiveness of existing district heating systems and the significance of changes in the regulatory framework of these systems.

In Green Energy Association's analysis from autumn 2016, called "Energiforsyning 2030", it was established that the average price of district heating in Denmark had difficulty competing with individual heating technologies, especially individual air/water heat pumps. Even though this conclusion is correct on an aggregated level, it does not mean that it is unfavorable to establish district heating. This is because, the results presented in "Energiforsyning 2030" was based on an average from very different and often older district heating systems. This was then compared to new individual heating technologies. The comparison between district heating and individual heating will in this case give a distorted view of the competitiveness when the goal is to investigate whether the lowest price of heat is achieved by using a newly established district heating or individual heating.

Based on this, Green Energy Association has made this analysis, with the goal of investigating district heating's competitiveness compared to various individual heating solutions. This is done by comparing the price of heat for a newly established district heating system, based on different heat producing technologies, with the price of heat from newly established individual heating solutions. In the analysis, only the economy of the company and not the socio-economy is considered. The newly established district heating system is modeled with inspiration from an actual area, which contains apartment complexes, detached houses and town-houses. The location consists of about 1800 households.

The combined heat demand for the district heating system is set to vary in two different ways in the analysis. The first way varies the heat demand of the average household in six scenarios from 4900 kW h/year as the lowest, to 13 800 kW h/year as the highest. The second way, constructs different scenarios with varying distances between the points in the district heating grid, to simulate different heat densities. These variations will affect the dimensioning of district heating pipes, heat production facilities and heat loss in the system. In addition to this, the price of heat for district heating is calculated using two different sources of heat production, a wood chip boiler and an electric heat pump.

In the analysis two different sets of assumptions are used with regards to the individual technologies. The first set of assumptions is based solely on data from the Danish Energy Agency's Technology Data Catalogue (Energistyrelsen, 2017b). In the second set of assumptions a select set of assumptions from the Technology Data Catalogue is replaced with either more up to date or more apt assumptions regarding the conditions, in which the technologies are used.

From the results, it is shown how big a share of the total costs the different cost elements represents, for both district heating and individual heating. This will, besides showing the difference in the structure of the costs for district heating and individual heating, also make the analysis easier to adapt to foreign conditions, where the taxation might be different, compared to Denmark.

# Data and method

This section contains a collection of the technology data that are used in the analysis, both with regards to individual heating units and district heating production units. In this section the fuel prices, taxes and economic parameters that are used in the analysis are presented. Furthermore, this section also describes the method that is used for calculating heat prices in the analysis.

The average household in this analysis is assumed to be existing buildings with a water-based heating system using radiators. In the calculations, it is further assumed that facilities are bought in 2017 and have 2018 as their first year of operation. In the following section specific technology data is specified, however the following are applicable for the building installations throughout:

- Costs for establishing a district heating unit includes service pipelines and a meter.
- Costs for establishing a wood pellet boiler includes a chimney.
- Costs for establishing a natural gas boiler includes service pipeline. Costs for establishing a natural gas distribution grid are not included in the analysis.
- Costs for establishing an oil boiler includes a hot water tank. It is assumed that an oil tank is already established.
- Costs for establishing both air-to-water and ground source heat pumps includes a hot water tank and all supplementing equipment.

## Technology data for individual heating solutions, Technology Data Catalogue

The following data are taken directly from the Technology Data Catalogue (Energistyrelsen, 2017b). The efficiency is total lower heating value efficiency and all prices includes Danish VAT.

| Type of heating | Investment [€] | Efficiency[%] | Lifetime [years] | Maintenance [€/year] |
|---|---|---|---|---|
| District heating unit | 6175 | 100 | 25 | 65 |
| Oil boiler | 7515 | 92 | 20 | 295 |
| Wood pellet boiler | 10 740 | 80 | 20 | 605 |
| Natural gas boiler | 6440 | 97 | 22 | 255 |
| Electrical panel/radiators | 4965 | 100 | 30 | 65 |
| Air-to-water heat pump | 12 485 | 325 | 20 | 360 |
| Ground source heat pump | 20 000 | 360 | 20 | 360 |

**Table 1:** Assumptions for the individual technologies and the district heating unit

Some of the values in Table 1 are either not up to date or are only applicable under conditions which are not representative for this analysis. As a replacement for these values, more applicable data are found from other sources. These data are described in the next section.

## Technology data for individual heating solutions, revised

The following data in Table 2 are taken partly from the Technology Catalogue and partly from different sources. The data, which are not from the Technology Catalogue is marked with a $*$.

| Type of heating | Investment [€] | Efficiency[%] | Lifetime [years] | Maintenance [€/year] |
|---|---|---|---|---|
| District heating unit | 6175 | 100 | 25 | 65 |
| Oil boiler | 7515 | 92 | 20 | 295 |
| Wood pellet boiler | 10 740 | 80 | 20 | 605 |
| Natural gas boiler | 6440 | 92* | 19* | 255 |
| Electrical panel/radiators | 4965 | 100 | 30 | 65 |
| Air-to-water heat pump | 12 485 | 233* | 15* | 360 |
| Ground source heat pump | 20 000 | 263* | 20 | 360 |

**Table 2:** Assumptions for the individual technologies and the district heating unit

**Natural gas boilers:** The total efficiency for natural gas boilers is set to 97 % in the Technology Catalogue. According to the report "Facts and figures about domestic gas boilers", (DGC, 2017a), the efficiency when domestic hot water is included, varies between 97.4 % and 100.2 % (depending on whether it is low temperature or traditional temperature). However, the included domestic hot water consumption is at most 2000 kWh, which is low compared to typical domestic hot water usage in residential units. This analysis uses 3100 kWh, which is a better representation of actual domestic hot water usage in that are used in this analysis. Furthermore, the heat demand is higher than the 4900-13 800 kWh which are used in this analysis. Because of this, and the fact that the yearly efficiency drops both when the domestic hot water share rises, and also when the heat demand drops it is determined, that these numbers are not accurate enough for use in this analysis.

Only few manufacturers of natural gas boilers inform of the efficiency for the domestic hot water part. One of these are Vaillant, who splits the efficiency in an efficiency for space heating and an efficiency for providing domestic hot water. The most efficient of their natural gas boilers has an efficiency for space heating of 94 % and an efficiency for domestic hot water of 87 % (Vaillant, 2017). If it is assumed, that domestic hot water is 30 % of the total heat demand, the resulting total efficiency of the boilers would be 91.9 %. This efficiency is used for all heat demand scenarios in the analysis. Even though, the total efficiency would be lower in the scenarios where the total heat demand is lower, because the domestic hot water part of the heat demand would be greater.

The lifetime of a natural gas boiler is set to 20 years in the Technology Catalogue, with the source being an internal memo from HNG Statistik. In 2016 DGC published an analysis (DGC, 2017b) in which, they determined that the lifetime of a natural gas boiler is around 19 years. These results are based on data from more than 50 000 units and is thus considered valid. Because of this a lifetime of 19 years is used here.

**Heat pumps:** In the Technology Catalogue the efficiency of heat pumps are set to 325 % for air-to-water heat pumps, and 360 % for ground source heat pumps in existing housing. With new houses (low energy consumption) the efficiencies are 285 % and 310 % respectively. The efficiencies are theoretically calculated values based on tests at different temperatures, made in accordance with EN14825 and EN16147 standards. These values are therefore, not necessarily representative of the efficiencies the consumer will experience.

In 2013 the Danish Technological Institute published a report regarding heat pumps with results from a metering program, concerning heat pump data (Teknologisk Institut, 2013). The report shows average yearly efficiencies for ground source heat pumps of 282 % and 303 % in October 2011 and October 2012 respectively. With regards to the yearly average efficiency of air-to-water heat pumps the report finds efficiencies of 251 % and 247 % in October 2011 and October 2012. Several of the sample sizes are small, but never the less, the report supports the notion that the system efficiency indicated in the Technology Catalogue is too high.

In the ForskEL-project "Styr Din VarmePumpe" (ForskEL, 2015), operational data from 53 individual air-to-water heat pumps and 219 individual ground source heat pumps was collected and analyzed over several years. Based on around 150 observations where the readings were found to be reasonable, the report finds a median yearly system efficiency of 257 %. If it is assumed that these results are representative of all heat pumps and that the relationship between the efficiencies of the heat pumps is the same as indicated in the Technology Catalogue. The efficiency of the air-to-water heat pump would be 233 % and the efficiency of the ground source heat pump would be 263 %, which are the values used in this analysis.

In the latest edition of the Technology Catalogue from September 2017 (Energistyrelsen, 2017b) the lifetime of air-to-water heat pumps was raised from 15 to 20 years. The uncertainty surrounding the lifetime of heat pumps is large and there is no documentation supporting the raise of the lifetime of heat pumps to 20 years. Because of this, a lifetime of 15 years is used for air-to-water heat pumps in the revised dataset of this analysis.

## Technology data for district heating production units

The following data in Table 2 are based partly on the Technology Catalogue, and partly on empirical results from Danish district heating projects.

| | Wood chip boiler | Electrical heat pump | Storage tank | Eletric boiler |
|---|---|---|---|---|
| Investment [mio. €/$MW_{heat}$] | 0.74 | 0.7 | 155[1] | 0.08 |
| Efficiency (LHV) [%] | 108[2] | 400 | 95 | 99 |
| Lifetime [years] | 20 | 20[3] | 20[4] | 20 |
| Fixed O&M [€/$MW_{heat}$] | 10 335 | 2010 | 0[5] | 1210 |
| Variable O&M [€/MWh] | 25 | 15 | 0[6] | 4 |

**Table 3:** Assumptions for district heating technologies, Danish VAT excluded

The investment cost is the turn-key cost for the plant. That is it includes the boiler, installation, building and a pipe connection to the boundary of the plant site.

The electrical heat pump with a COP of 4, is assumed to use groundwater as the heat source. If groundwater is not available, a COP of 3.5 should be achievable using outside air as a heat source (Grøn Energi, 2017).

In the analysis, construction costs for district heating pipes are based on the assumption that the pipes will be laid in suburban areas with asphalt and sidewalks. This increases the costs regarding the district heating grid compared to if the pipes were to be laid in unused areas or at the same time as other infrastructure (green field and brown field). The lifetime for district heating pipes is set to 50 years in the analysis.

In all scenarios investments in a storage tank dimensioned for 10 hours of peak heat production and an eletric boiler, for covering peak heat demand are made.

[1] The price is in €/$m^3$

[2] Investment in flue gas condensation is assumed

[3] The Technology Catalogue dictates a lifetime of 25 years for a compression heat pump for district heating. A lifetime of 20 years is used in this analysis

[4] The lifetime is not specified in the Technology Catalogue, but is assumed to be 20 years

[5] Fixed operation and maintenance costs are not specified for storage tanks in the Technology Catalogue

[6] Variable operation and maintenance are not specified for storage tanks in the Technology Catalogue

## Fuel prices

The fuel prices used in this analysis are the raw socioeconomic prices from Energistyrelsen (2017a). Figure 1 shows the fuel prices converted to €/GJ.

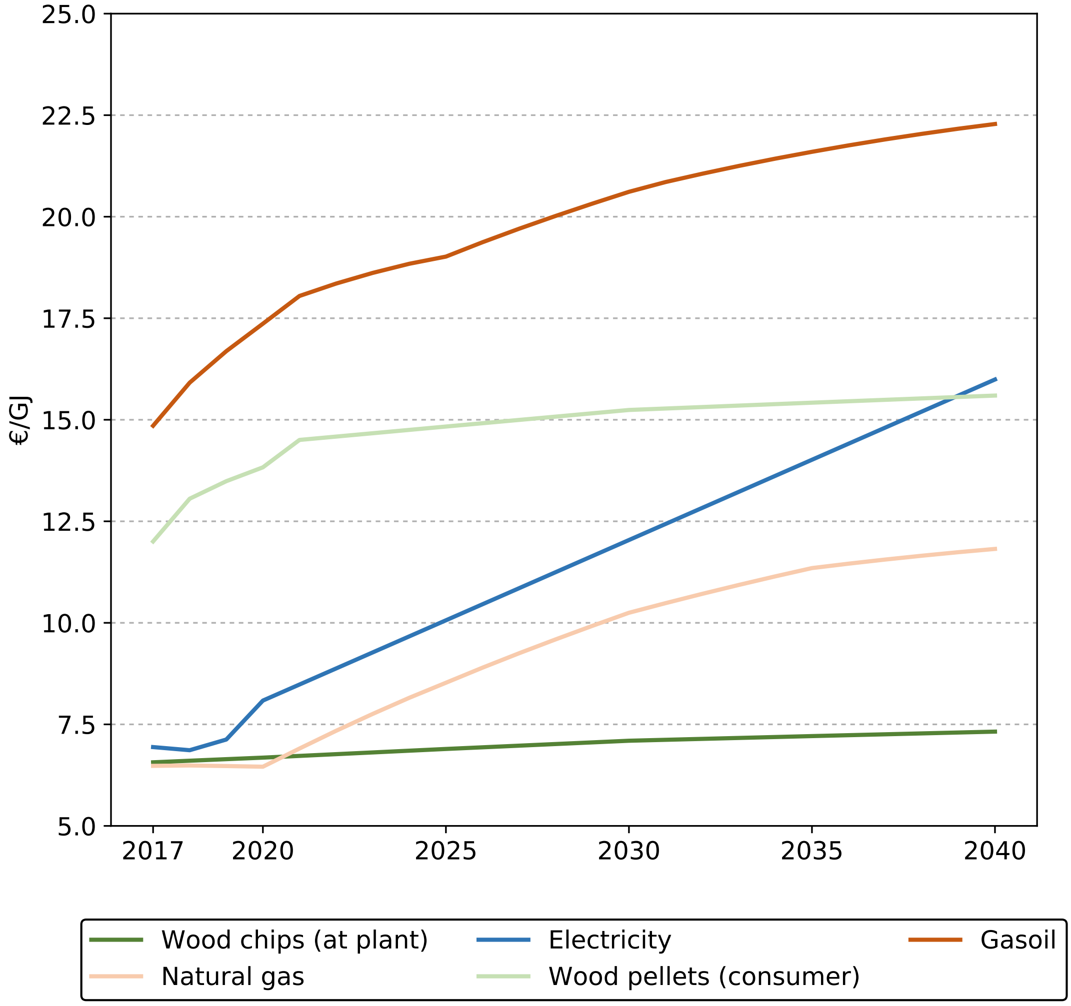


**Figure 1:** Raw fuel prices

## Taxes and economic parameters

This section contains information regarding the tax and tariff costs as well as the interest, distribution and administration costs that are associated with the district heating system.

The distribution and administration costs for the district heating system are based on average costs from Danish District Heating Association's Statistics 2015-2016 (Dansk Fjernvarme, 2016). The distribution costs are 8.05 €/MWh, while the administration costs are 4.7 €/MWh.

