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Abstract +

Local climate action is not only a domain of large cities, but also smaller urban areas that increasingly address climate change mitigation in their policy. The Danish municipality of Helsingør can achieve a substantial CO_2 emissions reduction by transforming its heat supply and deploying heat savings. In this paper, we model the heating system of Helsingør, assess it from a simple socio- and private-economic perspective, develop future scenarios, and conduct an iterative process to derive a cost-optimal mix between district heating, individual heating and heat savings. The results show that in 2030 it is cost-optimal to reduce the heating demand by 20-39% by implementing heat savings, to deploy 32%-41% of district heating and to reduce heating-related CO_2 emissions by up to 95% in comparison to current emissions. In 2050, the cost-optimal share of district heating in Helsingør increases to between 38-44%. The resulting average heating costs and CO_2 emissions are found to be sensitive to biomass and electricity price. Although the findings of the study are mainly applicable for Helsingør, the combined use of the Least Cost Tool and modelling with energyPRO is useful in planning of heating and/or cooling supply for different demand configurations, geographical region and scale.

Highlights

- Employing a combined energy modelling and Least Cost Tool method
- Finding the cost-optimal mix of heat savings, district heating and individual heating
- Up to 39% heat savings and up to 39% district heating simultaneously implemented in Helsingør
- Reduction of heating-related CO_2 emissions between 62% and 95% compared to 2014

Keywords

heat savings; district heating; individual heating; CO_2 emission reduction; Least Cost Tool; energyPRO

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Nomenclature

Sub- and superscripts

a, c, u, h	geographical area, construction period, use and heating source of the buildings, respectively
i	iteration number

Symbols

ADM	administration costs
AR	heated area of buildings (m^2)
CAP	capacity of a heat supply system (in the case of district heating (DH), including heat exchangers) needed to supply enough heat on the coldest day of the year (at -12 ℃)
CO2Q&T	CO_2 quota purchase and CO_2 tax
CRF	Capital Recovery Factor
DHC_A, DHC_B	district heating costs from perspective A and B, respectively
DHPR	district heating production
eff	efficiency of the heat supply system
ELSAL	electricity sales (in CHP plants)
ENT	energy taxes
HC	annuitized heating costs in the municipality (EUR/kWh)
HD, HS	specific heating demand and reduction of specific heating demand (heat savings), respectively (kWh/m^2)
INV, O&M, FUEL	components of annuitized heating costs related to investments, operation and maintenance, and fuel, respectively
INVC, FIXOM, VAROM, FC	investment costs (EUR/kW heat), fixed operation and maintenance costs (EUR/kW heat) and variable operation and maintenance costs (EUR/kWh heat), and fuel costs (EUR/kWh input fuel), respectively
$INVC_A$, $INVC_B$	annuitized network and capacity investments in DH using discount rate 2% and 0.99%, respectively
MT	methane tax
NHPC	net heat production cost of the modelled plant
NOXT	NOx tax
SUB	subsidies
VAT	Value Added Tax of 25%

Abbreviations

CHP	combined heat and power
CoM	Covenant of Mayors
DH	district heating
GIS	geographic information systems
LCT	Least Cost Tool
MSW	municipal solid waste
SEAP	Strategic Energy Action Plan
SEP	strategic energy planning

1 Introduction

Increasingly, urban areas are leading the way for energy efficiency and CO_2 emissions reduction actions. Currently, heating constitutes almost half of the total European energy consumption [1]. In Denmark, heat supply planning is one of the areas, where municipalities enjoy relatively significant influence, especially in relation to district heating [2]. Our case study, Helsingør (also known as Elsinore) is located in the northeastern part of the Zealand island, about 50 km from the Danish capital, Copenhagen. Helsingør has an area of 119 km^2 and has approximately 62,000 inhabitants, resulting in the population density of 522 inhabitants/km^2, which is about 13 times less than Copenhagen (6,846 inhabitants/km^2) [3]. Helsingør municipality has been involved in regional strategic energy planning efforts and is currently identifying the range of its local climate action. The municipality aspires to reduce its CO_2 emissions by 20% in 2020, reach a level of one tonne of CO_2 eq./inhabitant in 2030 and become CO_2 neutral in 2050 [4]. Heating in Helsingør emits about one third of the total CO_2, so implementing heat savings in buildings, switching oil- and natural gas-based individual supply to renewables or expanding the district heating network (which in the future is expected to be primarily based on renewable fuels) could help Helsingør achieve its climate mitigation goals.

