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Scenarios for sustainable heat supply in cities – case of Helsingør, Denmark

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ABSTRACT

The Danish municipality of Helsingør can achieve 30% of its CO_2 emission reduction by transforming its heat supply. We model Helsingør's heating system from a socio- and private-economic perspective, develop energy scenarios, and conduct an iterative process of cost curves and energy modelling to derive optimal supply and savings mix for two scenarios: Business-As-Usual 2030 (BAU2030) and REnewableS (RES2030). The results show that without forbidding oil and natural gas boilers (BAU2030), it pays off to deploy between 25-29% heat savings and 31-49% DH (district heating). With the restriction (RES2030), it pays off to implement between 27-33% heat savings and 68-71% DH. However, the results are sensitive to DH price and CO_2 emissions related to electricity production. Although the findings of the study are mainly applicable for Helsingør, the combined cost curve and energy modelling method is useful in planning for any heat supply and demand configuration, geographical location and scale.

KEYWORDS

Sustainable heat supply, heat savings, cost curves, optimization model, urban energy scenarios, municipal CO_2 goals

INTRODUCTION

Increasingly, urban areas are leading the way for energy efficiency and CO_2 emission reduction actions. Currently, heating is responsible for almost half of European total energy consumption [1]. Heat planning is one of the areas, where Danish municipalities enjoy relatively significant influence, especially in relation to district heating [2]. Our case study, Helsingør, Denmark, has been involved in regional strategic energy planning effort and is currently identifying its local climate actions. The municipality aspires to reduce CO_2 emissions by 20% in 2020, reach a level of one tonne of CO_2/inhabitant in 2030 and become CO_2 neutral in 2050. In relation to heating and cooling, Helsingør can achieve its goals by implementing energy savings in buildings,

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switching oil- and natural gas-based individual supply to renewables or expanding district heating network, primarily based on biomass and waste.

Strategic Energy Planning (SEP) is one of the commonest approaches to promoting local climate initiatives. Danish Energy Agency defines SEP in the following way: "Strategic energy planning in the municipalities is about long-term planning. The municipality can contribute to a long-term development towards a fossil-free energy supply and other municipal and national climate and energy related goals. SEP encompasses all types of energy supply and demand in all sectors (households, municipal and other public service, private service, industrial production and transport)" [3]. In Europe, Strategic Energy Action Plans (SEAPs) are promoted through the Covenant of Mayors (CoM). They focus on buildings, equipment/facilities and urban transport, but also on local electricity production and local heating/cooling generation. Industry is on the other hand not a target sector [4]. The first SEAPs show how the Covenant signatories will reach their commitments by 2020. In May 2014, the signatories of the CoM agreed to reduce their GHG emissions with 170 Mt CO_2 eq, which equals 28% of their total emissions and 15% of the EU GHG emissions reduction target [5]. This article identifies efficient and renewable heating supply as part of developing a strategic energy plan for the municipality of Helsingør.

Developing a strategic energy plan involves establishing a baseline emissions inventory including an energy balance. When focusing on the energy sector it may however be beneficial to make more detailed system analyses taking into account the fluctuations in demand and production, which we handle using an energy system analysis tool called energyPRO.

In the literature, municipal energy scenarios have been analysed e.g. for Danish [6], [7] and Brazilian cities [8]. Nielsen and Møller [9], Sperling and Møller [6] have used Geographic Information Systems (GIS) data for mapping heat consumption in Denmark. energyPRO has been used to analyse the operation of CHP (Combined Heat and Power) plants on electricity markets [10] and their possibilities for balancing services in Denmark [11] and Germany [12]. Moreover, [13] has used energyPRO for conducting an energy system analysis of a Hungarian town.

The novelty of our paper lies in linking GIS data and energyPRO modelling through an iterative cost curve calculation conducted in a spreadsheet model. Our methodology allows identifying optimal mix of heat savings, district heating expansion and individual heat supply, given a specific policy scenario. Since this work is part of the progRESsHEAT [14] project, our analyses will also contribute to the municipal energy policy development in Helsingør and other case municipalities in Europe.

METHODOLOGY

The methodology in this study consists of: **building aggregation**, district heating modelling with **energyPRO** tool and iterative modelling of heat supply and heat savings costs with a purposely-developed **spreadsheet tool**. Figure 1 shows how the methods link together.

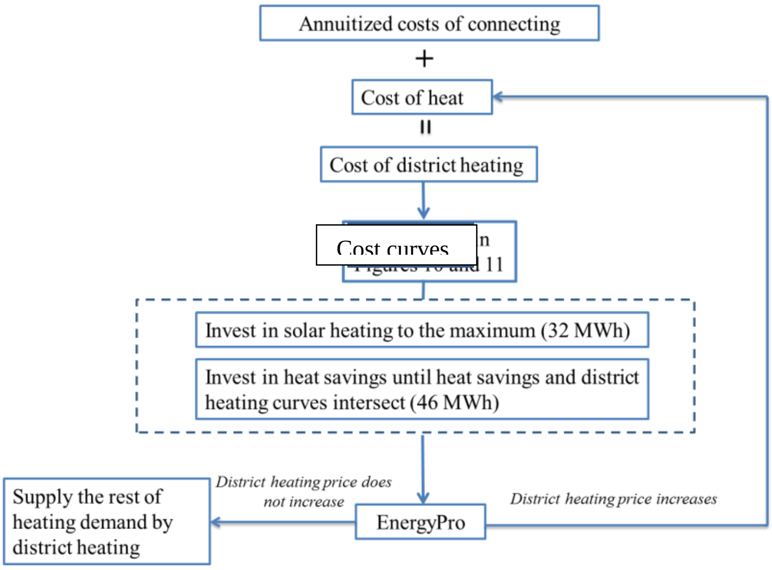

Figure 1. Iteration procedure between cost curves and energyPRO (investment potentials in MWh are illustrative exemples not related to Helsingør)

The energyPRO tool is used to calculate the costs of DH (district heating) production, depending on changes in the heat demand, which can increase if DH expansion takes place or decrease if heat savings are implemented. The costs of individual supply and heat savings are calculated in the spreadsheet model. Both DH and individual supply costs are compared with each other in an iterative process until definitive results are found (please note that Figure 1 shows exemplary values not related to Helsingør). Moreover, the focus in this paper is also on changes in CO_2 emissions resulting from transformation of heat supply.

Spreadsheet model

Building aggregation. The cost of DH depends on the geographical location, related to the distance to existing district heating and natural gas grids. Therefore, we divide Helsingør into four types of areas: DH, Next-to-DH, Individual areas and Scattered buildings.

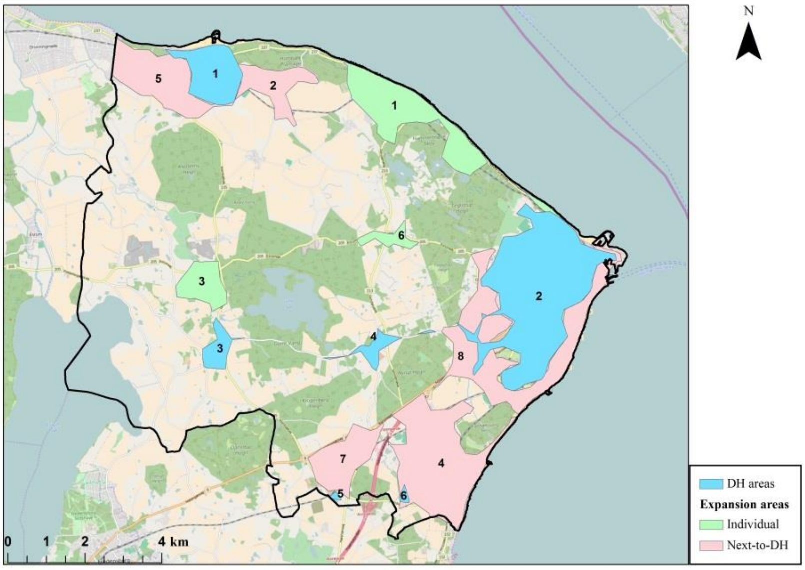

Figure 2. Division of Helsingør into DH areas, Next-to-DH areas and Individual areas

Figure 2 depicts the division of Helsingør municipality into DH areas and areas with an expansion potential: Next-to-DH areas and Individual areas. Figure 3 shows their heated area.