The taxes and tariffs shown in Table 4, are the rates concerning the individual technologies in the analysis and are specified without Danish VAT. It is assumed that taxes and tariffs are constant in the analysis, but the fuel prices develop as in Figure 1. The lower calorific value of gas oil is set at 9.964 kWh/l, the taxes on oil are from SKAT (2017d), SKAT (2017c) and SKAT (2017e). The lower calorific value for natural gas is set at 11 kWh/Nm$^3$, the taxes and tariffs on natural gas are taken from Energitilsynet (2017), SKAT (2017b), SKAT (2017c) and SKAT (2017e). The taxes and tariffs on electricity are from Energitilsynet (2016) og SKAT (2017a).

| Tax/Tariff | Gas oil [€/l] | Electricity [€/kWh] | Natural gas [€/Nm$^3$] |
|---|---|---|---|
| Energy tax | 0.266 | [7]0.054 | 0.294 |
| $CO_2$ | 0.061 | - | 0.052 |
| $NO_x$ | 0.001 | - | 0.001 |
| Distribution | - | [8]0.048 | [9]0.149 |

**Table 4:** Table containing taxes and tariffs for the individual technologies

The taxes and tariffs in Table 5 are the rates concerning the district heating technologies used in the analysis, and are specified without Danish VAT. The tax for wood chips is taken from SKAT (2017e). The taxes for electricity are taken from SKAT (2017a) and the tariffs are from Energinet.dk (2016) and Dansk Energi (2016). The PSO[10] tax is currently being phased out and is therefore not a part of this analysis.

| Tax/Tariff | Wood chips [€/MWh] | Electricity [€/MWh] |
|---|---|---|
| Energy tax | - | 54.362 |
| $NO_x$ | 0.242 | - |
| Distribution tariff | - | 14.349 |
| System and transmission tariff | - | 11.141 |

**Table 5:** Table containing taxes and tariffs for district heating technologies

The construction costs concerning the district heating grid are based on empirical values from projects in Jutland. The construction costs cover welding, earth moving and pipe delivery. The empirical values are from Danish district heating projects and can be seen in Table 7. The discount rate that is used in this analysis is 4 %. The price of heating for the different technologies is compared for a residence of 130 m$^2$.

[7]It is assumed that the electricity for heating is only subject to the lowered electricity tax
[8]Net tariff, transport and commerce
[9]Including emergency supply tariff
[10]The PSO tax is a Danish tax paid by the consumer as a subsidy to renewable energy

## Calculation methodology

To analyze whether district heating can compete with individual heating, both now and in the future, it is calculated what the costs would be, for a given technology to provide space heating and domestic hot water. The costs referred to here are the average costs in a technology's lifetime.

Due to different lifetimes of the available technologies it will not be sufficient to choose between different investment alternatives based on the present value method. This is because the investments can be seen as mutually exclusive, and the fact that a residence must be heated every year. It will in this case not make sense to compare the present value of an investment with a lifetime of 15 years to an investment with a lifetime of 20 years, as the investment with a 20-year lifetime is able to produce heat for 5 more years than the other investment.

In order to avoid this one can, via reinvestments, construct a payment series of such length that the lifetime of both alternatives is the same. Another option, is to calculate the equivalent annual annuity via the annuity method. By using the annuity method the average net payment per term is calculated, which in this case corresponds with the average price of heat per year. This is determined via Formula (1) (Christensen, 2005)

$$\text{Avg. yearly price of heat} = NV_j\left(k\right) \cdot \alpha_{T,k}^{-1} = \left[\sum_{t=0}^{T} NB_{j,t}\left(1+k\right)^{-t}\right] \cdot \alpha_{T,k}^{-1} \quad (1)$$

where $\alpha_{T,k}$, is the capital gains factor or the annuity factor which is defined in Formula (2)

$$\alpha_{T,k} = \frac{1-\left(1+k\right)^{-t}}{k} \quad (2)$$

$NB_{j,t}$ is the net payment at time $t$ for alternative $j$. $T$ is the lifetime of the investment and $k$ is the discount rate. $NV_j$ is the present value of alternative $j$ as a function of the discount rate.

This method is used to determine the average yearly price of heat for the consumer for establishment and operation of either an individual heating or a district heating system.

# District heating grid modelling

This section contains a description of the modeling of the district heating grid that was done as part of the analysis. Moreover, the section describes the variations in heat density that is analyzed as part of the heat demand and grid variations in the analysis.

## The district heating area in the analysis

In order to calculate the price of heat for newly established district heating, the district heating grid part of the district heating system is modelled. As inspiration for the district heating grid's size, an area in Fredericia which represents different types of residences, and contains sub regions with different heat densities, is used as a starting point. It is assumed that the district heating grid is of a size which makes it sufficient to only have a single point where heat enters the grid. The area used as inspiration is shown in Figure 2.

**Figure 2:** Air photo of the area in Fredericia

## Subareas in the district heating grid

The analyzed area is divided into three subareas with different characteristics as shown in Figure 3. Area 1 has a large share of apartment complexes in the center with detached houses and townhouses surrounding it. Area 2 is an area with mainly detached houses and only few apartment complexes and townhouses. Area 3 consists solely of detached houses. The total amount of residences in the modelled subarea is around 1800. In this analysis it is chosen to look at the areas as one collective whole, meaning there will not be shown any results for the different subareas.


**Figure 3:** The district heating area split into three subareas

## Placement of the main pipes in the district heating grid

Figure 4 shows the placement of the main district heating pipes in the model.


**Figure 4:** Placement of the main pipes in the district heating area

## Placement of the distribution pipes in the district heating grid

Figure 5 shows the placement of the distribution grid in subarea 2. The distribution grids are placed after the same method in the other two areas.


**Figure 5:** Placement of distribution pipes in area 2

A more detailed description of the grid modelling is shown in Appendix B.

In the analysis different variations in heat demand is used, which represents building stock with different heat demands. In the analysis a constant domestic hot water demand of 24.1 kWh/m$^2$/year is assumed. For a residence of 130 m$^2$ this corresponds to a consumption of about 3100 kWh domestic hot water per year. In the analysis six different variations for space heating is used; these are shown in Table 6. The method used to create these variations is described further in Appendix A.

| Variation | Space heating demand [kWh/m²/year] | Domestic hot water demand [kWh/m²/year] | Total demand at 130 m² [kWh/year] |
|---|---|---|---|
| 1 | 82.0 | 24.1 | 13 800 |
| 2 | 68.3 | 24.1 | 12 000 |
| 3 | 54.6 | 24.1 | 10 200 |
| 4 | 41.0 | 24.1 | 8500 |
| 5 | 27.3 | 24.1 | 6700 |
| 6 | 13.7 | 24.1 | 4900 |

**Table 6:** Heat demand variations in the analysis

The different heat demands have the purpose of showing the competitiveness between district heating and individual heating, in cases with buildings that have a high energy consumption, and cases with newer buildings that have a low energy consumption. It should be noted, that in the scenarios with a low total heat demand, the domestic hot water part of the total heat demand will be greater, which for individual technologies, will reduce the efficiency, but the lower efficiencies are not reflected in the analysis. For natural gas boilers the total efficiency change from case 1 to case 6 would be 92 % to 90 %, respectively.

Besides varying the size of the heat demand, the size of the district heating grid is also varied in the analysis. This is done by increasing the distance between the buildings in the network. The grid is still based on the same physical area, but it is simulated how the grid would look if the distance between the buildings is greater than is the case. The grid is modelled in the lengths 1, 1.5, 2, 2.5, and 3 where 1 is the original grid, and 3 represents a grid, in which the distance between the buildings are three times greater than in the original grid. An illustration of this is shown in Figure 6.

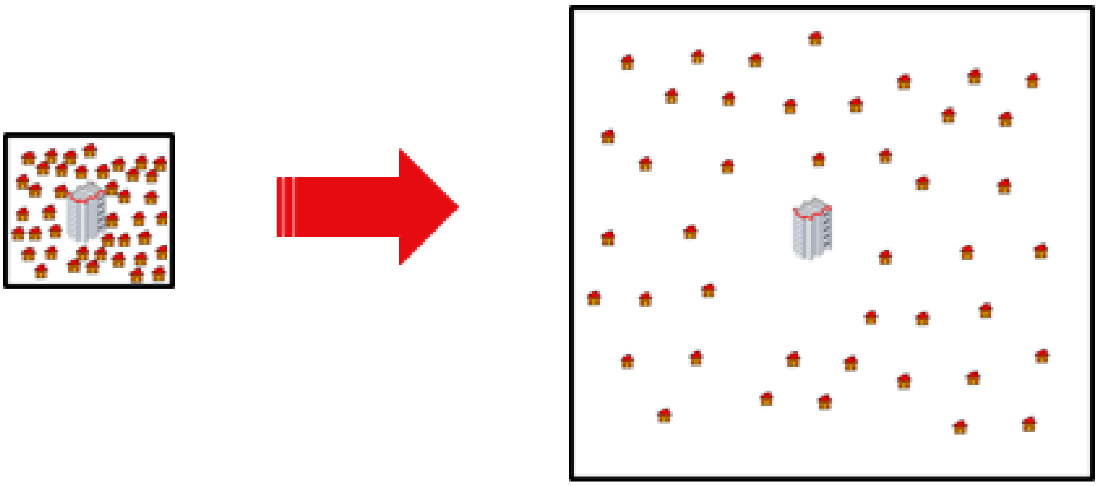

**Figure 6:** Illustration of network scaling

The variation in heat demand and the variation in grid length both change the heat density in the district heating system, and thus the heat loss from the pipes. Varying the heat demand only changes the absolute heat loss, while changing the grid length both changes the absolute and relative heat loss. In the scenario with 82.0 kWh/m$^2$/year demand (variation 1 in Table 6) will thus have the lowest relative heat loss, due to high heat demand in combination with the smallest grid. In the model there is a total heat demand of about 27 500 MWh, of which around 8.5 % are pipe heat losses in this scenario. The highest relative heat loss will be the case which has a low heat demand and the biggest grid, meaning the scenario with grid length 3 and a heat demand of 13.7 kWh/m$^2$/year. In this scenario the model shows a total heat demand of approximately 14 000 MWh, of which 36 % are due to pipe heat losses.

The variations in heat density changes not only the heat loss, but also investment costs. Where the change in heat demand primarily changes the pipe dimensions in the grid (smaller/greater pipe dimension, higher/lower investment costs) the change in distance between the buildings only change the length of the pipes (longer pipes, higher investment costs) given, that the maximum pressure level is not exceeded for the pipe dimension. The variation of grid length in the analysis, is done to examine the competitiveness of district heating in areas, that are more sparsely populated than the original area.

# Parameters that affect the price of district heating

This section contains a description of the important parameters that affect the investments when establishing a new district heating system, and consequently the price of heating in the resulting system. Grid size and heat demand determines the heat density of the system and by extension heat loss and capacity. The type of production unit determines the cost of producing the heat.

## Grid size

The size of the pipe grid in a district heating system affects the price in two ways. Firstly, the investment costs in a pipe grid is larger the bigger it is. The investment in the pipe grid is a significant part of the total investment in a district heating system, which means the size of the grid is an important factor. Secondly, a larger pipe grid will, all other things being equal, mean that the heat density is lower. This means, that the relative and absolute heat loss in a longer pipe grid will, all things being equal, be greater. This in turn means that more heat needs to be produced at the plant to cover the same district heating demand in the residences.

Figure 7 shows the effect different district heating grid sizes have on the price of district heating, when the heat demand at the consumer is kept at 13 800 kWh. The fixed costs for the household includes investment in a district heating unit, operation and maintenance of said unit, service pipeline and meter. The fixed costs for the district heating plant contains investment in heat production units and storage, as well as operation and maintenance. The district heating grid costs consist of investment costs for the pipe grid. The variable costs consist of costs regarding variable operation and maintenance, fuel, distribution and administration.

The figure shows, that the yearly district heating price rises with increasing grid length. The difference for a household between the smallest (Network Scale 1 or NS1) pipe grid and the longest (NS3), correspond to a tripling in size, is about 310 €/year.

The price difference occurs due to increased grid investment, increased heat loss and a marginally larger investment in heat production capacity due to the increased heat losses in the grid. The same tendency can be seen if the heat demand is lowered, just in a smaller scale.

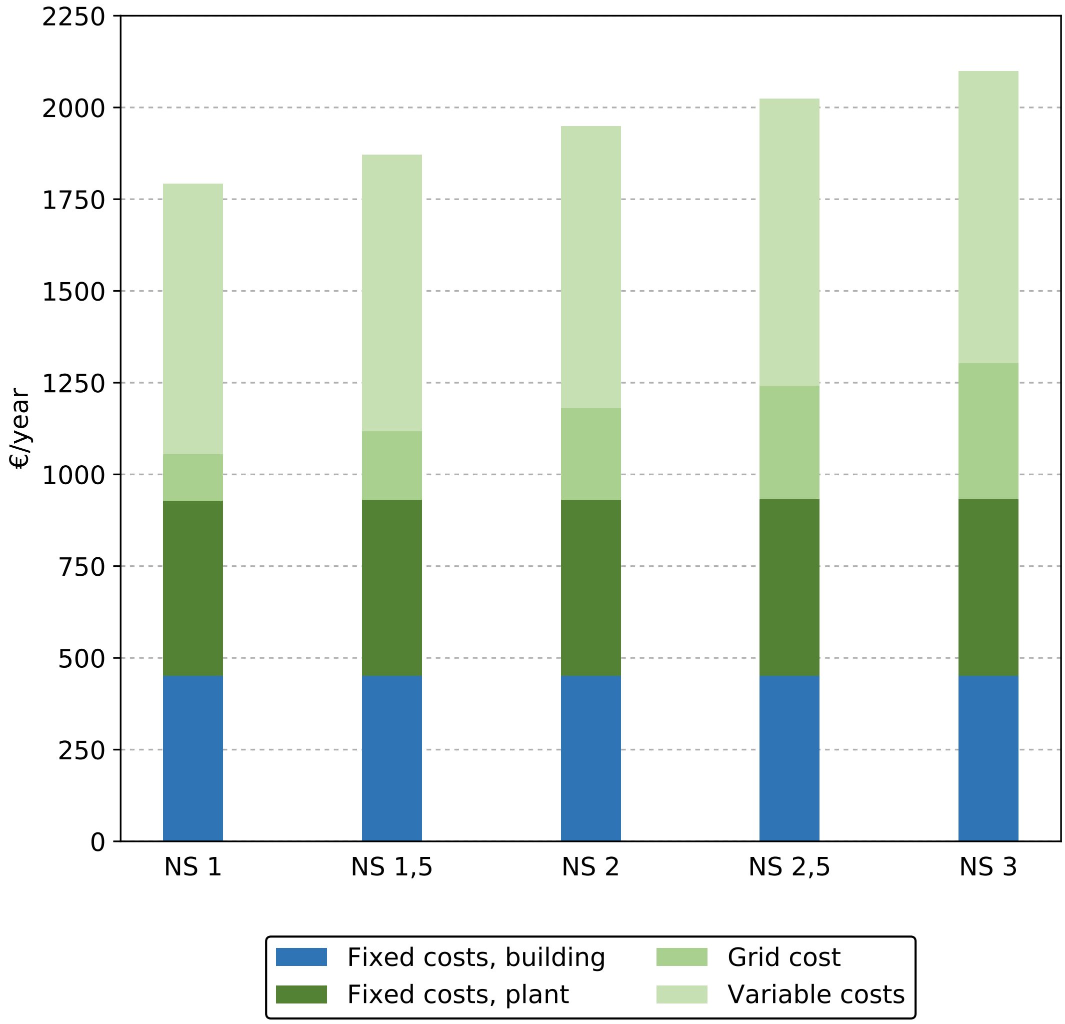


**Figure 7:** The effect of grid length on the price of heat in a newly established district heating system with a demand of 13800 kWh per residence. The district heating is produced on a wood chip boiler.

## Heat production units

The actual costs of producing the heat in the district heating system, depends on what type of heat production unit is invested in. For district heating technologies the operational costs are very dependent on the fuel price (including taxes and tariffs).

The offset in this analysis is two different heat production facilities, a wood chip boiler and an electrical heat pump. These two technologies have different cost allocations even though the total costs are not far from each other. Figure 8 shows the price of heat for a household with a yearly heat demand of 13 800 kWh and Network Scale 1. The only difference is that in one case the heat is produced on a wood chip boiler, and in the other case an electrical heat pump.