One of the most common approaches to promoting local climate initiatives is the strategic energy planning (SEP). The 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)" [5]. In Europe, Strategic Energy Action Plans (SEAPs) are promoted through the Covenant of Mayors (CoM). SEAPs 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 [6]. 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 [7]. This article identifies cost-efficient and renewables-based heating supply as part of developing a strategic energy plan for the municipality of Helsingør.

Developing a SEAP involves establishing a baseline emissions inventory including an energy balance. However, when focusing on the energy sector it may be beneficial to conduct more detailed system analyses taking into account the fluctuations in demand and production, which we handle here using the energy system analysis tool energyPRO (see also section 3.1).

In the literature, various urban energy models have been reviewed by Refs. [8,9]. The works concentrating specifically on local heat planning include: using statistical methods to determine district heating feasibility in a Russian city [10], using a spreadsheet model and an optimization model for heat supply planning in a Danish housing community [11], modelling design and operation of a distributed energy system and a decentralised district heating network with an optimization model [12], quantitative scenario analyses of the socio-economic feasibility of energy renovations and renewable energy supply in Copenhagen area [13] and determining an optimal dispatch of large-scale heat pumps in Copenhagen using Balmorel model [14].

Modelling of the balance between heat savings and heat supply has been conducted, for example by Merkel et al. [15], who focus on soft-linking models for building stock, decentralized heat supply and energy optimization. Åberg [16] uses a linear optimization model to investigate the changes in CO_2 emissions, heat production and electricity co-generation depending on incremental heat demand reductions in Swedish district heating systems. Zvingilaite [17] incorporates heat saving investments into an optimization model of the Danish heat and power sector. Hansen et al. [18] compare the use of levelised costs of heat and an energy system analysis tool to calculate the feasible levels of heat supply and savings in selected European countries.

Geographic Information Systems (GIS) data for Denmark have been applied in peer-reviewed literature before. For instance, GIS data has been used to map Danish heat consumption by Petrović and Karlsson [19], Nielsen and Möller [20] and Sperling and Møller [21]. The energyPRO tool has been used in industry and in several peer-reviewed publications, for example to compare energy storage systems [22], analyse the operation of CHP (combined heat and power) plants on electricity markets [23,24] and their possibilities for balancing services in Denmark [25] and Germany [26]. Moreover, [27] has used energyPRO for conducting an energy system analysis of electricity, heat and transport systems of a Hungarian town.

In this paper, we model Helsingør's heating system, assess it from a socio- and private-economic perspective, develop future scenarios, and conduct an iterative process of heating cost curve analysis and energy modelling to derive optimal supply and savings mix. As a result, the following research questions are answered:

- Which future energy systems setups for Helsingør are viable?
- What levels of district heating and heat savings are feasible given various scenarios?
- How sensitive are the results to changes in biomass and electricity prices?

The novelty of this paper lies in linking a detailed representation of heat savings in the building stock and district heating modelling using energyPRO through an iterative calculation conducted in a spreadsheet-based Least Cost Tool. 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 [28] project, our analyses will also contribute to the municipal energy policy development in Helsingør and other municipalities in Europe.

While a combination of a GIS tool and energyPRO has already been used by Nielsen and Möller [29], our work is novel in the way it provides a holistic methodology to derive the optimal mix of district heating (including expansion), individual heating and heat savings, which are intertwined and modelled dynamically. Moreover, two perspectives are considered: a simple socio-economic and a private-economic (see also section 2.4).

2 Input data

2.1 Current energy system

District heating in Helsingør municipality is currently supplied from a natural gas-fired CHP and several boilers located within its boundaries, and from a municipal solid waste (MSW) incineration plant Norfors and natural gas units located in nearby Hørsholm. In energyPRO, two district heating grids are modelled: one for Helsingør municipality and the other for Norfors (supplying Helsingør and several other municipalities), connected with a bidirectional heat capacity transmission line. Individual heating (modelled in the Least Cost Tool) mainly consists of oil and natural gas boilers and few heat pumps and biomass boilers.