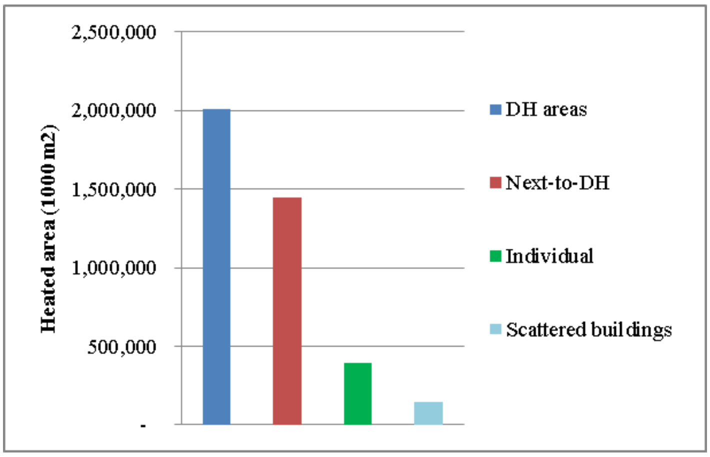

Figure 3. Aggregation of building stock according to area type

DH areas are the areas where the majority of buildings are supplied by district heating. Despite of Helsingør being supplied by two district heating companies, from a geographical perspective (presence of transmission lines) there are six such areas. Not all buildings located within DH areas are connected to DH - in order to connect them to DH investments in connecting pipes and heat exchangers are necessary.

Next-to-DH areas share a border with existing district heating areas, but are not supplied by district heating. From a geographical perspective, there are five such areas in Helsingør. To connect the buildings located in Next-to-DH areas, investments in distribution pipes, connecting pipes and heat exchangers are necessary.

Individual areas are not supplied by district heating and do not share a border with existing district heating areas. From the geographical perspective there are four such areas in Helsingør. To connect the buildings located in Individual areas to DH, investments in transmission pipes and distribution pipes, connecting pipes and heat exchangers are necessary.

Scattered buildings represent individual buildings scattered across the municipality. The expansion of district heating to these areas is not considered, as they are typically located far from the transmission grid.

Buildings located within DH, Next-to-DH and Individual areas can be supplied by DH and individual heating sources or their demand for heat can be reduced by heat saving measures, while for the Scattered buildings only the supply from individual heating sources and heat saving measures are possible.

The costs of heat saving measures depend on the construction period and use of buildings. Due to ever-improving standards for energy efficiency in buildings [15], newer buildings usually have lower heating demand and consequently lower and more expensive heat saving potential. The use of buildings determines the annual heating demand and consequently the costs of heat savings. For example, a public building has lower specific heating demand per area than a single-family house from the same construction period because it is utilised less frequently. The aggregation of building stock according to construction period and use is adopted from the Invert/EE-Lab model [16] and presented in Figure 4. "Very old", "Old" and "Normal" buildings are built before 1950, between 1951 and 1978 and after 1979, respectively. Buildings of the same use belong to the same use-group; buildings built in the same construction period belong to the same age-group. Buildings within the same age-group and use-group located in the same geographical area belong to the same group of buildings. According to the adopted aggregation there are 3 age-groups, 11 use-groups and 4 geographical areas; in total 132 building groups.

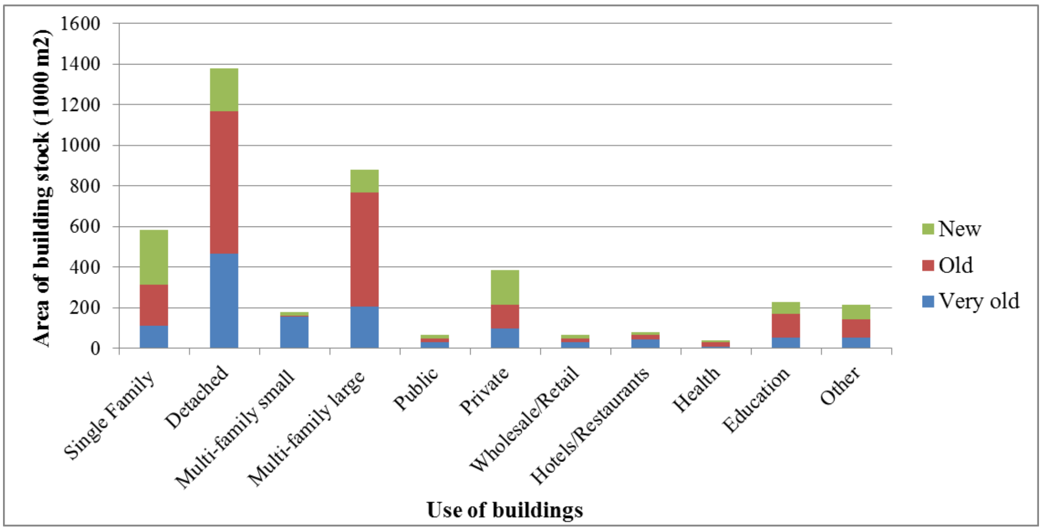

Figure 4. Area of building stock aggregated according to use and construction period

Cost-curve approach

Technically, every building can be supplied with heat and domestic hot water either from an individual heating source or from district heating. When we consider economy, a certain heat density is needed for DH (district heating) to achieve cost-effectiveness. This issue is well elaborated in [17]. Similarly with heat saving measures: space heating demand can technically be reduced to very low levels, but their costs vary greatly within the building stock. Except for natural gas boilers, the cost of heat from individual heating sources does not vary much depending on the geographical position, construction period and the use of building.

To add to the complexity, to choice of a new type of heat supply or heat savings for a building can also influence the costs of other heat supply alternatives; additionally, it can also have an effect on the costs of heat supply and heat savings in other buildings. For example, implementing heat saving measures in a building connected to district heating will reduce its heat demand, increase the cost per unit of produced district heating and thus increase the cost of district heat for other DH consumers connected to the same grid. Consequently, DH becomes less competitive in the remaining buildings compared to individual heating alternatives and heat savings. However, the impact of this change is only significant in case of substantial heat savings in a larger group of buildings or a part of a city. From the previous discussion it is obvious that in order to find the least expensive heat supply alternative, it is necessary to take into account DH, individual heating options, heat savings and even combinations of heat savings and heat supply.

For every building group, potentials and associated costs can be assigned to DH, individual heating options and heat savings. By ordering these costs from the least to the most expensive, we get the cumulative cost curves. To illustrate how the cumulative cost curves can be used to determine the cost-optimal heat supply configuration, cost curves for four heat supply alternatives are presented as an illustrative example (not related to Helsingør) in Figure 5. This approach resembles the priority order dispatch: the cheapest heat supply alternative is utilised until its maximum heat supply/saving potential is reached, and then the second heat supply alternative takes over. The second cheapest heat supply alternative is utilised until its maximum potential, then the third cheapest alternative takes over, etc. until entire heat demand is supplied. In Figure 5, Technology 2 is the cheapest, supplying the heating demand until its full potential (at around 35 MWh). Heat savings represent the second cheapest alternative. It is utilised to reduce the heating demand for the remaining 50 MWh, because at around 85 MWh the price of heat savings becomes higher than the price of Technology 1. The third cheapest alternative, Technology 1, supplies the remaining part of the heating demand. The resulting heat supply configuration is composed of a mix of technologies. Since the present method for calculating the optimal heat supply configuration is based on comparing the cost curves among themselves and comparing them with the existing heating demand, we have named this method the "cost-curve approach".