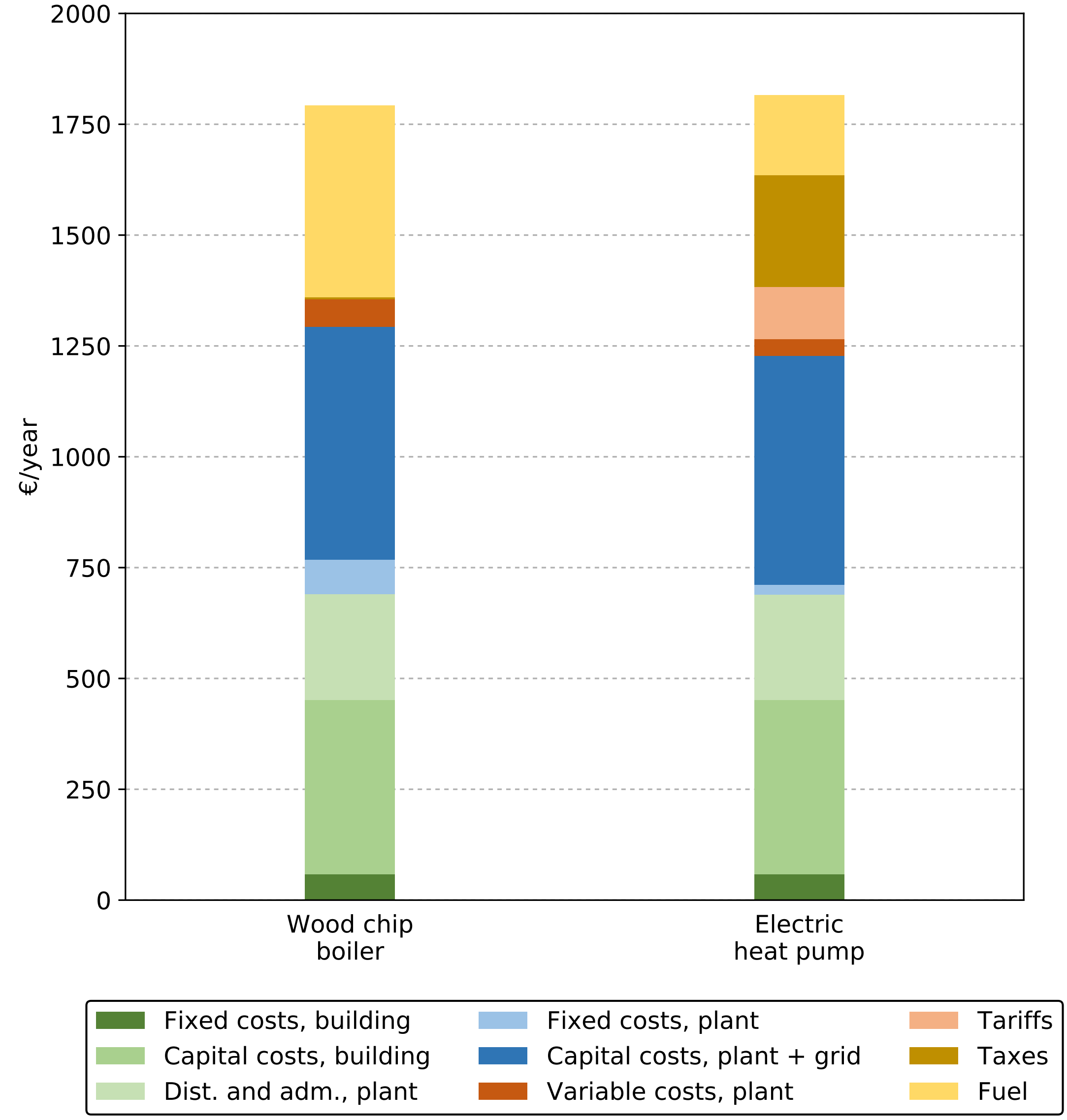


**Figure 8:** Comparison of price of heat for newly established district heating with Network Scale 1 and a heat demand of 13800 kWh per residence. The district heating is produced on a wood chip boiler and an electrical heat pump respectively.

The two columns in Figure 8 have the same fixed and capital costs for the household (dark and medium green colors), because neither the investment nor the yearly maintenance costs for the household are dependent on what kind of heat production facility is at the district heating plant. The capital costs cover expenses relating to the pipe grid (dark blue color). Similarly, the costs for distribution and administration of the district heating plant is the same in the two columns since this does not depend on the production technology (light green color). The differences lie in the investments tied to the heat production facility, and the operational costs. The wood chip boiler has significantly higher fixed costs for operation and maintenance compared to the electrical heat pump, 10 335 €/MW and 2010 €/MW respectively (light blue color). The variable costs for operation and maintenance are likewise greater for the wood chip boiler than they are for the electrical heat pump, being 3.36 €/MWh and 2.01 €/MWh respectively (dark red). The investment costs for the wood chip boiler is approx. 33 500 €/MW greater than for the electrical heat pump.

The major difference is the costs regarding fuel and taxes/tariffs. The wood chip boiler's costs for fuel and taxes/tariffs are 99 % fuel and a small part $NO_x$ tax. The electrical heat pump's costs for fuel and taxes/tariffs are approximately 21 % tariffs, 46 % taxes and 33 % fuel (electricity) (pink, dark yellow and bright yellow colors respectively). The heat pump's fuel costs are as such 1/3 electricity and 2/3 tariffs and taxes. Comparatively the wood chip boilers costs are almost solely related to fuel.

The total costs for fuel and taxes/tariffs are greater for the electrical heat pump than for the wood chip boiler. This causes the price of heat for the household to be roughly 27 €/year greater when the heat is produced on the electrical heat pump compared to when it is produced on the wood chip boiler.

## The heat demand's effect on the price of heat

This section contains a description of how the size of the heat demand affects the price of heat in the district heating system and in an individual heating system.

The heat demand in the district heating system affects the price of heat in two opposite ways. A lower heat demand will lower the heat density of the system, which in turn increases the relative heat loss in the pipes. Simultaneously, a lower heat demand also means that the fixed costs is shared between fewer energy units. The price of heat per MWh will therefore be higher. A lower heat demand will on the other hand, result in a smaller investment in heat production capacity and smaller dimensions for the district heating pipes. However, this is dependent on an assumption of continuous pipe dimensions which has not been used in this analysis. In actuality a reduction in the space heat demand from for instance 82.0 kWh/m$^2$/year to 13.7 kWh/m$^2$/year does not cause a significant change in total costs if the district heating pipe is a size or two smaller.

A reduction in heat demand on a given pipe distance does not necessarily mean that it is possible to reduce the pipe dimension one size. This is partly because requirements regarding flow velocity and pressure loss needs to be adhered to, but also because the preparation of domestic hot water dictates a demand for the ability to provide a high amount of energy. The scenarios with a low space heat demand are especially affected by the domestic hot water part regarding pipe dimensioning. A reduction in pipe dimensions is most likely in the center of the grid, because of simultaneity in the demand for domestic hot water. In the outer branches of the grid the lower demand for space heating will be less significant regarding a reduction in pipe dimension because the required capacity is determined mainly by the domestic hot water.

Figure 9 shows the price of district heating per year for six different heat demands. As expected, the figure shows a lower heating bill at lower consumption. What the graph does not show is what happens to the price of district heating per unit of energy when the consumption and thus the heat density drops.

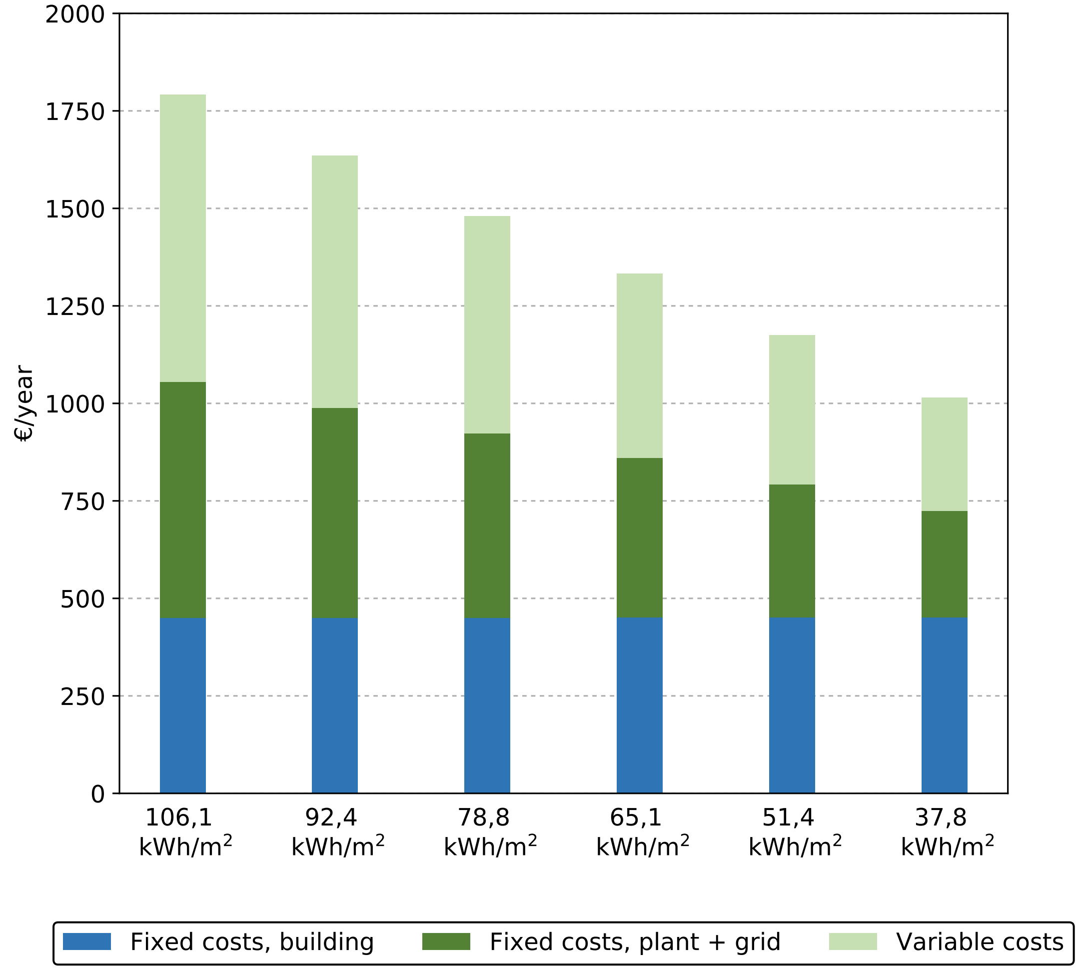


**Figure 9:** Comparison of the price of heat per year for newly established district heating at different heat demands, with a Network Scale of 1. The district heating is produced on a wood chip boiler.

Figure 10 shows, that the price of district heating per MWh is higher the lower the heat demand per household is. The cause of this is mainly the fixed costs of the household, but also the fixed costs for the district heating plant. In the households, it is due to the operating and maintenance being the same in all cases, because the same district heating unit would be used in all the scenarios. The fixed costs at the district heating plant and grid increases per MWh when the heat demand lowers. This is, as described earlier, due to the available pipe dimensions and the fact, that the simultaneity in consumption does not reduce the necessary heat production capacity at the same rate as the heat demand lowers.

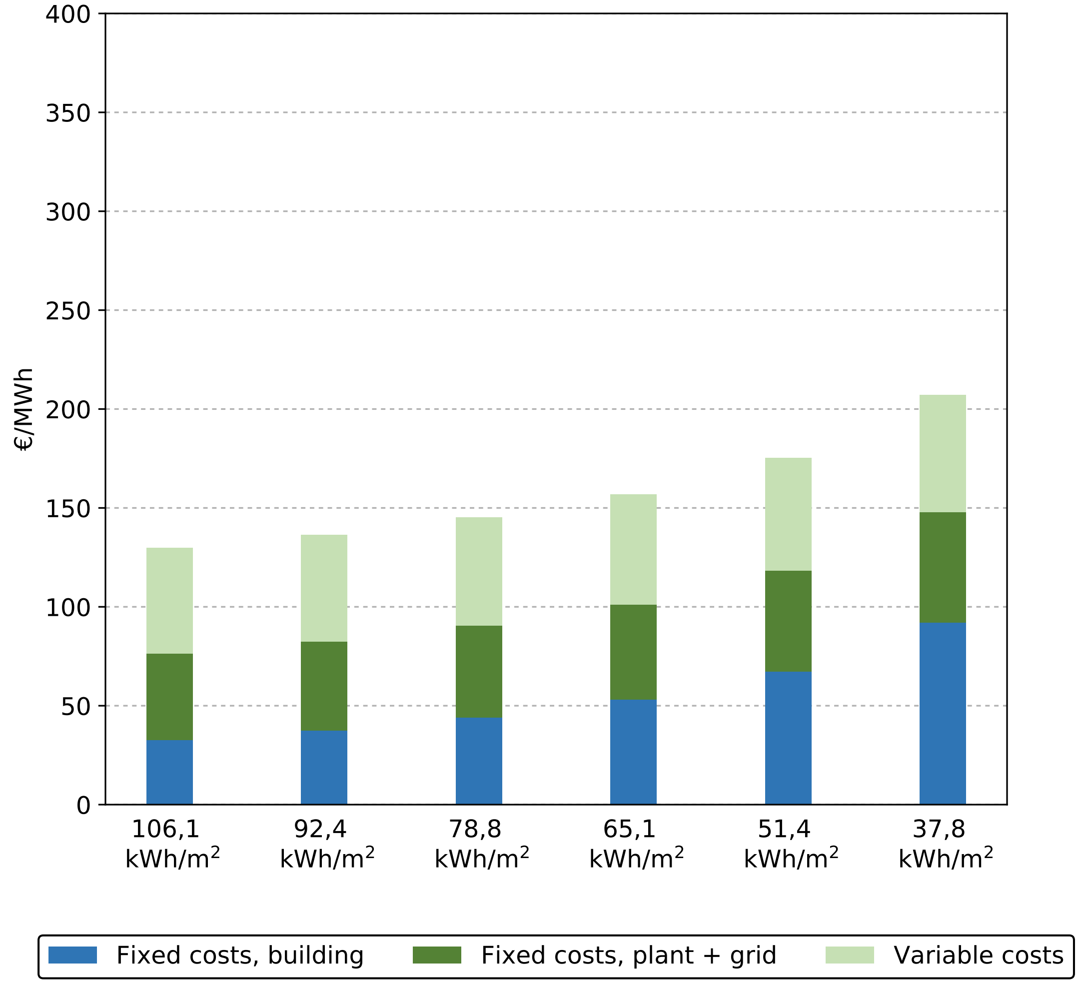


**Figure 10:** Comparison of price of heat in €/MWh for newly established district heating, at different heat demands with a Network Scale of 1. The district heating is produced on a wood chip boiler.

## Individual wood pellet boiler

Figure 11 shows the price of heat per MWh for a wood pellet boiler for the six different heat demands. The figure shows the same tendency as the one for district heating, namely that the price per MWh increases as the heat consumption drops. The cause is the same in that the investment and maintenance costs does not change with the heat demand. This is due to wood pellet boilers only being available in sizes from 10 kW and up. Because of this one often invests in capacity that will not or will rarely be used. The Technology Catalogue prescribes the same size of wood pellet boiler for both new and existing buildings as well. The total efficiency is lowered to 75 % for new buildings (low energy consumption) though, this consideration is not included in the analysis and the boiler efficiency is kept constant at 80 %.