2.2 Local renewable energy resources

The locally-sourced energy crops and forest wood potential for energy production in Helsingør municipality is 44.5 GWh [30]. The solar energy available is up to 162 GWh on roofs and 139 GWh within agricultural area [30]. The possible heat sources for large-scale heat pumps are: a nearby lake, wastewater or seawater [30], as well as low-temperature industrial excess heat, amounting for 100 GWh potential [31]. Additionally, there is potential for air-to-water heat pumps.

2.3 Techno-economic data

The energy content of fuels, based on standard factors from the Danish Energy Agency [32], is shown in Table 1.

Table 1. Energy content of fuels

Fuel	Value	Unit
Natural gas	0.04	GJ/Nm^3
Wood chips	9.3	GJ/t
MSW	10.6	GJ/t

In district heating modelling, electricity and heat capacities are derived from the Danish Energy Producers Count and applied efficiencies and costs of similar technologies from the Technology Catalogue developed by the Danish Energy Agency [33]. The investments and O&M costs of individual heating technologies are based on the Technology Catalogue for individual plants [34]. Economy of scale is taken into consideration by having lower capacity costs for large units in e.g. multi-family buildings.

Fuel prices for both DH and individual heating (excluding taxes) are shown in Table 2. For 2030, they are projected by the Danish TSO Energinet.dk [35]. For 2050, they are based on Eurostat's Energy price statistics [36] and European Commission's EU Reference Scenario [37].

Table 2. Fuel prices excl. taxes in 2030 and in 2050

	Year 2030	Year 2050
Fuel type	Price (EUR/MWh)	Price (EUR/MWh)
Natural gas	2.67	3.28
Wood chips	2.16	3.39
Oil	63.0	73.0

The electricity price profile for 2030 is created by scaling the average hourly spot electricity price profile (2011-2015) for Eastern Denmark to the average price (excl. taxes) forecasted by Energinet.dk in 2030: 57.4 EUR/MWh [35]. The electricity price profile for 2050 is created by scaling the average price profile (2011-2015) to the average price (excl. taxes) forecasted for 2050 in Denmark (67.7 EUR/MWh), based on [36] and [37]. The electricity price for individual heat pumps is not represented as hourly time series, but an average yearly price, using the aforementioned values.

2.4 Scenarios and perspectives

This study focuses on two years: 2030 and 2050, representing a mid- and long-term future. For all the scenarios, the following results (indicators) are calculated for the municipality of Helsingør: heat supply mix, heating costs, share of district heating and heat savings, and CO_2 emissions (see section 4).

The scenarios for 2030 are modelled from two perspectives: a simple socio-economic (denoted with "A") and a private-economic (denoted with "B"). The scenarios for 2050 are evaluated only from a simple socio-economic perspective due to the uncertainty of long-term projections of tax policies. The term "perspective" refers only to the used interest rate and inclusion or exclusion of taxes and subsidies in the heating costs, so the technical system boundaries (district heating and individual heating supply in Helsingør) remain the same. The purpose of examining the two perspectives is to understand whether the cost-optimal results differ if we include or exclude current taxes and use different rates and is a step towards modelling policy interventions for increasing renewables and energy savings in the heat supply.

According to the Danish Energy Agency, socio-economic analyses can be used to determine "the most appropriate way to achieve energy policy objectives" [38], such as CO_2 emission targets. Our analyses do not encompass wider socio-economic consequences, such as employment or public acceptance. We define the simple socio-economic perspective as one used by a policy-maker to assess certain costs for society, i.e. where investments are discounted with a socio-economic rate of 2% [39] and only some costs borne by heat producer are included (see Eq. 1).

We consider the private-economic perspective as one of a private investor - it includes energy taxes and subsidies and applies the following discount rates: 0.99% for investments in district heating plants and grid, 2.18% for heat savings and heat installations in large buildings (e.g. public offices) and 4.46% for investments in heat savings and heat installations in small buildings (e.g. single/multi-family houses). We assume 1% yearly inflation. In this perspective, discount rates are different for the three categories, because their current conditions for loan taking are also different. Except for district heating, which in Denmark is characterised by a possibility of taking inexpensive municipal loans, the private-economic discount rate is higher than the socio-economic rate, because it includes inflation and industry-specific risks.