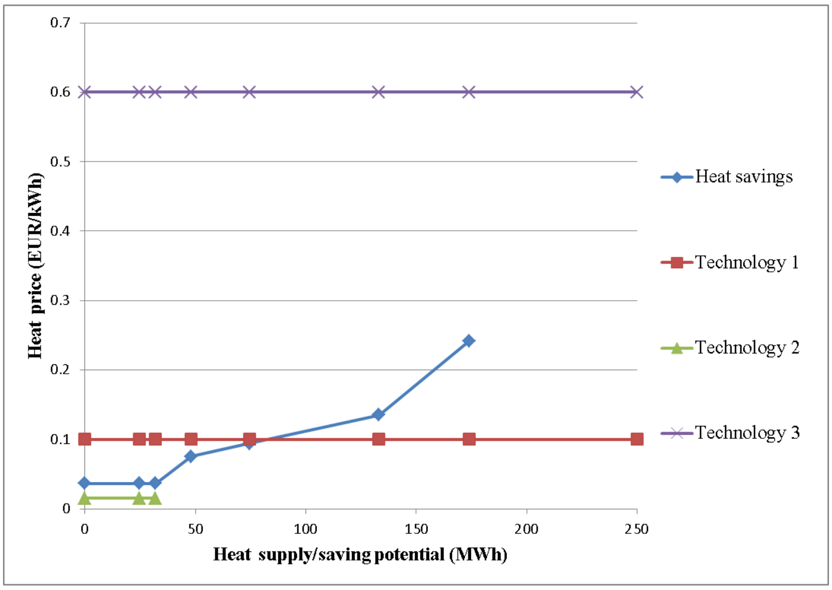

Figure 5. Costs and potentials of heat supply options (prices and potentials are illustrative)

In the cost-curve approach, we compare supply and savings on equal terms. In other words, in this approach it does not matter if the heat is supplied (e.g. from a heat pump) or saved (e.g. by insulating walls) as long as the supply and the demand are equal. Implementing heat savings affects the cost of heat supply alternatives. The cost-curve approach is modified to account for these factors and can be summarized as follows:

1. For a certain building group i, costs of DH ($c_{DH,i}$), individual heat supply ($c_{IH,i}$) and heat savings ($c_{HS,i}$) are compared:

    1.1. If $\min(c_{DH,i}, c_{IH,i}, c_{HS,i}) = c_{HS,i}$, the heat savings are implemented in the building group i and the new cost of heat from individual heating sources in the building group i, $c_{IH,i}^1$, is calculated.

1.2. If min($c_{DH,i}$, $c_{IH,i}$, $c_{HS,i}$) = $c_{IH,i}$, the individual heating solution overtakes the building group i. The costs of DH, individual heating and heat savings are not recalculated in this case.

1.3. If min($c_{DH,i}$, $c_{IH,i}$, $c_{HS,i}$) = $c_{DH,i}$, DH overtakes the building group i. The costs of DH, individual heating and heat savings are not recalculated in this case.

1.4. If during the changes in steps 1.1, 1.2 and 1.3 DH production (p_{DH}^1) increases or decreases, the new cost of DH, ($c_{DH,i}^1$) is calculated. This calculation is performed in energyPRO model.

2. For a certain building group i, new costs of DH ($c_{DH,i}^1$), individual heat supply ($c_{IH,i}^1$) and heat savings ($c_{HS,i}$) are compared:

2.1. If heat savings are implemented in step 1.1, then the cheaper remaining solution takes over. In other words, if min($c_{DH,i}^1$, $c_{IH,i}^1$) = $c_{DH,i}^1$ then DH takes over. Otherwise, the cheapest individual heat supply option takes over.

2.2. If individual heating option took over in step 1.2, then its cost should be compared with the recalculated cost of DH ($c_{DH,i}^1$). If min($c_{DH,i}^1$, $c_{IH,i}$) = $c_{IH,i,}$ then the individual heating solution should be implemented and the iteration procedure stops. If this is not the case, then DH takes over and the iteration procedure continues. At this point, neither cost of heat or savings is recalculated.

2.3. If DH took over in step 1.3, then the new DH price is compared with the remaining alternatives. If min($c_{DH,i}^1$, $c_{IH,i}$, $c_{HS,i}$) = $c_{DH,i}$, then DH is implemented in the building group i. Otherwise, the cheapest remaining option overtakes and the iteration procedure continues.

2.4. If during the changes in steps 2.1, 2.2 and 2.3 DH production (p_{DH}^2) changes, i.e. if $p_{DH}^2 \neq p_{DH}^1$ then new cost of DH, ($c_{DH,i}^3$) is calculated. This calculation is performed in the energyPRO model.

The symbols have the following meaning:
c_{DH} , c_{IH} , c_{HS} – cost of DH, individual heating and heat savings. The cost of DH differs between building groups i because they have different location relative to existing DH areas, i.e. they are located in DH, Next-to-DH and Individual areas
$_i$ – building group
$^{1,\,2,\dots}$ – number of iteration
p_{DH} – Total DH production in Helsingør

The iteration procedure for the building group i stops when the leading heat supply option stays the cheapest also in the consecutive iteration. This procedure is conducted for all 132 building groups and the resulting heat supply is cost-optimal. The cost of heat supply changes from iteration to iteration for the following reasons:

- If heat savings are performed in a certain building group, the net heating demand decreases. Since the domestic hot water needs to be prepared fast enough, we have set the minimal boiler capacity (10 kW) to be installed despite the amount of the specific heating demand.
- If the total DH production in Helsingør increases (as a result of additional heating demand being connected to district heating) then the quantity of DH sold to consumers increases as well; in order to pay for the investment, O&M (operation and maintenance) and fuel costs (assuming that the profit does not change), the DH cost is reduced. However, if there is not enough idle capacity in the system and new

investments are required to cover the increasing heat demand, the DH price may also stay the same or slightly increase. On the contrary, if DH production in Helsingør decreases, the cost of DH rises, because the installed capacity is not used efficiently enough.

We have chosen to run three iterations, because the changes of prices between the iterations are minor and it does not take more than two iterations to achieve convergence.

Modelling with energyPRO

energyPRO, developed by EMD International [18], is a commercial modular software for techno-economic analyses of energy projects, where energy production units operate according to a number of regulation strategies such as operation cost minimization. While year 2013 is modelled for model calibration purposes, we focus on year 2030 for calculating the optimal heat supply mix.

Year 2013. The model of Helsingør depicts two district heating grids: one for Helsingør municipality and the other for neighbouring Norfors (consisting of several municipalities). Although we concentrate on the administrative boundary of Helsingør, we also represent heat exchanges with a bidirectional 5.5 MW heat capacity transmission line. In Helsingør, the system consists of: units running on natural gas: a heat-only boiler, a CHP (Combined Heat and Power plant) and an engine; and a woodchip-fired heat-only boiler. In Norfors, the system consists of a CHP and a boiler running on waste and natural gas boilers.

Year 2030. Since by 2030 all the units from 2013 will have been in service at least for 30 years, we assume that they will be decommissioned and new units will be implemented. In Helsingør, the system consists of a woodchip-fired CHP and a heat-only boiler. In Norfors, the system consists of a waste incineration CHP and a boiler running on waste, and natural gas boilers.

Calculation of CO_2 emissions from scenarios

The CO_2 emissions calculated concern only heat supply. For each scenario they are a sum of emissions from district heating relative to the size of production (calculated by energyPRO) and emissions from individual supply, depending on fuels used. The CO_2 emission factors used are shown in Appendix C.