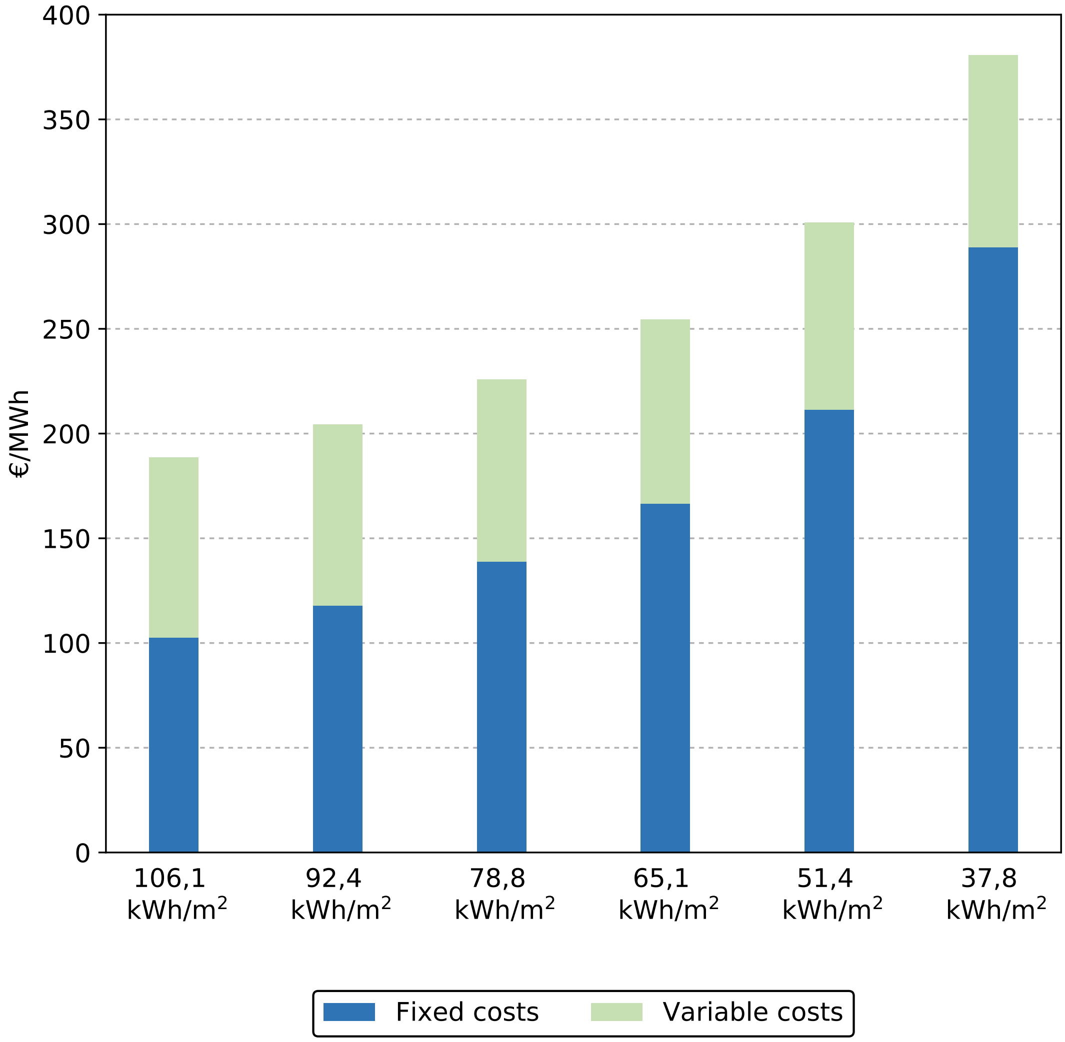


**Figure 11:** Comparison of the price of heat in €/MWh for an individual wood pellet boiler at different heat demands

## Individual air/water heat pump

Figure 12 shows the price of heat per MWh for the six different heat demands for an air/water heat pump. The tendency is the same as with district heating and the wood pellet boiler. The Technology Catalogue stipulates that one can, for a new one family residence, buy a heat pump with a lower power rating than one can for existing buildings. This can according the Technology Catalogue, reduce the investment costs by approximately 3760 €, which in turn would reduce the yearly capital costs by 415 €. However, the Technology Catalogue also states that the heat pump's efficiency drops by about 40 percentage points, due to the lower heat demand. In the analysis it is chosen to use the same costs and efficiencies in all the different heat demand scenarios, because it is difficult to differentiate how costs and efficiencies are impacted for the different heat demands.

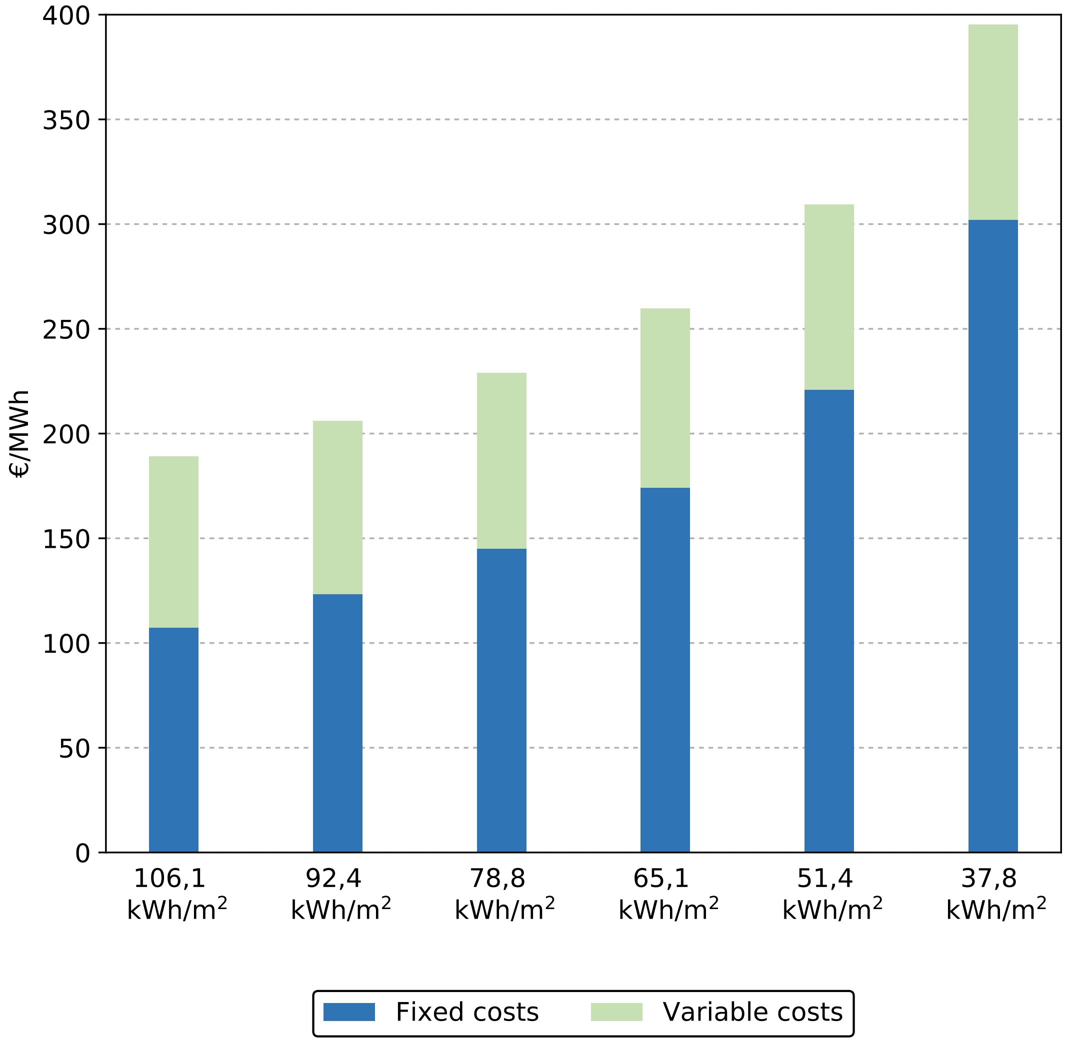


**Figure 12:** Comparison of the price of heat in €/MWh for individual air/water heat pumps at different heat demands

# The competitiveness of district heating compared to individual heating

This section contains results from the analysis regarding the competitiveness between district heating and individual heating. The section contains results for households with a heat demand of 4900 kWh/year and 13 800 kWh/year year. A Network Scale of 1 and the revised data, see Table 2, are used. Furthermore, results for a heat demand of 4900 kWh/year with a Network Scale of 3 are also shown. Finally, the importance of the assumptions regarding the results is explained. The results using the revised data set and those using data from the Technology Catalogue are compared for a heat demand of 13 800 kWh/year.

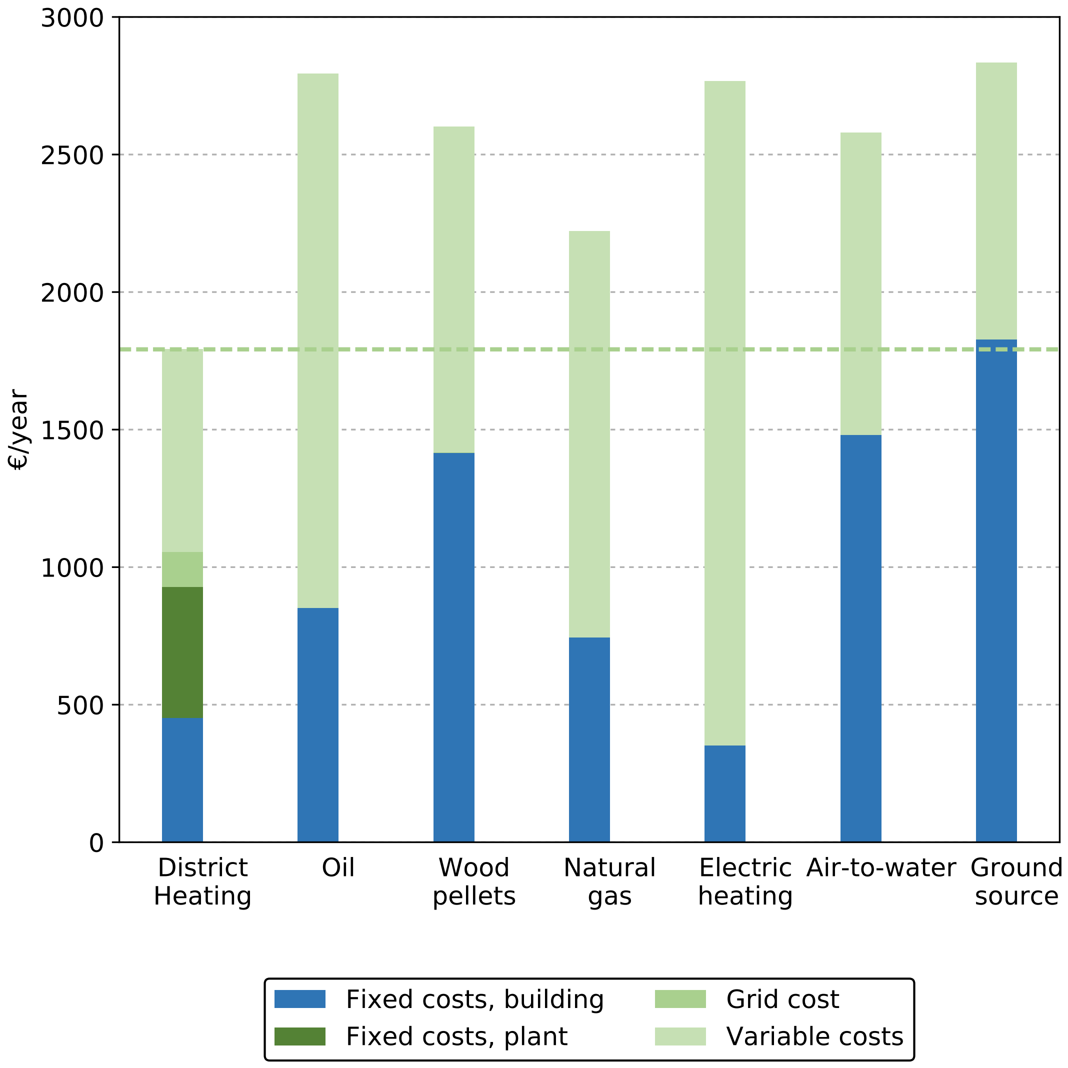


**Figure 13:** Comparison of the price of heat for newly established district heating produced on a wood chip boiler, and different kinds of individual heating. The heat demand is 13 800 kWh/year the Network Scale is 1 and the revised data set is used.

Figure 13 shows the yearly costs for providing space heating and domestic hot water, to a household with a total heat demand of 13 800 kWh/year. The district heating is produced on a wood chip boiler. The figure shows that newly established district heating is the cheapest form of heating for a household, with these assumptions. District heating is around 430 € or what corresponds to about 19 %, cheaper than the second cheapest alternative, which in this case is individual heating by natural gas. Next,after natural gas, is the air/water heat pump and wood pellet boiler at around 790 € and 805 € more than district heating respectively. This corresponds to an increase in price of around 30 % and 31 %.

The individual technologies have widely different cost structures, which provides different reasons as to why district heating is cheapest. This will be further elaborated in the final chapter.

Figure 13 shows that newly established district heating is competitive in a situation where the yearly heat demand is 13 800 kWh/year. The requirements for newly built residences are significantly lower than this. Because of this, it is also necessary to investigate if district heating is competitive in a future where the heat demand is lower than it presently is.

Figure 14 shows the yearly costs for providing space heating and domestic hot water for a household with a total heat demand of 4900 kWh/year. The Network Scale and type of production facility for district heating are the same as in Figure 13. A heat demand of 4900 kWh/year is consistent with the energy framework provided in BR15 for a residence of 130 $m^2$ (Trafik-, Bygge- og Boligstyrelsen, 2017). The figure therefore, represents a situation in which the building stock is converted to low energy buildings. The figure shows, that newly established district heating, under these conditions, is the cheapest form of heating for a household. District heating is roughly 270 €, or what corresponds to around 21 %, cheaper than the next cheapest alternative which is electrical heating. Individual natural gas is around 40 € more expensive than electrical heating in this case. The heat demand in this scenario is so low, that the capital costs are a significant factor. Electrical heating is the cheapest to establish but has the highest variable costs. Technologies such as wood pellet boilers and heat pumps have too high investment and maintenance costs, for them to be offset by the lower variable costs (lower compared to the individual heating options of; oil, natural gas and electrical heating).