DATA FOR MODELLING

Year 2013

District heating demand. Table 1 shows the heat demand input in energyPRO. District heating is supplied from municipality-owned companies Forsyning Helsingør (88% total sales) and Hornbæk Fjernvarme (12% total sales).[19]

Table 1. Heat demand input in Helsingør

Demand location	Amount (GWh)
DH sales Helsingør	200.5
Grid losses Helsingør	38.1
DH sales Norfors	205.0
Grid losses Norfors	48.0

Technology data and prices.

Energy and CO_2 content of fuels (see Appendix B and C) is based on data from Energinet.dk. [20]

From September to April, 80% of heat demand depends on outdoor temperature (the reference being 17°C, as suggested by the Danish Technology Institute), with remaining 20% left for hot water demand. Outside of the heating season 100% of the demand is for hot water. The time series for outdoor temperature is Danish Reference Year for coastal areas of Zealand, delivered with energyPRO, prepared by the Danish Meteorological Institute and based on data from 2001 – 2010.

The electricity time series used is the hourly spot electricity price for Eastern Denmark from 2013.[21]

Fuel prices (see Appendix D) come from multisource data collected by Fraunhofer ISI, based on Eurostat and wood pellet market data. [22]

Electricity and heat capacities are taken from the Danish Energy Producers Count [23] and applied efficiencies and costs from similar technologies found in the Technology Catalogue developed by the Danish Energy Agency. [24]

Taxes and subsidies. The tax information is based on guidelines from the Danish Tax office [25]. The Danish energy and CO_2 tax system is quite complex and consists of taxes on supply and demand side. Biomass is exempted from energy and CO_2 taxes. In general, production of electricity is exempted from taxation, but not the heat. Heat-only boilers are taxed on their fuel consumption, but in CHPs (Combined Heat and Power plants) taxes are paid only for the part of fuel that is used for heat production. CHPs can choose between two methods for taxation. For calculating energy and CO_2 taxes in the waste and natural gas CHPs, a so-called E-formula or V-formula has to be chosen for division of fuel for electricity or heat production. The part of fuel that is charged with tax payment is calculated in one of the following way:

- V-formula: Heat production/1.2
- E-formula: Electricity production/0.67

For 2013, it was more favourable for the natural gas turbine to pay taxes according to the E-formula, while for the waste CHP – according to the V-formula. In 2030, the waste CHP pays tax calculated according to the V-formula as well.

Natural gas consumption for heat is subject to an energy tax and CO_2 tax (both vary for engines and non-engines). Additionally, in stationary engines a methane tax has to be paid on natural gas consumption for heat. Moreover, a NOx tax is paid per measured emissions.

Municipal waste used for heat production is subject to an energy tax and a supplementary tax on the amount of waste as fuel. For exact values, please consult Appendix E.

All units above 20 MW fuel capacity require CO_2 permits (quotas), which they receive from the state (for free according to an allocation plan or at an auction) or purchase on the free market. We use 8.05 EUR/t CO_2 as CO_2 quota price in 2013.

District heating cost calculation. By law, Danish municipalities only accept new heat planning projects if they are optimal from a socio-economic perspective. Municipalities can implement forced DH connection and some exert this right: however, low-energy buildings may be exempted from this requirement. District heating companies (fully or partly municipally-owned) operate according to the "break-even" rule, meaning that their costs and revenues have to balance every year. In this study, we use two prices: socio-economic and private-economic. District heating companies are allowed to recover all their necessary costs resulting from operation and maintenance in the heat price they charge.

This paper concentrates on energy production within Helsingør municipality and the share of production from a neighbouring Norfors area, which supplies the municipality (mainly in summer). The sum of price elements, shown in Table 2 is divided by the production to get a variable district heating cost in EUR/MWh. The main difference between the private-economic and socio-economic prices is that taxes including VAT are included. In the socio-economic analysis only taxes, which represent an environmental cost are included.

Administration costs are yearly employment costs of 30 people (in Forsyning Helsingør) with gross salary of about 51kEUR per capita per year.

Table 2. Cost elements for socio-economic and private-economic district heating price

Socio-economic	Private-economic
Costs:	**Costs:**
fuel	Fuel
Plant operation and maintenance	Plant operation and maintenance
Network operation and maintenance	Network operation and maintenance
Network investments	Network investments
Administration	Administration
CO_2 quotas, CO_2 tax, methane tax	CO_2 quotas, CO_2 tax, methane tax
NOx tax	NOx tax
Revenue:	Energy tax
Spot market electricity sales	Energy savings tax
	Revenue:
	Spot market electricity sales
	+VAT

Year 2030

This section will only contain data that differs from assumptions used for modelling year 2013. District heating demand is the same as 2013, because both expansion and heat savings are expected to happen in the time left until 2030.

Energy scenarios. We use the cost curve approach (see subsection "Spreadsheet model") to define the optimal mix of heat savings, district heating expansion and renewable energy in individual supply. BAU2030 (Business-As-Usual 2030) scenario is a baseline scenario, where natural gas and oil boilers are still allowed for installation. In contrast, in RES2030 (REnewableS 2030), natural gas and oil boilers are forbidden, in line with the Danish political energy agreement from 2012 [26], forcing the choice of renewable alternatives. Since this ban was suggested by the former government, it is to date unclear to what extent it will be enforced. Both BAU2030 and RES2030 have two variants: socio-economic, marked with A

(BAU2030A and RES2030A), and private-economic, marked with B (BAU2030B and RES2030B). The difference is the inclusion of energy taxes and subsidies in the private-economic costs. In DH, on top of the costs comes VAT, as well as additional charges: subscription kWh meter and area contribution per m^2.

Spreadsheet model. Potentials and costs of heat savings are from the Heating Model from DTU Management Engineering developed by Stefan Petrović, calibrated with Danish Energy Statistics, also used in [27] and [28].

Helsingør representation. Since by 2030 all the units from 2013 have been in service at least for 30 years, we assume that they are decommissioned and new units are implemented. In Helsingør, the system consists of: a woodchip-fired CHP and heat-only boiler. In Norfors, the system consists of a waste incineration CHP and a boiler running on waste and natural gas boilers.

Technology data and prices. The electricity price profile for 2030 is created by scaling the average 5-year (2011-2015) price profile to the forecasted average in Eastern Denmark in 2030: 57.4 EUR/MWh [29].

Taxes and subsidies. We assume that energy units buy the quotas at the forecasted price in 2030: 28.32 EUR/t CO_2. [29]

District heating cost calculation. The calculation method is the same, but due to changes in fuels, technologies and tax legislation since 2013, no methane tax nor energy savings tax have to be paid. Moreover, a subsidy for electricity generated using biomass is obtained.

Investment costs for heat boilers are per heat capacities and for CHPs – per electricity capacity.

For network renewal investments (10% of existing capacity) we assume 4% interest rate running for 30 years (considering the long lifetime of heat networks). For investments in energy units we assume 1.5% interest rate for 20 years, in line with Kommunekredit [30], a loan, which municipality-owned entities such as district heating companies can take. We assume that the investment in the biomass CHP is financed in the following way: 50% of investment cost is paid off with savings from before 2018 and the remaining 50% of investment cost is transferred to the following years and calculated as a loan. This is in line with guidelines from the Danish Energy Authority [31].

RESULTS AND DISCUSSION

The results below are presented for 2013 and 2030. There are two main scenarios for 2030: BAU2030 and RES2030, which we investigate from two perspectives: socio-economic (BAU2030A, RES2030A) and private-economic (BAU2030B, RES2030B). For a methodological discussion on these scenarios, please consult the Methodology section.

Current system (2013)

The calculated socio-economic district heating price is: 52.9 EUR/MWh, the private-economic ("break-even") price is: 73.3 EUR/MWh, which is almost exactly the real variable price from 2013 (73.2 EUR/MWh) [32]. This means that the model calibration has been successful.