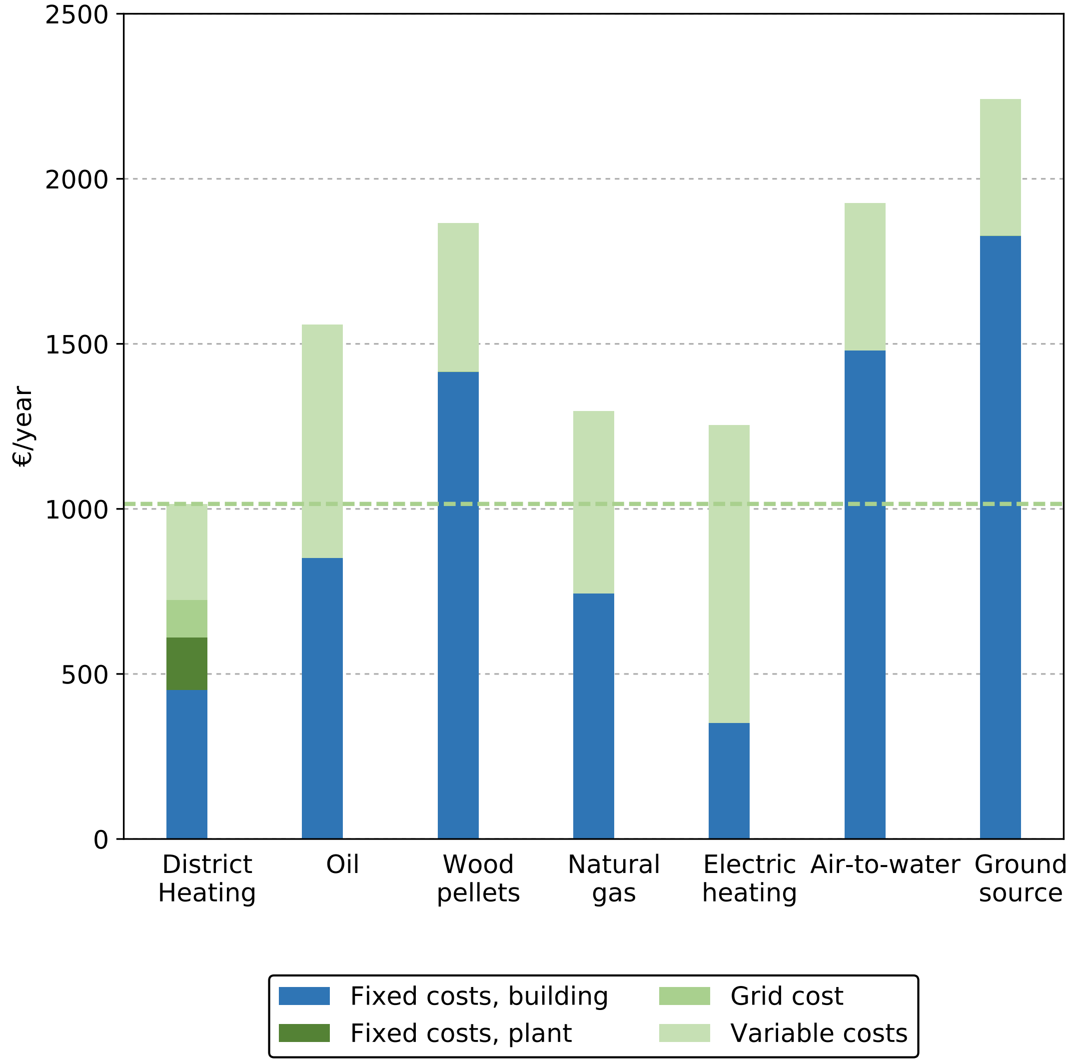


**Figure 14:** Comparison of the price of heat between newly established district heating with a Network Scale of 1 produced on a wood chip boiler and different types of individual heating. The heat demand is 4900 kWh/year and the revised data is used

Figure 15 shows results for a scenario where the total heat demand is the same as in Figure 14, but the district heating grid is scaled to triple the size. Because of this the heat density is lower and the heat loss is higher than in Figure 14.

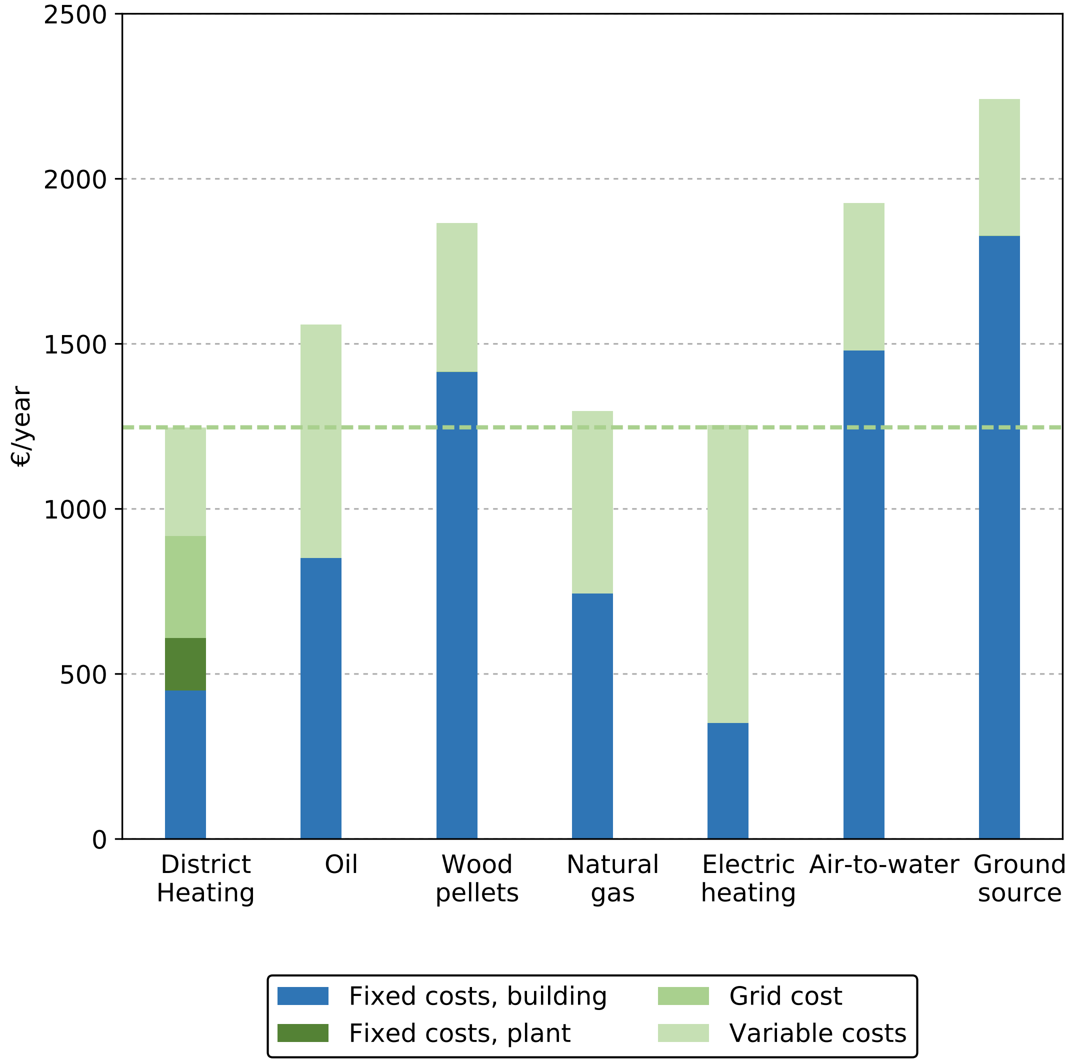


**Figure 15:** Comparison of the price of heat between newly established district heating with a Network Scale of 3 and wood chip boiler production, and different types of individual heating. The heat demand is 4900 kWh/year and the revised data set is used

The price of heat for the individual technologies in Figure 15 is identical to the price in Figure 14, but the price of district heating is increased by around 230 €. Newly established district heating is, together with electrical heating, the cheapest form of heating and about 50 € cheaper than natural gas under these assumptions. It is around this grid size (and corresponding heat density) that district heating no longer is the most cost-efficient form of heating in this analysis. At this point local conditions like price of earth moving and whether there is industry in the area can be deciding factors in determining whether establishing district heating is more advantageous than establishing individual heating.

The case shown in Figure 15 does not have room for increased district heating grid costs. On the other hand the Figures 13 and 14 do. In Figure 13 the grid costs can increase by up to 350 % before the price of district heating are equal to the price of natural gas heating, while the grid costs can increase by up to 200 % in Figure 14 before the price of district heating is equal to the price of electrical and natural gas heating. This indicates, that there is room for uncertainty regarding the construction costs of district heating in these cases.

**Summary:** The results in this section have shown that newly established district heating, to a large extent, is able to compete with individual heating, when establishing new heat supply. This is because the district heating system requires lower production capacity, use cheaper fuels and is more efficient to such an extent, that it offsets the heat loss in pipes and the establishment costs of the grid. Another advantage of district heating is, that in some areas it will be possible to take advantage of surplus heat from industry, which is useable in district heating, but not in individual heating solutions. Furthermore, the district heating system has a number of non-economical advantages, which can mean that district heating is chosen over individual heating for an area, if the prices are similar. Advantages, such as a high level of comfort and a collective green transition. The heat supply for a large number of residents can be changed at once in district heating by, for instance, changing the heat production unit or establishing solar heating, which would further reduce the price of heat for district heating.

The price of heat production on the electric heat pump can be reduced, compared to what is shown in this analysis. In this analysis it is assumed, that all electricity for the collective electrical heat pump is bought at the average price for the year (just as it is with individual technologies). On a district heating plant, it would be possible to use the fluctuating electricity process and the storage tank to reduce the operational costs. The operational costs of the heat pump could also be reduced by committing the heat pump on the power regulating market, this is however not considered in this analysis. Furthermore, district heating plants are subject to a lower distribution tariff on electricity, partly because one can be connected at a higher voltage level than an individual consumer, but also because one pays a lower distribution tariff per MWh as a large electricity consumer.

In the cases where these advantages are large enough to offset the heat loss in the district heating grid and investment in that same grid, district heating will be the obvious choice. In areas where the population density is too low (too big a district heating grid) or there are no cheaper heat sources available, establishing district heating will not be cost efficient and individual heating will in these cases be the obvious choice.

### The effect of assumptions for the competitive conditions

In this section it is investigated, what the significance of using Technology Catalogue data compared to using the revised dataset is. This is done, in order to asses what kind of impact the assumptions have on the competitive conditions between district heating and individual heating.

Figure 16 shows the yearly costs for providing space heating and domestic hot water for a household with a total heat demand of 13 800 kWh/year. The columns with the green shades are calculated based on the revised data set, while the columns with the blue shades are based solely on data from the Technology Catalogue.

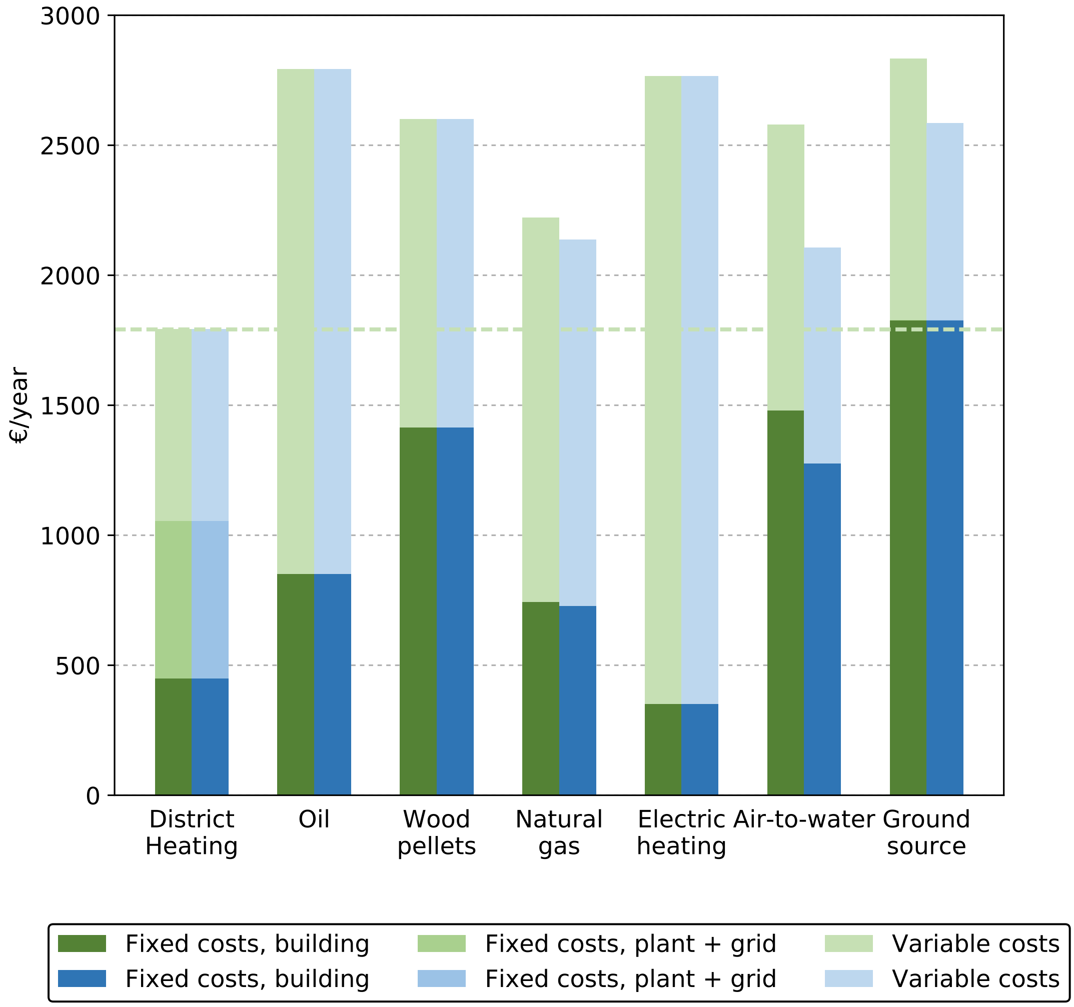


**Figure 16:** Comparison of the price of heating between newly established district heating with a Network Scale of 1 and wood chip boiler production and different individual technologies. The heat demand is 13 800 kWh/year. The green shades are revised data. The blue shades are Technology Catalogue data

The data is only different for natural gas and heat pumps. The result for natural gas is a change in the price of heat of about 80 € This is because, the changed assumptions only pertain to a slight adjustment in lifetime (lowered from 20 years to 19 years) and efficiency (lowered from 97 % to 92 %). The most significant changes are the ones for the heat pumps and especially the air/water heat pump. In the revised data set the efficiency of the air/water heat pump is lowered from 325 % to 233 %, while the ground source heat pump's efficiency is lowered from 360 % to 263 %. Furthermore, the lifetime of the air/water heat pump is lowered from 20 years to 15 years. The results on the yearly price of heat, is a drop of about 470 € for the air/water heat pump, while it is a 255 € drop for the ground source heat pump.

Figure 17 is made with the same dataset as Figure 16 but with a total heat demand of 4900 kWh/year instead of 13 800 kWh/year. The conclusion is the same as in Figure 16, district heating is competitive using both datasets.