Figure 6 depicts the private-economic heat price elements. Fuel costs represent the majority of costs, followed by energy taxes. The main revenue comes from electricity sales.

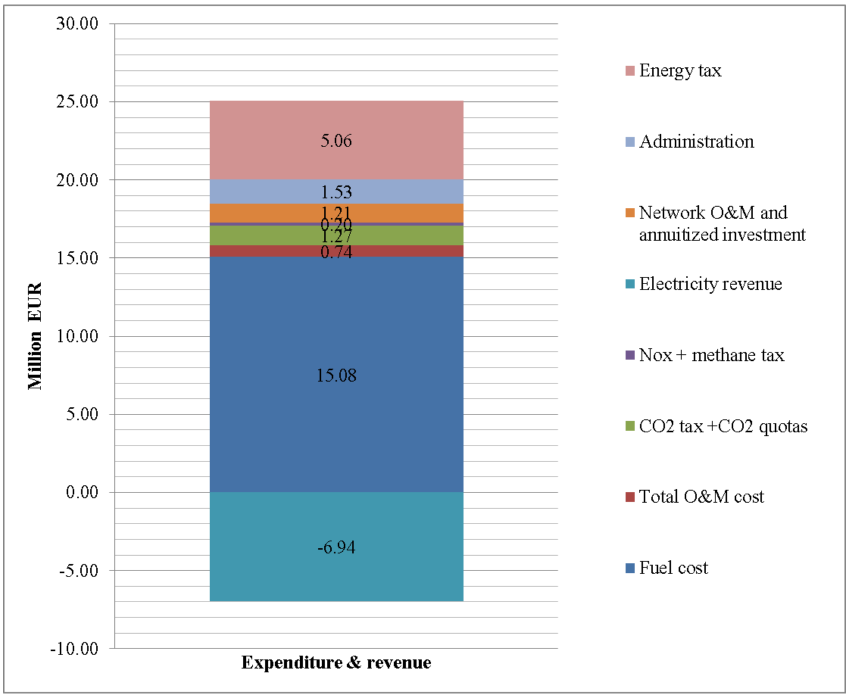

Figure 6. District heating price elements in 2013

District heating price in 2030

As shown in figure 7, both price types follow each other very closely. This is due to lower energy taxes in 2030 since only waste and natural gas production in Norfors is taxed, as well as subsidy is given to electricity producers using biomass.

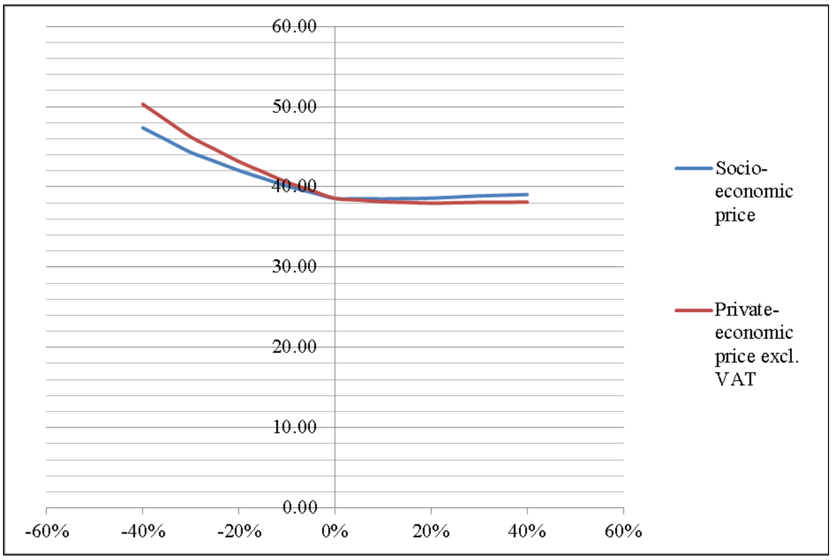

Figure 7. Socio- and private-economic prices of district heating in 2030.

The tax and subsidy balance each other, resulting in a low private-economic variable heat price. The variable price increases with falling district heating production. The main reason is not using the installed capacity enough: costs such as investment or part of fixed O&M (operation and maintenance) costs occur independently of production levels, while electricity revenues fall with low production. However, the situation is less clear in case of increasing district heating production. Although a decrease in prices could be expected, the prices stay almost the same. The cause for this is that the capacity planned for 2030 is insufficient for covering increased demand, thus additional investments are required.

Heat supply types in 2030

Figure 8 below shows the results of three iterations between the cost curve spreadsheet tool and energyPRO, from which optimal shares of various heating supply types in Helsingør are derived.

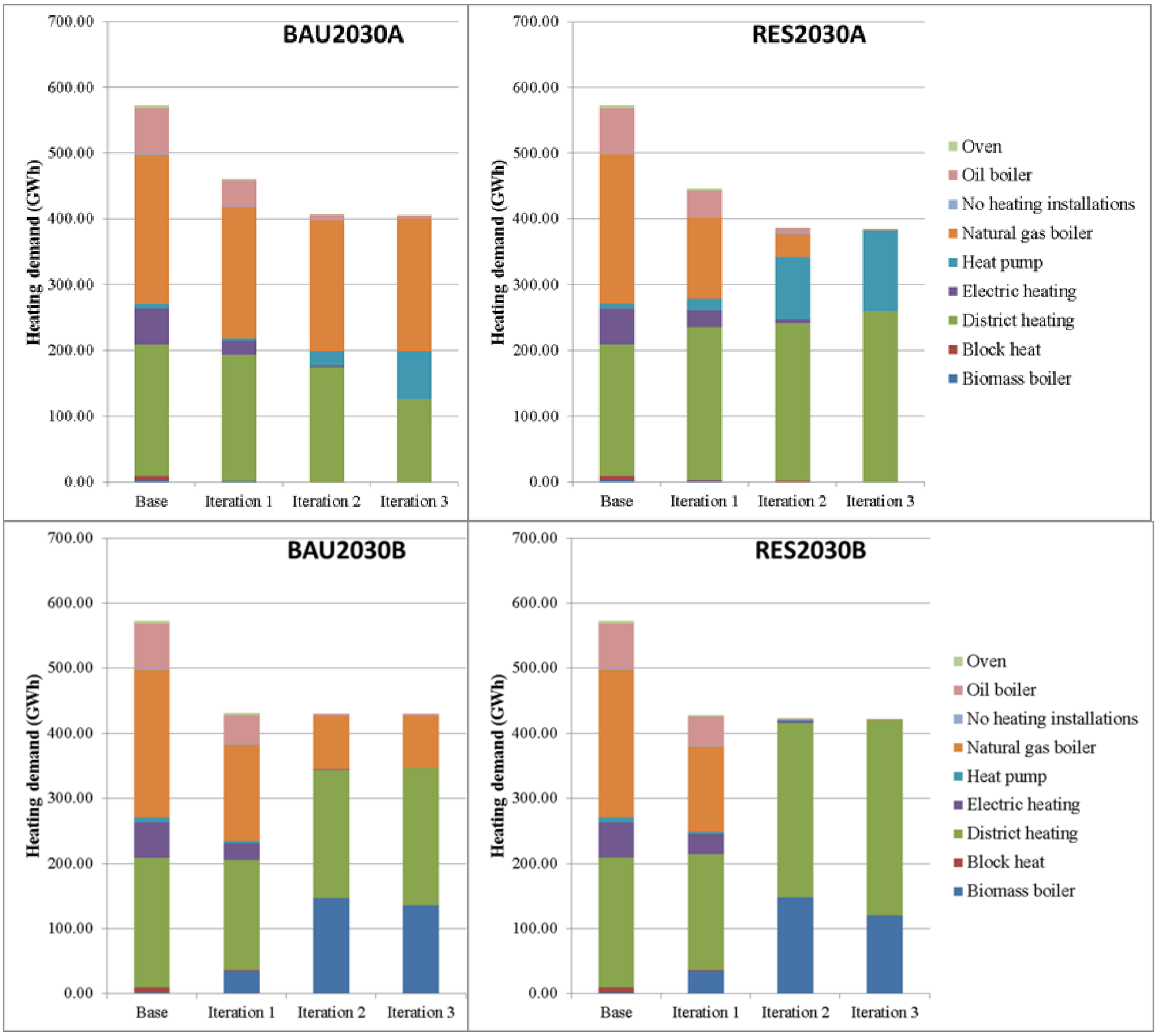

Figure 8 Heat supply types in Helsingør in base case and after three iterations. BAU2030A (upper left) and RES2030A (upper right) are socio-economic variants; BAU2030B (lower left) and RES2030B (lower right) are private-economic variants.

In base case (before iterations), natural gas boilers dominate the heat supply, followed by district heating and oil boilers. Electric heating is mainly used in summer houses. Minor heat supply sources are: block heat (one source supplying e.g. a multi-storey building), heat pumps and biomass boilers. After three iterations, the results are different for each scenario.

The main difference between the BAU scenarios is that natural gas, heat pumps and heat savings are more feasible in BAU2030A than in the private-economic BAU2030B, where DH dominates. In comparison, in the RES scenarios, more DH is selected in both perspectives, but this is supplemented with heat pumps and heat savings in the socio-economic optimisation and with biomass in the private-economic. These results are dependent on assumptions such as natural gas and woodchip prices, which are here assumed to be 9.6 EUR/GJ and 7.8 EUR/GJ, respectively.

Figure 9 shows the shares of DH by age of buildings in total in Helsingør.

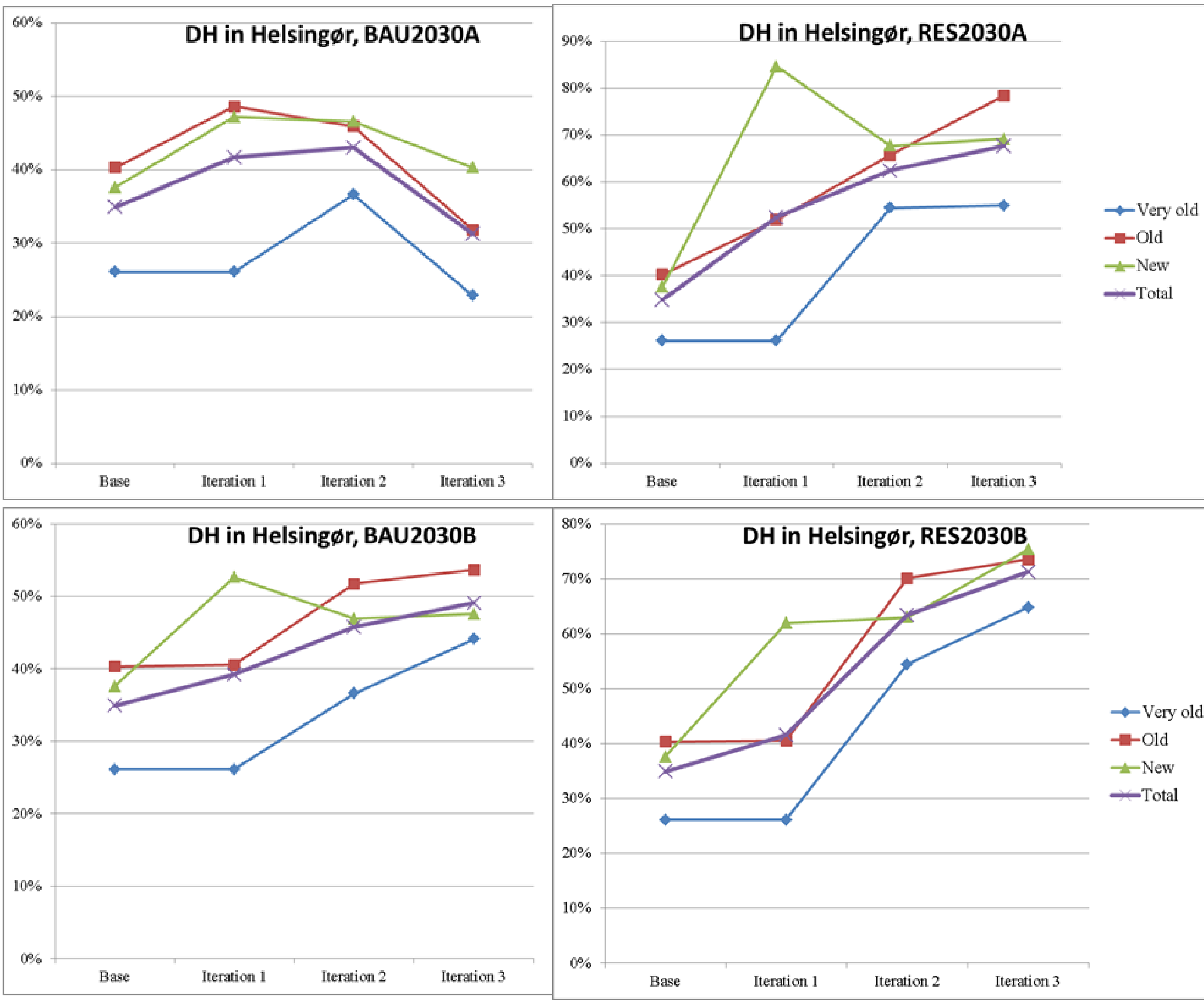

Figure 9. Shares of DH by age of buildings in total in Helsingør BAU2030A (upper left) and RES2030A (upper right) are socio-economic variants; BAU2030B (lower left) and RES2030B (lower right) are private-economic variants.

While DH increases in DH areas due to lowest cost caused by proximity to the grid, the growth in DH share is most visible in old and new buildings. Since from socio-economic perspective DH expansion or even current connection levels are infeasible, as BAU2030A shows, private-economically DH is able to reach 49% of heat demand. The total DH share is highest in RES2030B and RES2030A scenarios: 71% and 68%, respectively, because buildings can only select either DH or renewable-based individual supply.