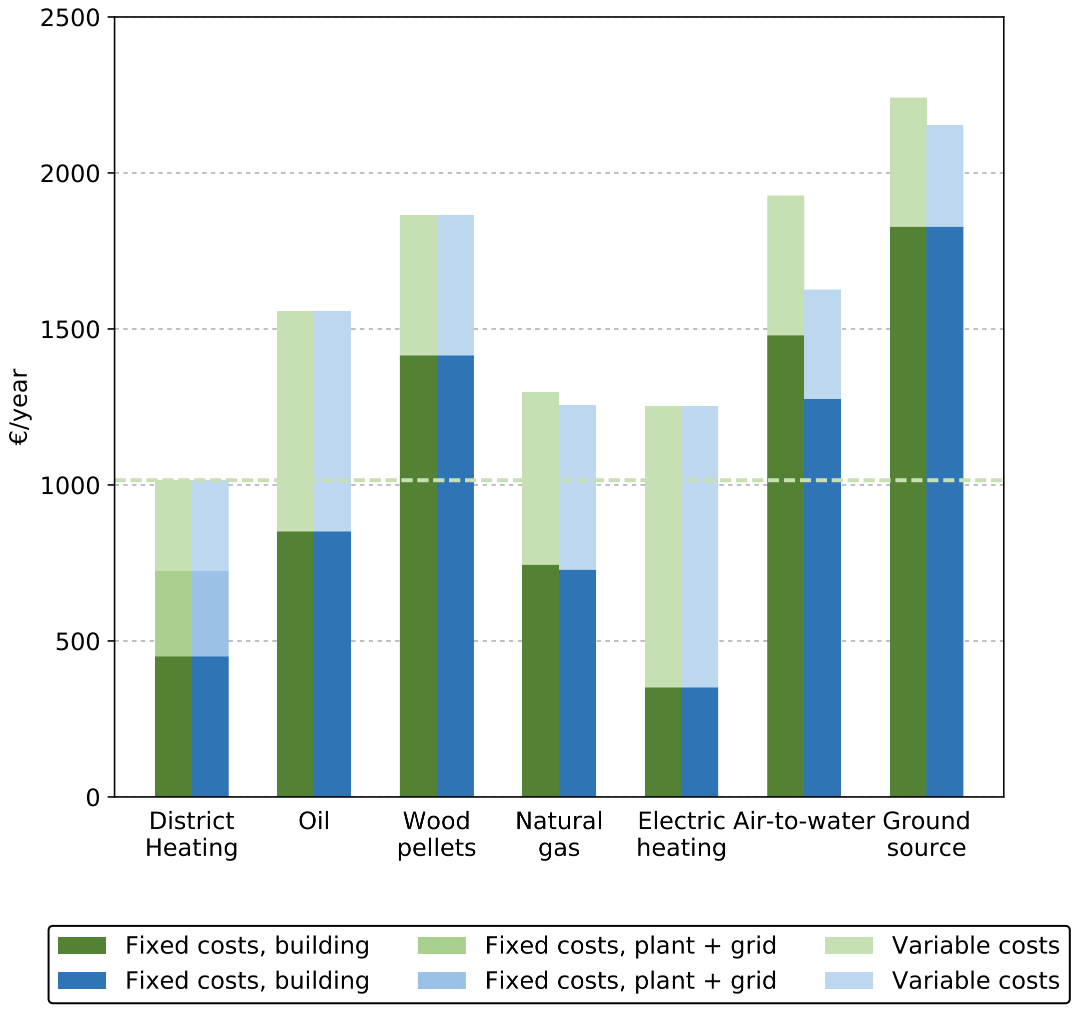


**Figure 17:** Comparison of the price of heating between newly established district heating with a Network Scale of 1 and wood chip boiler production and different individual technologies. The heat demand is 4900 kWh/year. The green shades are revised data. The blue shades are Technology Catalogue data

**Summary:** Overall, using only values from the Technology Catalogue instead the revised data set does not change the conclusions regarding the competitiveness of district heating, both for a heat demand of 13 800 kWh/year and 4900 kWh/year. The change lowers the yearly price of heat for air/water heat pumps to the level of individual natural gas. District heating is still as competitive compared to individual solutions, but the air/water heat pump is now competitive with natural gas under these assumptions.

## The effect of taxes on the competitive conditions

In this section the effect of taxes on the competitive conditions between district heating and individual heating is examined. The cost elements of the different heat production technologies are divided into more detailed parts than previously in the analysis. This makes it possible to see the impact on the competitive relation if the Danish taxes are changed. This also enables perspectivation of the results for conditions outside of Denmark where especially taxes, but also fuel prices are different from the Danish.

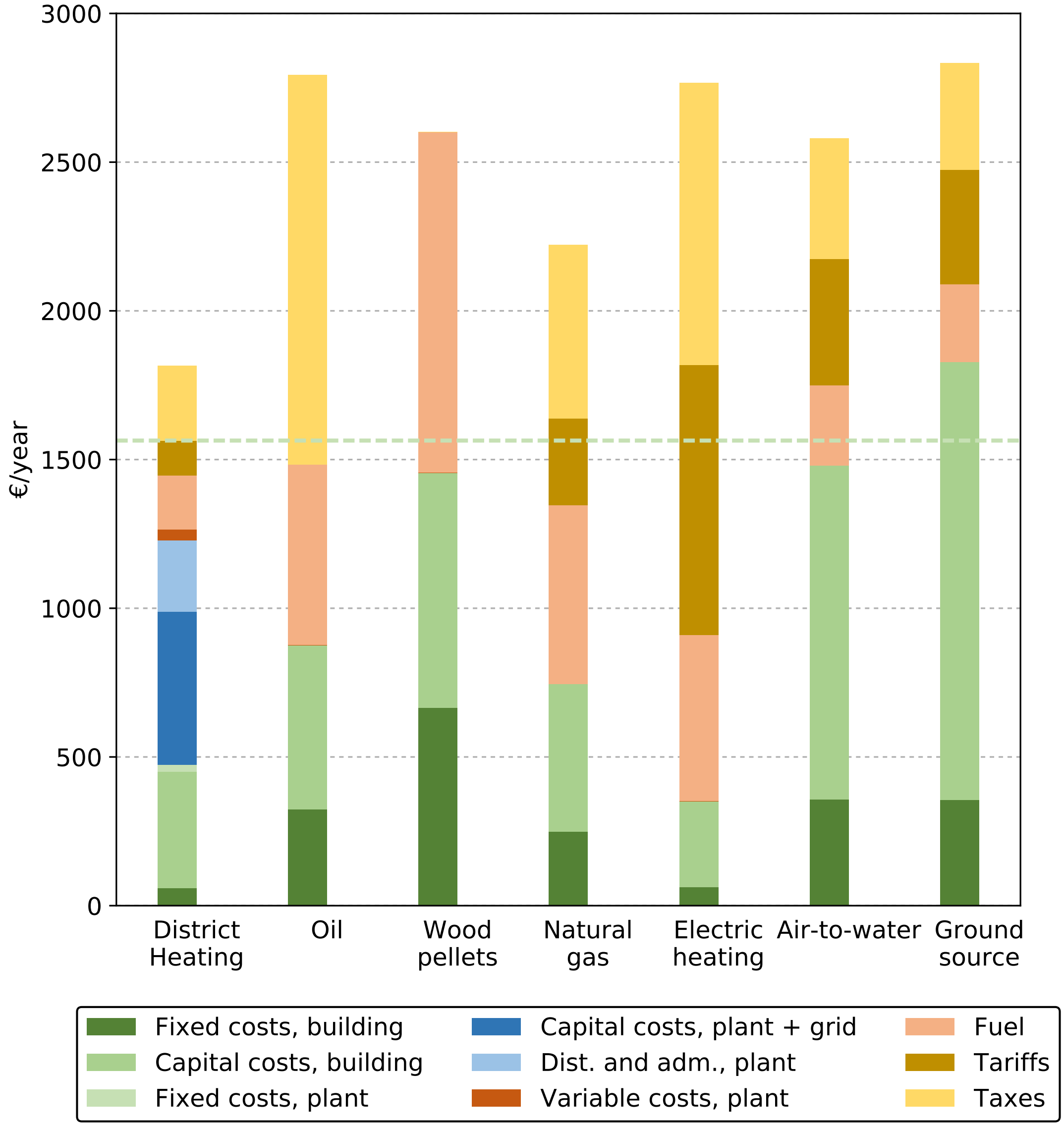


**Figure 18:** Comparison of the price of heat between newly established district heating produced by an electric heat pump and a Network Scale of 1 and different types of individual heating. The heat demand is 13 800 kWh/year and the revised data set is used.

Figure 18 shows the yearly costs of supplying space heating and domestic hot water for a household with a total heat demand of 13 800 kWh/year. The district heating is produced by an electrical heat pump. Under the current Danish taxation, newly established district heating is definitely competitive, when compared to individual heating in the scenarios depicted in Figure 18. Looking at the price of heat without any taxes, only heating by oil is cheaper than newly established district heating (note that around half of the costs for heating by oil are taxes). In a future where the goal is less dependency on fossil fuels, it should be reflected upon whether oil is an actual competitor to district heating. Newly established district heating is thus cheaper than both natural gas and the electricity-based technologies when taxes are ignored.

If the tax on electricity used for heating is lowered in Denmark, newly established district heating would still be able to compete with individual heating. Individual natural gas-based heating is the technology, that is the closest to district heating when comparing yearly heating costs. It should be noted, that Denmark has very low prices on natural gas (looking only at the fuel) compared to other European countries, see Figure 25 in Appendix C. Including taxes and tariffs, the price of natural gas in Denmark is at the high end of the scale. In a situation where the pure price of natural gas is higher than in Denmark (but taxes and tariffs are lower than the Danish ones), newly established district heating should have a clear competitive advantage compared to individual natural gas-based heating.

The same is applicable for the electricity-based heating technologies. The pure price of electricity in Denmark is among the lowest in Europe while the price including taxes and tariffs is the highest in Europe, see Figure 26 in Appendix C. In a situation where the pure price of electricity is higher than the Danish (but the total of taxes and tariffs is lower than the Danish), newly established district heating should have a clear competitive advantage compared to electrical heating and especially the heat pumps. The high efficiency of the district heating system along with lower capital costs, makes district heating the cheapest source of heat in this case.

Figure 19 shows the yearly costs for providing space heating and domestic hot water for a household with a total heat demand of 13 800 kWh/year, where the district heating is produced by a wood chip boiler. The fuel costs for an electrical heat pump is approximately split between taxes 46 %, price of electricity 33 % and 21 % tariffs, while the fuel costs for a wood chip boiler is split 99 % wood chips and 1 % tax. The very low tax payment compared to electricity ensures that the wood chip boiler today has a lower price of heat than an electrical heat pump. If the tax on electricity used for heating is halved, the electrical heat pump will have the lowest heat production price.

Looking at the prices for heating with no taxes shown in Figure 19, it is seen that individual heating by natural gas is cheaper than district heating, but only by around 105 € This is based on the low price of natural gas in Denmark. In a foreign case where the price of natural gas is higher (and the taxes lower than the

Danish ones), newly established district heating will be competitive, given that the price of wood chips is not that much greater than in Denmark. According to the Danish Energy Agency's guide lines for socio-economic calculations, the CIF-prices (import prices to Denmark) are around 0.67 €/GJ higher than the price from a Danish manufacturer (Energistyrelsen, 2017a).

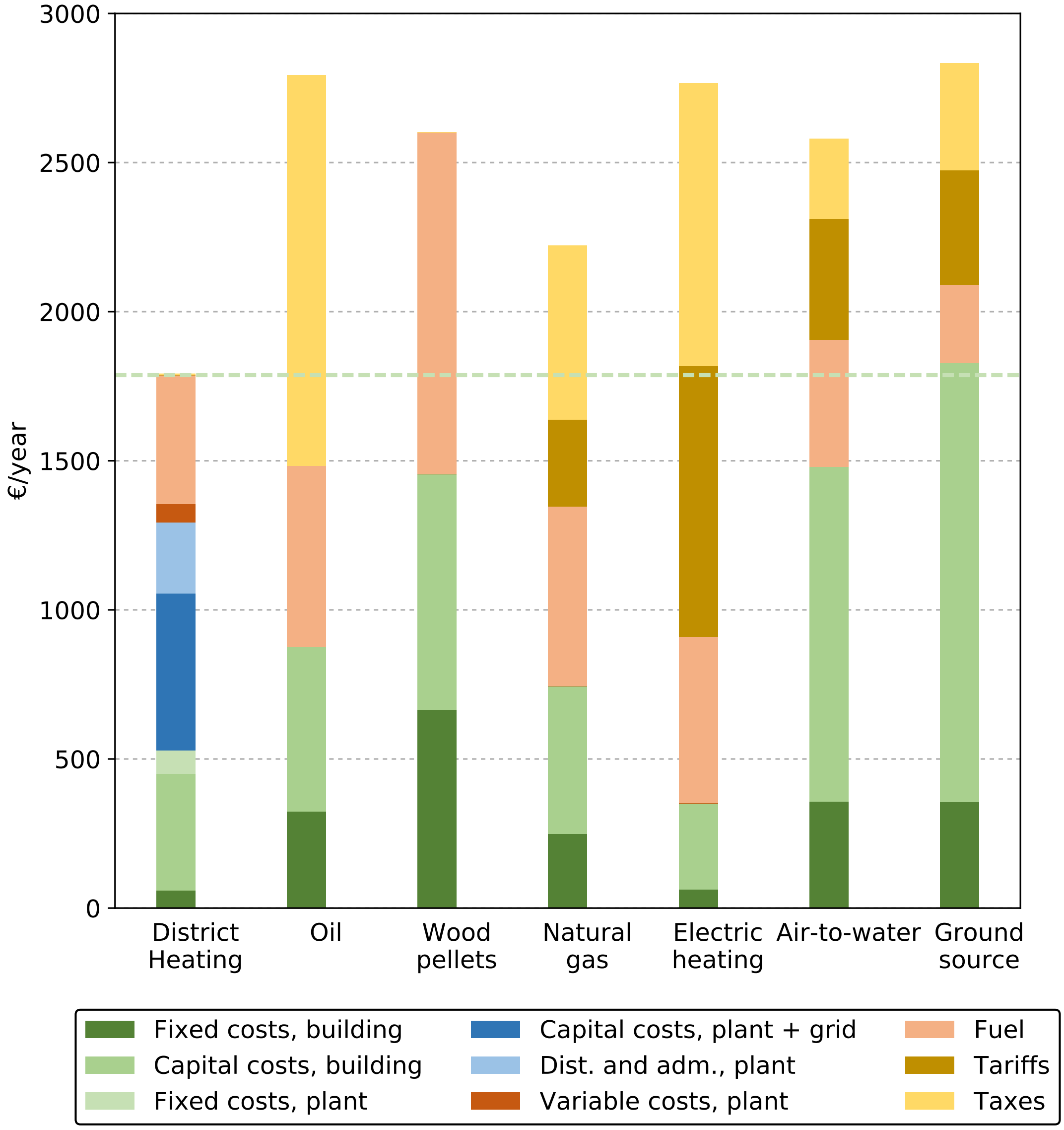


**Figure 19:** Comparison of the price of heat between newly established district heating produced on a wood chip boiler and a Network Scale of 1 and different types of individual heating.The heat demand is 13 800 kWh/år and the revised data set is used.

Figure 20 shows the yearly cost of supplying space heating and domestic hot water for a household with a total heat demand of 4900 kWh/year, with the district heating being produced by an electrical heat pump. In this case as well, district heating is shown to be competitive compared to all the individual heating technologies. If the yearly price of heat is compared without taking taxes into account, the price of district heating is equal to the price of electrical heating because the investment costs are low for electrical heating. Moreover, the price of electricity is low in Denmark, if one disregards taxes and tariffs. At higher electricity prices the greater efficiency of district heating based on electrical heat pumps will cause district heating to be cheaper than individual electrical heating. Furthermore, the heat demand is low in this scenario, which allows for the low efficiency of electrical heating to be negated by the low capital costs.