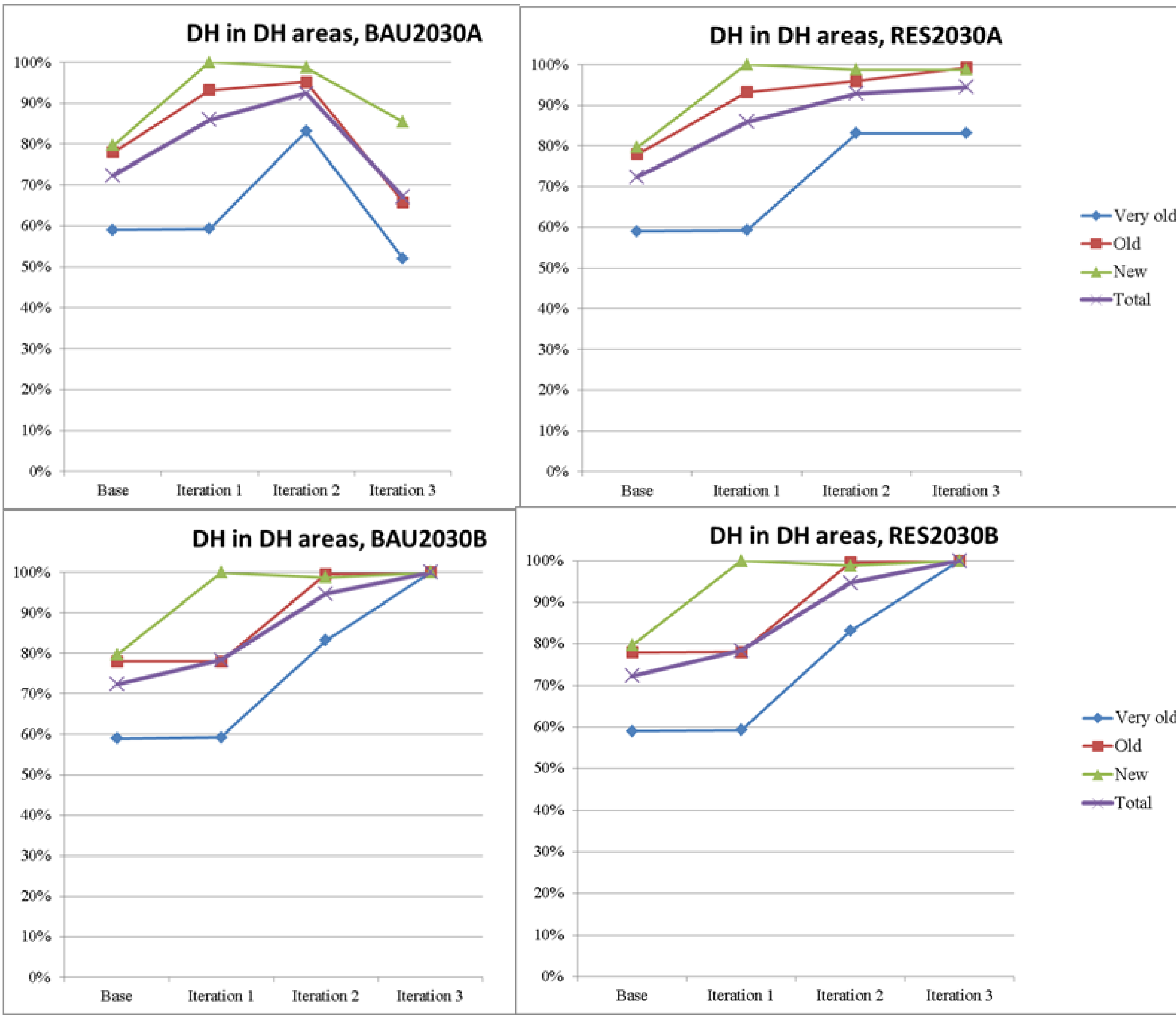

Figure 10 Shares of DH by age of buildings in DH areas

Based on socio-economic costs, DH is an expensive solution, thus in BAU2030A an expansion occurs only for new buildings. In RES2030A an increase of DH share takes place, however not until the full technical potential. In private-economic variants of BAU and RES, DH reaches 100% of heat demand in DH areas. It is important to keep in mind that although it can be technically possible to expand DH so far, there are many other factors, such as private preferences, that could influence the heat supply decision.

Since most of the expansion takes place in DH areas, we show the aggregated values for Next-to-DH areas in the Table 3 below. RES scenarios are characterized by significant increase in DH, which happens despite the increasing network investment cost. No expansion takes place in individual areas.

Table 3. Share of DH in Next-to-DH areas after 3rd iteration. The base level was 0%

Scenario	Share of DH
BAU2030A	0%
BAU2030B	2%
RES2030A	46%
RES2030B	53%

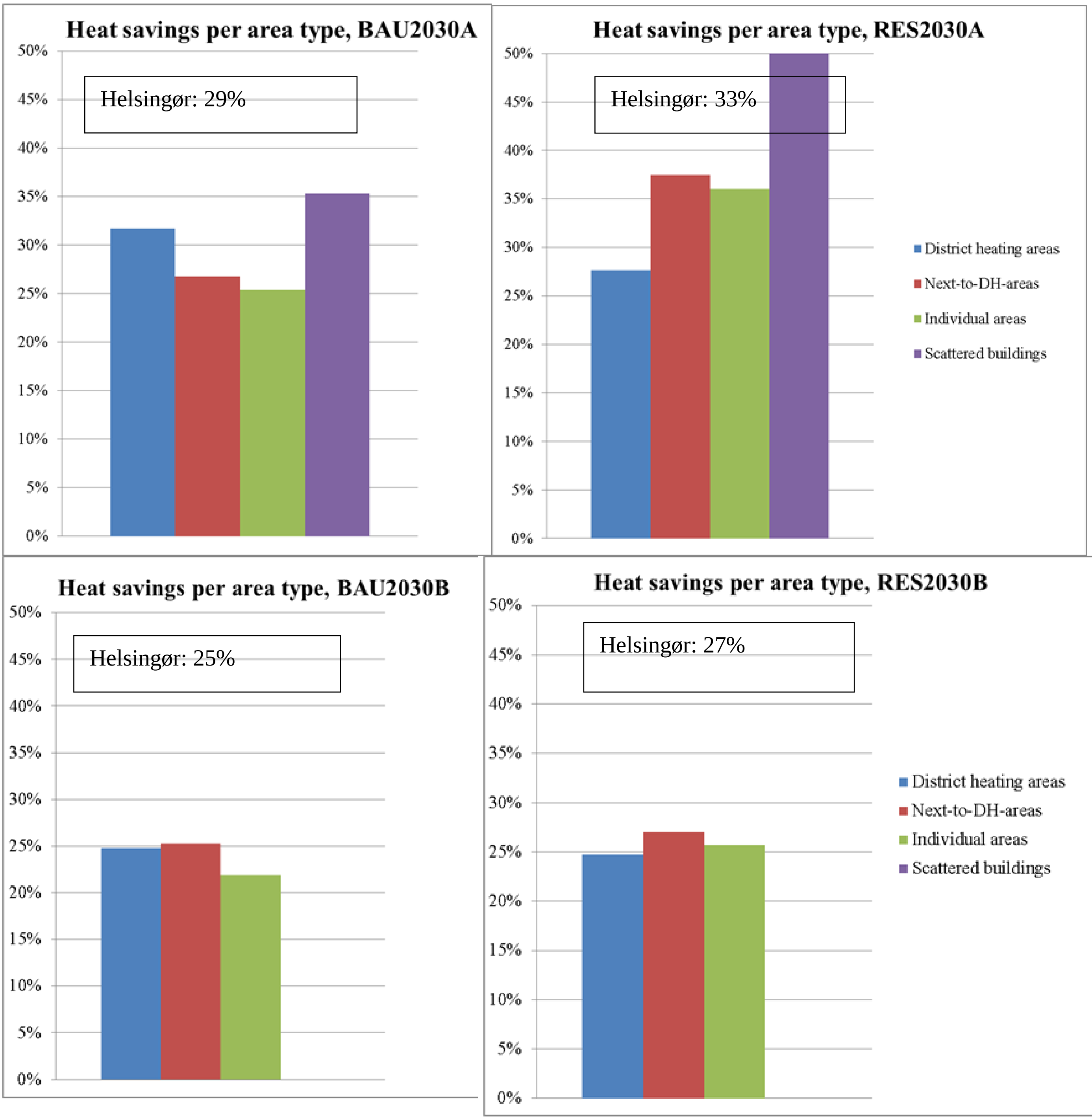

Figure 11 Heat savings share per area type

Socio-economically, it pays off more to invest in heat savings than from a private-economic perspective and the difference is especially visible in Scattered buildings. However, RES scenarios result in more heat savings than BAU, because they are cheaper than supply options based on renewables.

CO_2 emissions for each scenario

Table 4 shows the results of CO_2 calculation for each scenario.

Table 4. CO_2 emissions for each scenario

Scenario	tCO_2
BAU2030A	14,069
BAU2030B	7,183
RES2030A	14,255
RES2030B	**6,059**

RES2030B scenario would cause the least CO_2 emissions, thanks to limiting possibilities for oil and natural gas deployment and having largest share of DH and a second largest share of biomass. Similar situation occurs in BAU2030B, here, however the use of natural gas causes higher emissions. From a private-economic perspective, mostly biomass boilers and DH is chosen. From a socio-economic, there are more heat pumps, which from this perspective are "punished" by a high CO_2 content in electricity. For sensitivity analysis concerning the influence of 100% renewables in electricity supply on CO_2 emissions, please see next subsection.

Sensitivity analyses

CO2-free electricity in 2030. Denmark is heading towards 100% renewables in its energy system. Since heat pumps in the future may operate more flexibly than today, usually correlating with low electricity prices (caused by high production of electricity, e.g. based on wind), we check how CO_2 emissions will change if we assume that the electricity which heat pumps use is CO_2-free.

Table 5. Results of the sensitivity analysis

Scenario	tCO_2
BAU2030A	9,185
BAU2030B	7,167
RES2030A	**5,941**
RES2030B	6,040

While emissions drop for all scenarios (each scenario results in some deployment of heat pumps and/or electrical heating), RES2030A scenario, in which heat pumps constitute 18% of total heat supply in Helsingør, now has lowest CO_2 emissions. This analysis shows the importance of integrated approach in energy planning: electrification of heat supply will be more beneficial, if renewable electricity can be used.

Variable vs. average electricity price. As shown by [33], if heat pumps are operated flexibly, they consume electricity at low prices, even in the heating season. Since we assumed one (average) electricity price for 2030, we conduct a sensitivity analysis on variable electricity price to see how it could influence the fuel (electricity) price for heat pumps and thus implementation of this technology. We assume that 10% savings on electricity can be achieved in case of socio-economic price and 10% in case of private-economic price. However, the results of scenarios remain the same; though it cannot be excluded, that assuming higher savings would increase heat pumps deployment.

CONCLUSION

In this study, we developed a methodology for deriving an optimal mix of heat savings, district heating (DH) expansion and individual heat supply, using a spreadsheet model and energyPRO modelling tool. We applied this methodology in the municipality of Helsingør, Denmark. We found out that if natural gas and oil boilers are still allowed in 2030 (scenarios BAU2030), the least expensive solutions from a socio-economic perspective are: implementing 29% heat savings and 31% district heating in Helsingør, which actually is a 4% decrease in DH share. From a private-economic perspective, it is feasible to increase DH share to 49% and invest in 25% heat savings. If fossil fuel-fired individual boilers are forbidden (scenarios RES2030), it will pay off to implement 68% DH and 33% heat savings from a socio-economic perspective and up to 71% DH and 27% heat savings from a private-economic perspective. DH is more feasible than other options from a private-economic perspective, because it has lowest cost of energy, even after expansion costs and taxes are considered.

The iteration methodology is useful, because it represents the link between heat demand, individual supply, DH and heat savings. energyPRO is especially suitable for representing district heating systems for techno-economic analysis like ours, because it is flexible and has a short computational time. Our methodology can be further developed to analyse how Helsingør can achieve their 2050 CO_2 goals cost-efficiently. It can also be used in other cities with energy strategies or other towns, for example signatories to the Covenant of Mayors movement.

Forbidding natural gas and oil boilers allows substantial increases in DH implementation. Expansion of DH is a better solution from an environmental perspective, since in Helsingør it will be based on primarily on biomass and waste incineration. However, the sensitivity analysis shows that the feasibility of further expansion is limited by high costs related to operation of the system.

As expected, scenarios with no fossil fuels in individual supply (RES2030) are optimal from CO_2-emission perspective. However, the definitive answer depends very much on how much CO_2 is assigned to electricity consumption. Despite the energy efficiency of heat pumps, high CO_2 factor of electricity makes them worse-off compared to biomass boilers. On the one hand, deployment of biomass allows CO_2 emission reduction, although its complete CO_2 neutrality is under debate. On the other, from a broader environmental perspective, individual biomass boilers in dense urban areas could cause increased air pollution from particulate matter (PM).

Our results show the importance of modelling district heating costs and revenues. Biomass is exempted from energy taxes and receives a subsidy, which means that private-economic price is almost the same (sometimes lower) than the socio-economic price. However, if in the future biomass is not be exempted from energy tax anymore, the production costs will also increase. The capacity in 2030 will be insufficient for supplying the DH system if the demand for DH increases, thus new investments will be required. It may be beneficial to consider investing in another CHP unit instead of simple boiler, bringing additional revenue in the form of subsidy for electricity generation on biomass. However, other technologies such as large heat pumps or large scale solar heat could also be applicable, which has also been mentioned by a municipality representative [34]. While this is not the scope of this paper, it could form part of future work.

A number of limitations occur in the study. We assume that heat savings are implemented within the year of focus (2030). However, it is more likely that they will be spread over the years. Moreover, due to system boundary setting, it was assumed that Norfors system stays the same: while the municipalities it supplies will probably undergo some developments (renovations, changes in energy plant capacity). Thus, there may not be enough capacity in the system to expand DH as much, due to expansion in other systems. Furthermore, in calculating individual heating cost for heat pumps, a yearly average electricity cost is assumed, which may not reflect the changes in electricity prices or the possibility to optimise the operation of heat pumps to hours with low prices. We have tried to address this issue with a sensitivity analysis, but modelling of different heat pumps could give a more definitive answer. Further work will focus on conducting a series of sensitivity analyses to see how robust the results are.

Although the findings of the study are mainly applicable for Helsingør, they can be representative for towns of similar size, climate conditions, access to natural resources and district heating share. Moreover, the combined cost curve and energy modelling method is useful in energy planning for any heating configuration, geographical region and scale. To encourage other cities to conduct energy planning, displaying solutions and having impact on national regulation is also vital.

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APPENDIX A Calculation of the price of heat

$$HC = \frac{CRF \cdot C_I + C_{O\&M} + C_{fuel} + C_{tax}}{HD}$$

$$\text{CRF} = \frac{i \cdot (1+i)^n}{(1+i)^n - 1}$$

CRF – Capital Recovery Factor
i – interest rate
n – economic lifetime
HC – Heat Cost
C_I, $C_{O\&M}$, C_{fuel}, C_{tax} – investment and O&M (operation and maintenance) costs in 2015, fuel costs from 2030 and taxes

APPENDIX B Energy content of fuels [20]

Fuel	Value	Unit
Natural gas	0.04	GJ/Nm^3
Wood chips	9.3	GJ/t

Waste	10.6	GJ/t

APPENDIX C CO_2 emission factors

Fuel	CO_2 factor	Source
Electricity	201.9 g/kWh	[35]
Natural gas	56.95 t/TJ	[20]
Oil	77.4 t/TJ	[20]

APPENDIX D Fuel prices

Fuel type	Price 2013	Source	Price 2030	Source
Natural gas	10.17 EUR/GJ	[22] based on Eurostat	9.6 EUR/GJ	[29]
Woodchips	9.10 EUR/GJ	[22]	7.8 EUR/GJ	[29]
Biooil	9.10 EUR/GJ	Assumed based on woodchips	fuel not used	-
Waste	0	Assumed	0	Assumed

APPENDIX E Tax rates implemented in the model [25]

Type of tax	Tax rate
Energy tax on natural gas consumption for heat	0.37 EUR/Nm^3
Energy tax on natural gas consumption for heat in engines	0.39 EUR/Nm^3
CO_2 tax on natural gas consumption for heat	0.05 EUR/Nm^3
CO_2 tax on natural gas consumption in engines	0.01 EUR/Nm^3
Methane tax on natural gas consumption of stationary piston engines	0.05 EUR/Nm^3
NOx tax on natural gas (per measured emissions)	3.42 EUR/kg NOx
Energy tax on heat produced from waste incineration	3.49 EUR/GJ
Supplementary energy tax on amount of waste used as fuel	4.27 EUR/GJ

NOMENCLATURE

CHP – combined heat and power
CoM – Covenant of Mayors
DH – district heating
GIS – Geographic Information Systems
O&M – operation and maintenance
PM – particulate matter

SEAP – Strategic Energy Action Plan
SEP – Strategic Energy Planning

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