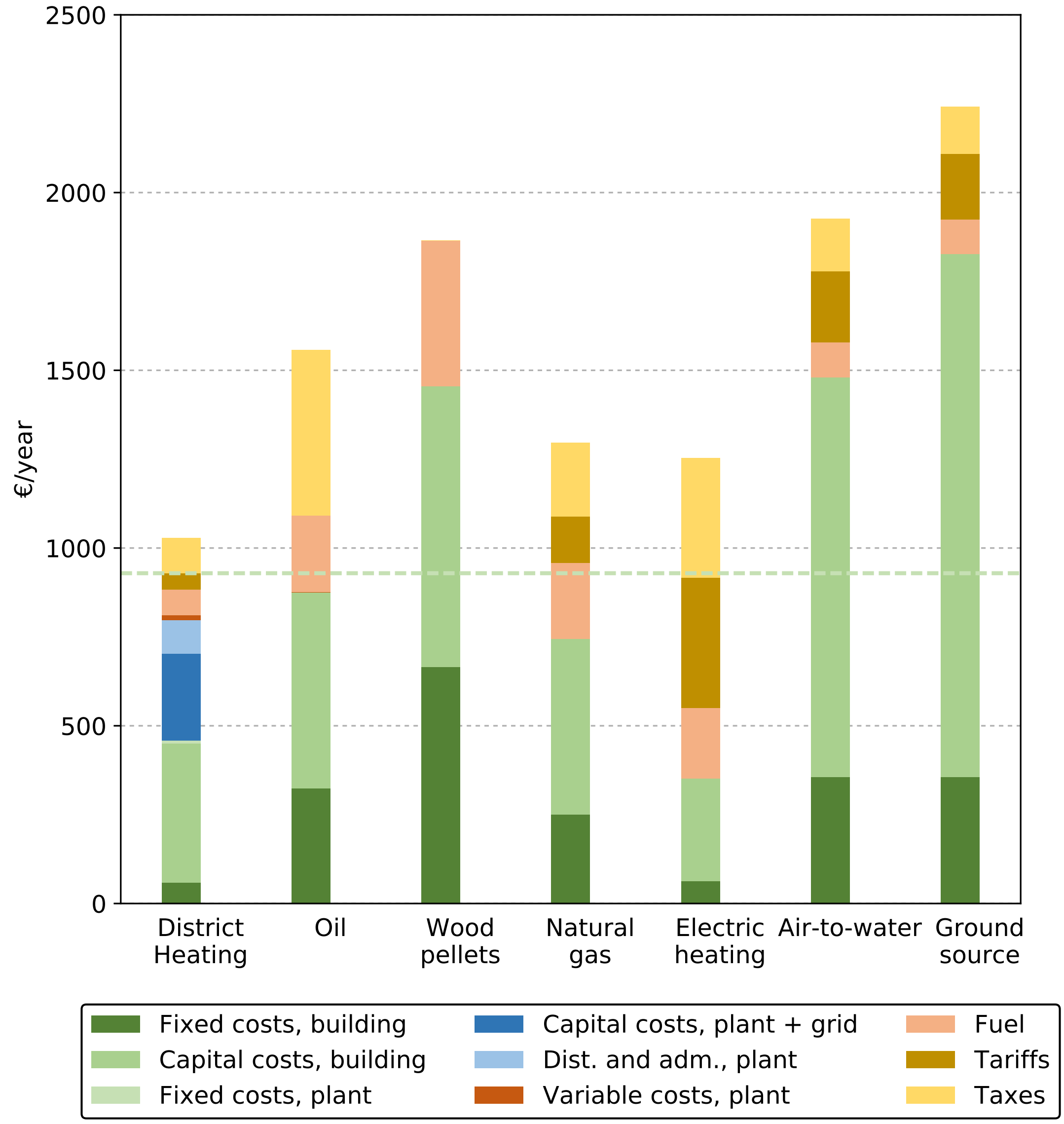


**Figure 20:** Comparison of the price of heat between newly established district heating produced on an electrical heat pump and a Network Scale of 1 and different types of individual heating.The heat demand is 4900 kWh/year and the revised data set is used.

Upon establishment of district heating outside of Denmark, it is not a given that the district heating should be produced in the same way as it is in Denmark, because taxes, tariffs, subsidies and fuel prices are distinctive to each country. In Germany for instance, the taxes on electricity are very high, but the taxes on natural gas are very low. Furthermore, combined heat and power production is subsidized which, most likely, will make establishing natural gas based combined heat and power production more preferable than establishing wood chip boilers and electrical heat pumps for heat production.

In addition, the costs of establishing a district heating grid outside of Denmark are uncertain. The figures in the analysis have shown that under Danish conditions, there is room for higher establishing costs for the district heating grid, without affecting the competitiveness compared to individual heating.

**Summary:** The graphs generally show, that there are different disadvantages for the individual technologies, that makes them unable to compete with newly established district heating. Wood pellet boilers have low efficiency, high capital costs and high fixed costs. Individual electrical heating has high taxes, while heat pumps have high taxes and high capital costs. Individual natural gas has high costs for fuel (when taxes and tariffs are included).

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# A Heat demand variations

This section contains a description of how the variations of heat demands are done in the analysis.

The different heat demand variations that are used in the analysis are based on a heat index curve under the condition that the heat loss in a building is primarily dependent on the outside air temperature. In order to make the heat index curve the buildings dimensioning heat loss is specified, which in this case is at $-12\,°C$, along with the temperature at which there no longer is a heat demand, which is at $16\,°C$ in this case. It is assumed that there is a linear correlation between these two points. In the case where the dimensioning heat loss at $-12\,°C$ is $30\,W/m^2$ the heat index curve looks like what is shown in Figure 21.

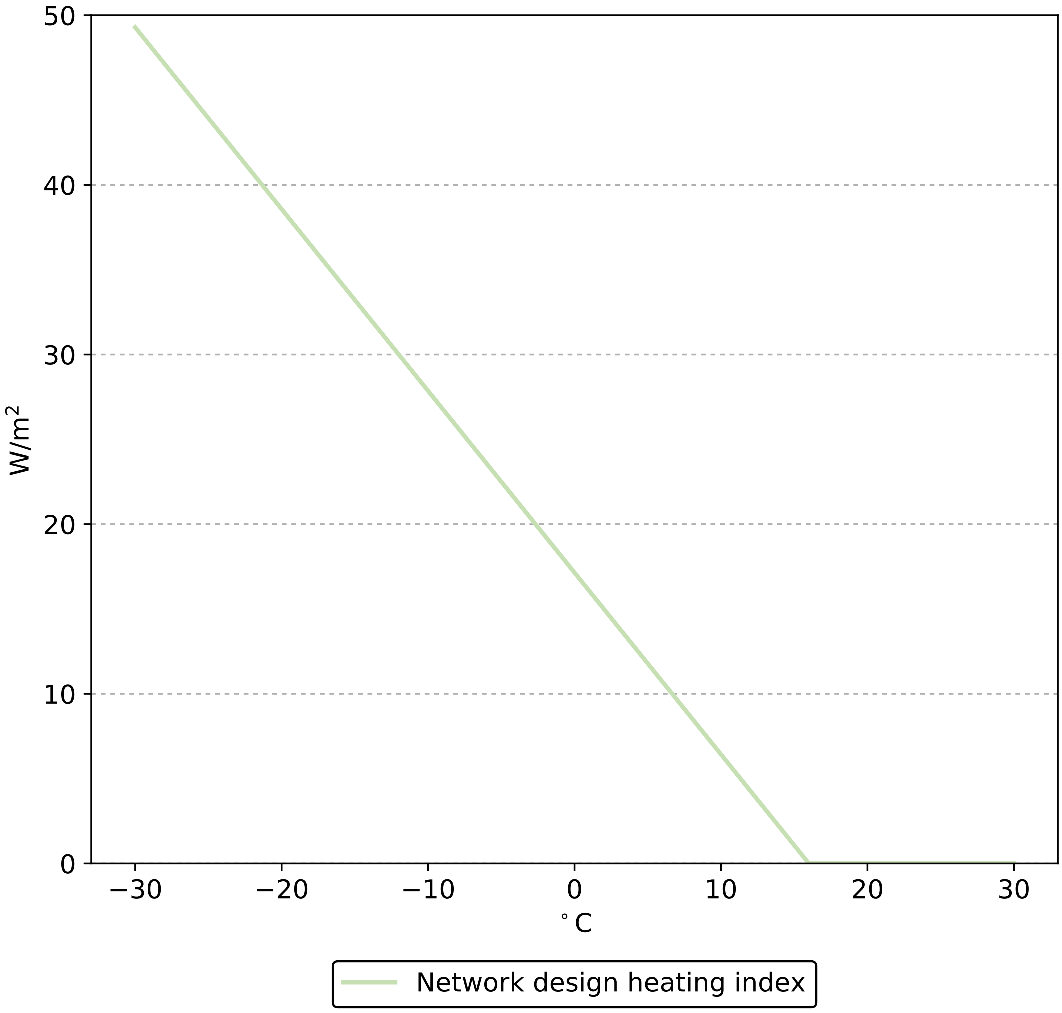


**Figure 21:** Heat output as a function of outside air temperatures

This can also be viewed as the heat output per $m^2$ the building requires at a given temperature.

The same method has been used to create heat index curves for 25 W/m$^2$, 20 W/m$^2$, 15 W/m$^2$, 10 W/m$^2$ and 5 W/m$^2$, which together forms the six heat demand variations that are used in the analysis. When the building's heat demand is known for a given temperature, it is then possible to determine the yearly heat demand from a timeseries of weather data. In this case, a years' worth of hourly values from EQUA (2017), see Figure 22.

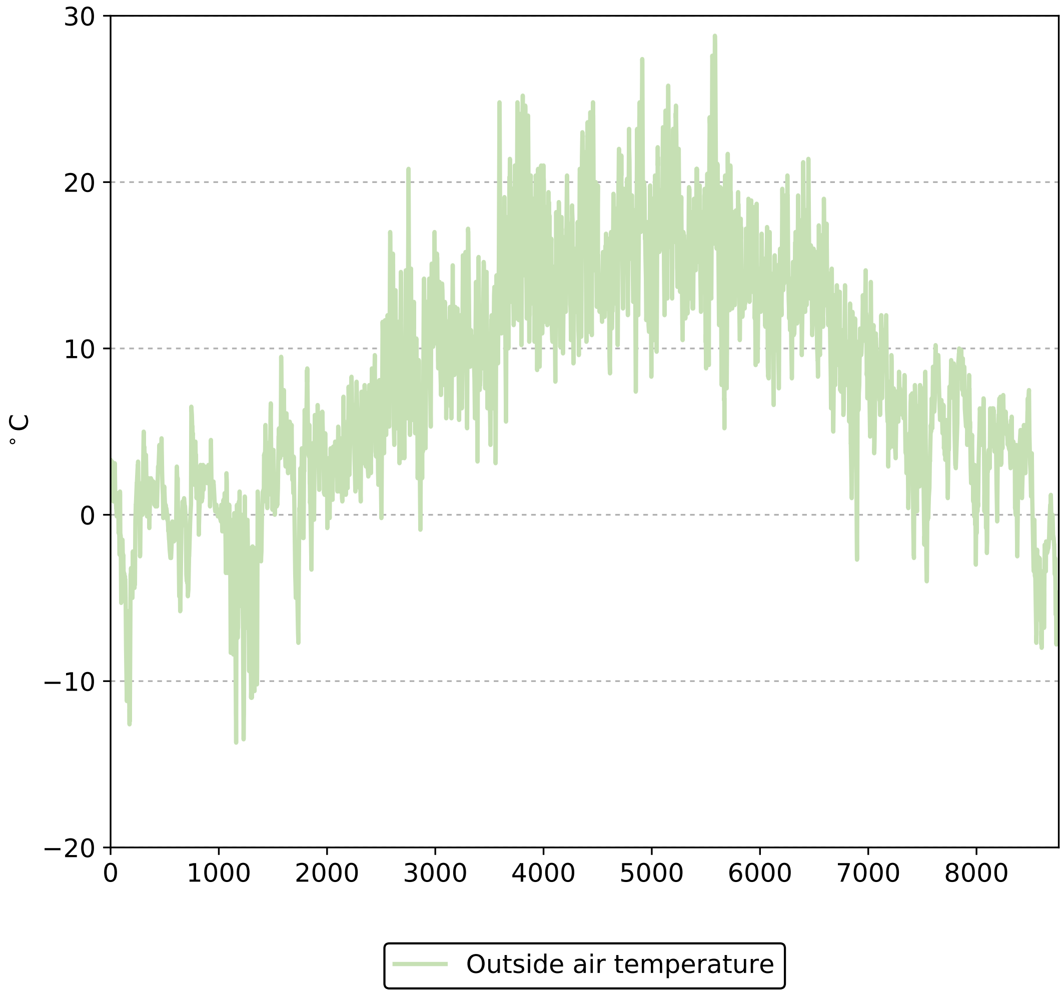


**Figure 22:** Outside air temperatures at different hours during the year

The resulting heat demand for a building of 130 $m^2$ with a demand per $m^2$ of 30 W is shown as a duration curve in Figure 23. The figure is based on the heat index curve and a year's worth of outside temperatures.

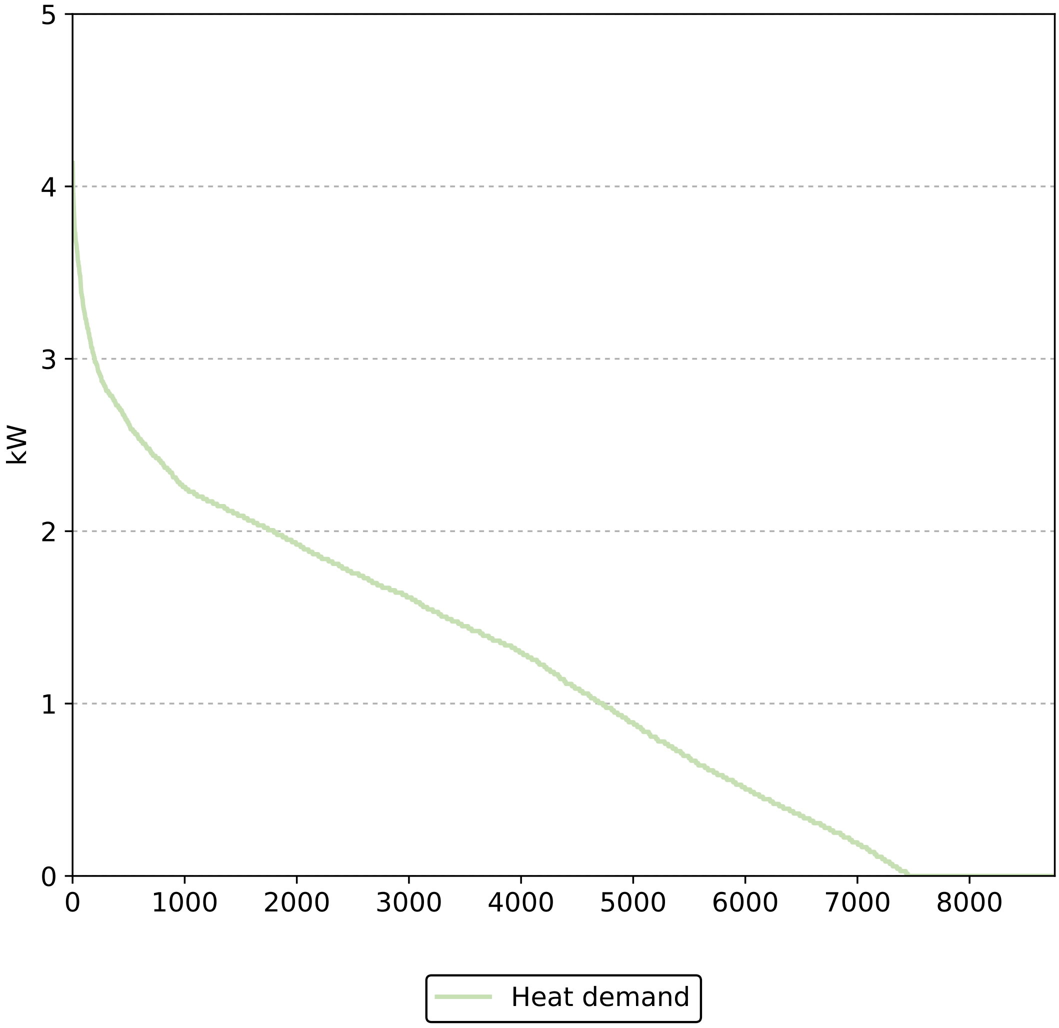


**Figure 23:** Duration curve of the space heating demand for a building

# B Grid modelling

This section contains a more in-depth description of the method, that is used for the grid modelling in the analysis.

When the capacity of the buildings that are part of the modelled area is determined, dimensioning the grid is possible. The grid is dimensioned based on the following parameters:

- Forward and return temperatures
- Maximum allowed flow velocity and pressure loss per meter pipe (the first limit that is crossed, determines the pipe dimension)

It is possible to reduce the pipe dimensions by using a simultaneity factor, because the consumption at the different points in the pipe grid is not simultaneous. In the analysis this is done according to Nick Bjørn Andersen (2015) for both space heating and domestic hot water use. The simultaneity factor of space heating is therefore

$$\mathrm{S_{rv}} = 0,62 + \frac{0,38}{n}$$

While the simultaneity factor for domestic hot water is based on Euroheat & Power (2008). The simultaneity factors are illustrated graphically in Figure 24.

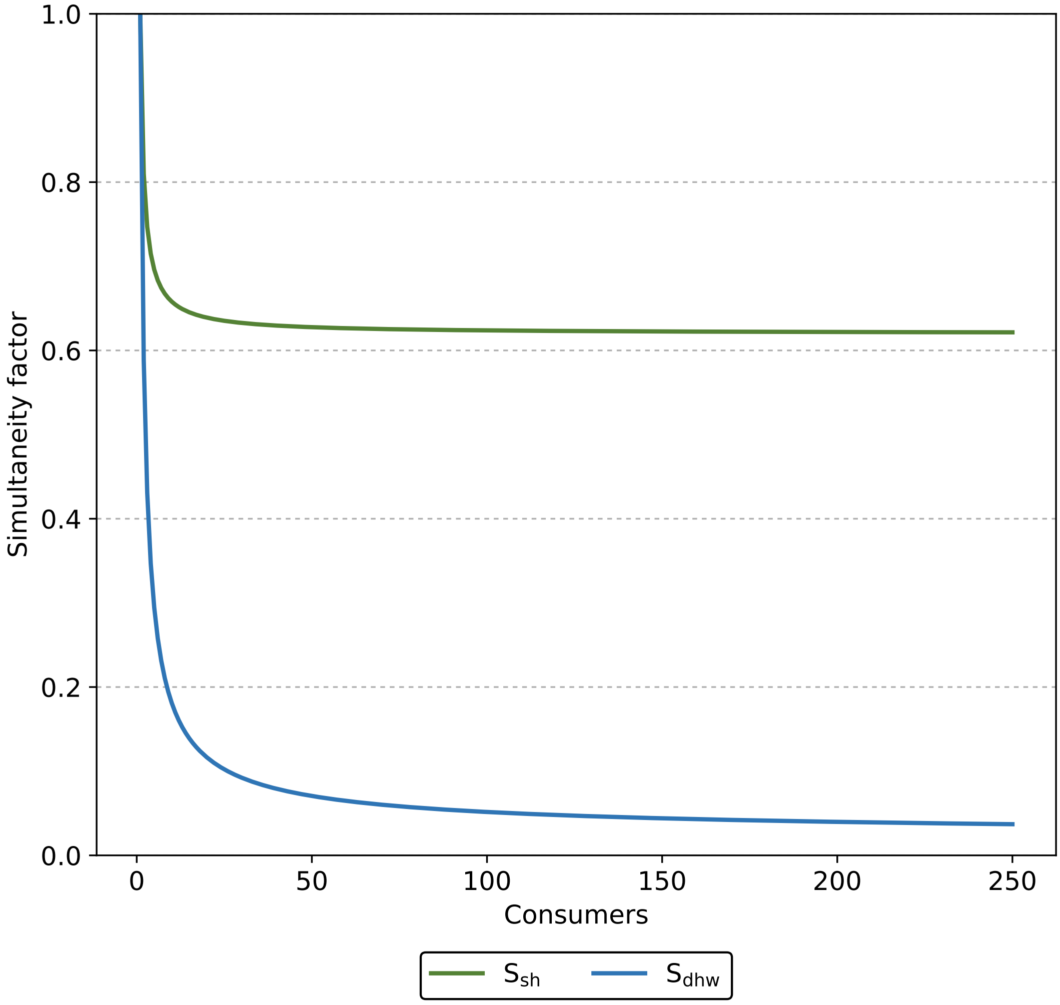


**Figure 24:** Simultaneity factors for space heating and domestic hot water preparation

Note that the simultaneity factor for space heating approaches 0.62 as the number of consumers increase. When the number of consumers is greater than 50, an increase in space heating demand of 1 kW at the consumer, only requires a 0.62 kW increase in capacity in the district heating pipe.

This method is used to determine the necessary capacity of all pipes (for area 2 the pipes are shown in Figure 5). The pipe grid in the analysis is designed for a forward temperature of 65 °C and a return temperature of 30 °C. The size of the pipes for each section can now be calculated based on the two parameters; flow velocity and pressure loss.

The flow in $\frac{\mathrm{m}^3}{\mathrm{s}}$ can be found from the formula

$$V = \frac{E_{heat}}{c_p \cdot (T_{forward} - T_{return}) \cdot \rho} \cdot \mathrm{S_v}$$

where $E_{heat}$ is heat output in $\frac{\mathrm{kJ}}{\mathrm{s}}$, $c_p$ is the specific heat capacity (for water) in kJ/kg · K, $\rho$ is the density (for water) in $\frac{\text{kg}}{\text{m}^3}$, $T_{forward}$ og $T_{return}$ is forward and return temperatures respectively and $\text{S}_\text{v}$ the specific volume (for water) in $\frac{\text{m}^3}{\text{kg}}$. The smallest possible pipe dimension can now be determined via the formula

$$d_{min} = \sqrt{4 \cdot \frac{A}{\pi}}$$

where $A = \frac{V}{v_{max}}$ and $v$ is flow velocity. The calculated pipe dimension is then adjusted upwards, to the nearest physical pipe dimension.

The pressure loss in Pascal is estimated for the available pipe dimensions based on the following formula

$$\Delta P = \lambda \frac{L}{d} \frac{\rho v^2}{2}$$

using one of the following friction factors:

$$\lambda_{\text{Karman}} = \left(2 \cdot \log \frac{d}{e} + 1,14\right)^{-2}$$

$$\lambda_{\text{Swamee-Jain}} = 0,25 \left[\log \frac{e/d}{3,7} + 5,74 \left(\frac{Vd}{v}\right)^{0,9}\right]^{-2}$$

where $L$ is the pipe length in meters and $e$ is a roughness factor in meters. In the analysis the pressure loss is calculated as the highest total of pressure loss on a given pipe distance. In order to cover smaller losses like shut-off valves and bends 10 % is added to this. Furthermore, 30 kPa is added to account for operation of district heating units.

The final pipe dimension for a given distance is chosen based on the smallest possible pipe dimension, that can comply with the maximum allowed flow velocity (but still move the required amount of heat) and the maximum allowable pressure loss.

The heat loss $hl$ in W for a given pipe distance, which can be determined based on the heat loss coefficient $k$ (with the unit W/m · K), is estimated based on the formula

$$hl = k \cdot (T_{forward} + T_{return} - 2 \cdot T_{ambient}) \cdot L$$

# C European energy prices

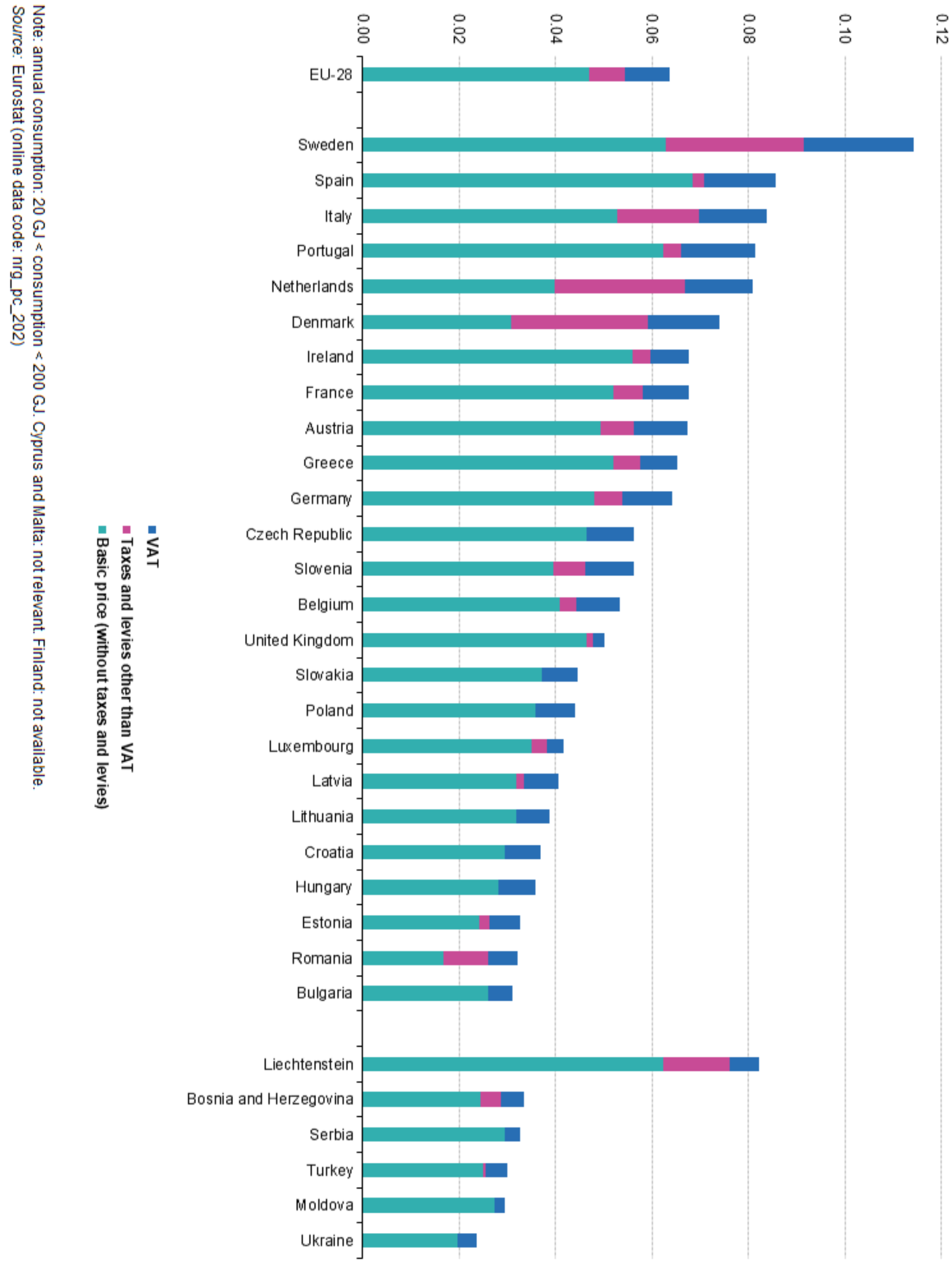


**Figure 25:** Natural gas prices for European households
**Source:** Eurostat (2016)

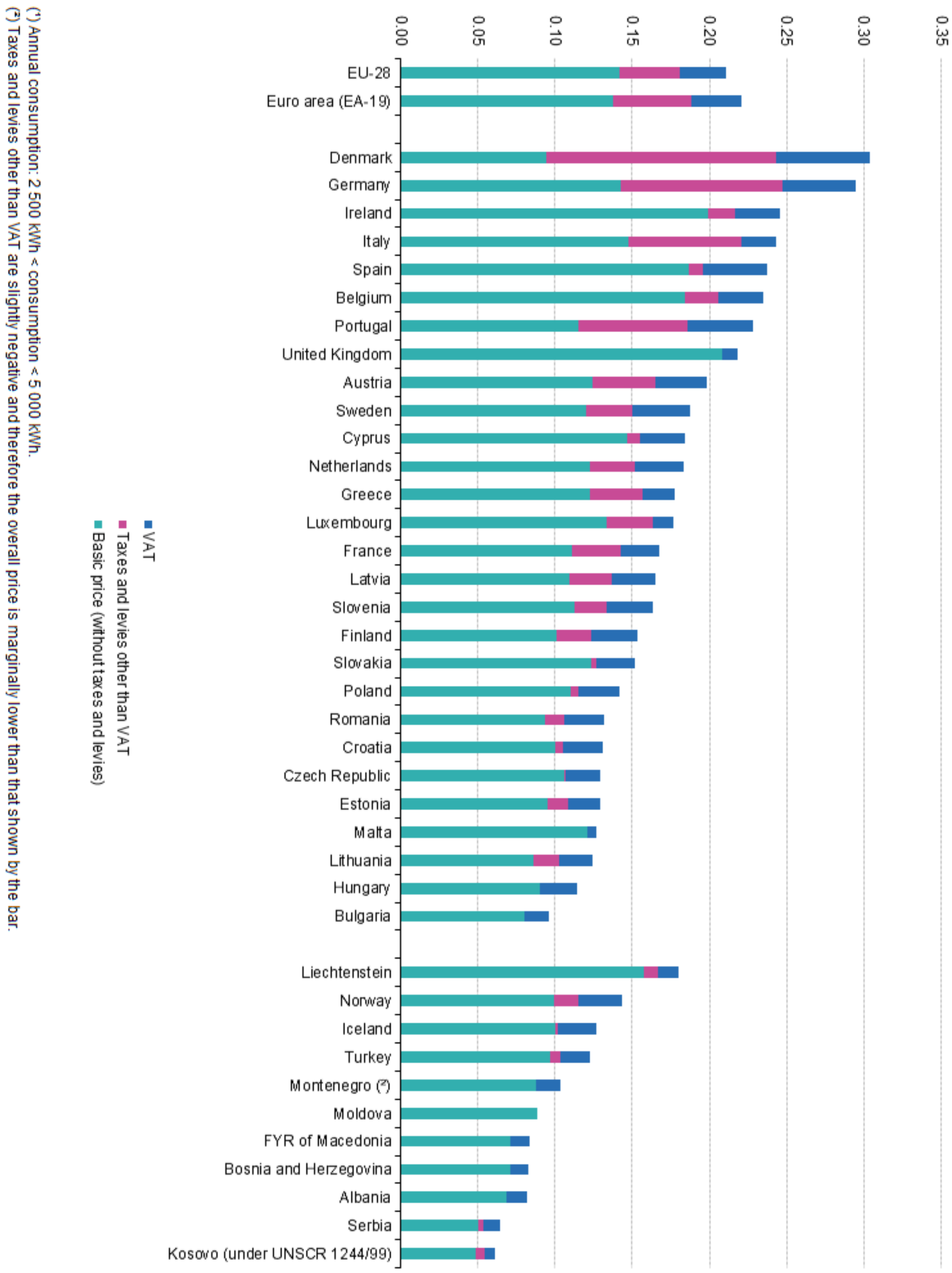


**Figure 26:** Electricity prices for European households
**Source:** Eurostat (2015)

# D District heating pipe costs

The costs in Table 7 are empirical values from Danish district heating projects.

| Pipe dimension | Green field | Park areas | Outer city | Inner city |
|---|---|---|---|---|
| DN25 | 170 | 216 | 264 | 293 |
| DN32 | 178 | 224 | 271 | 301 |
| DN40 | 178 | 224 | 271 | 301 |
| DN50 | 193 | 239 | 285 | 316 |
| DN65 | 208 | 255 | 299 | 332 |
| DN80 | 224 | 270 | 320 | 355 |
| DN100 | 247 | 301 | 361 | 401 |
| DN125 | 293 | 347 | 403 | 448 |
| DN150 | 347 | 409 | 458 | 509 |
| DN200 | 432 | 502 | 570 | 633 |

**Table 7:** District heating pipe costs used in the analysis, without Danish VAT. Costs are in [kr./m]