The private-economic discount rate for district heating investments is calculated based on the assumption that the investment is financed partly from a municipal loan (currently 1.5%) and partly from a municipal overhead (0.5%) [40]. For the individual heating and heat savings the available private-economic discount rate is adjusted for the effect that part of the investment (33%) is deducted from income tax (assuming income tax of 50%), i.e. the reduction in income tax is reflected in the reduced interest rate. For large buildings, we assume that 80% is a loan based on equity and 20% is the equity. For small buildings, the assumption is that 100% is a loan based on the equity of the house.

Eq. (1) and Eq. (2) show the cost components in district heating cost calculation depending on the perspective taken (A or B). This cost is applied further to the Least Cost Tool (see section 3.2), where the balance between all heating supply types and heat savings in each geographical area is calculated. Heating cost components are somewhat different for individual heating and district heating. While usual costs, such as fuel, operation and maintenance and investment costs are incorporated in both heat supply types, the cost of district heating in Denmark additionally depends on administration costs (e.g. employment), energy taxes and subsidies.

$$DHC_A = \frac{(FC + FIXOM + VAROM + INVC_A + ADM + CO2Q\&T + MT + NOXT - ELSAL)}{DHPR} \quad (1)$$

$$DHC_B = \frac{(FC + FIXOM + VAROM + INVC_B + ADM + CO2Q\&T + MT + NOXT - ELSAL + ENT - SUB)}{DHPR} \quad (2)$$

The VAT (Value Added Tax) is added only in the private-economic analysis, on top of DHC_B (see also section 3.2).

The tax and subsidy rates applied in district heating modelling are shown in Table 3.

Table 3. Tax and subsidy rates for the Danish district heating based on [41], [42], [43]

Type of tax/subsidy	**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
Heat pumps: various taxes (PSO, distribution etc.) on large-scale heat pumps (per MWh consumed electricity)	119 EUR/MWh
Subsidy for electricity production using biomass (per MWh electricity produced)	20.13 EUR/MWh

In the individual heating sector, the private-economic fuel prices are the final prices charged by the fuel distributor, i.e. include fuel taxes and are based on current prices for natural gas, fuel oil and wood pellets.

Table 4 shows the scenarios and perspectives analysed in this study.

Table 4. Scenarios and perspectives in this study. The scenarios describe the district heating setup - for each of them, the final cost-optimal mix including the individual heat supply and heat savings occurs as a result of the iterative process with LCT (see section 4). In all the scenarios, Norfors area supplies about 15% of heat and is assumed to be based on natural gas boilers and a MSW CHP and a boiler.

Year	Scenario description	Scenario name	Perspective
2030	Helsingør: woodchip CHP and boiler	BAU2030**A** (Business As Usual)	Simple socio-economic
		BAU2030**B** (Business As Usual)	Private-economic
	Helsingør setup as above; additionally, a policy of forbidding fossil fuel fired individual heat supply	RES2030**A** (REnewableS)	Simple socio-economic
		RES2030**B** (REnewableS)	Private-economic
	Helsingør: Heat pumps and heat storage	HP2030**A** (Heat Pumps)	Simple socio-economic
		HP2030**B** (Heat Pumps)	Private-economic
2050	Helsingør: woodchip CHP and boiler	BAU2050**A** (Business As Usual)	Simple socio-economic
	Helsingør: Heat pumps, heat storage, solar heating and wood chips	Combi2050**A** (Combined)	Simple socio-economic

In 2030, three scenario types are investigated: BAU, RES and HP, each from a simple socio- and private-economic perspective. Due to their age, all currently existing district heating plants are assumed to be decommissioned by 2030 and a biomass CHP will be implemented in Helsingør in 2018, making this technology choice the "business as usual" scenario. Norfors is assumed to have a renewed capacity of the same type of energy units as currently. In the RES scenarios, the basic setup of the district heating production system is the same. The difference comes from prohibiting existing and new individual natural gas and oil boilers, as discussed in the Danish political agreement from 2012 [44] and considering Helsingør's climate goals. In HP scenarios, the district heating production in Helsingør is based exclusively on heat pumps and heat storage, since the locally-sourced biomass is too scarce to cover all the demand.

In 2050, two scenarios are examined, only from a simple socio-economic perspective: BAU and Combi. All district heating plants are assumed to be decommissioned by 2050 and a new biomass CHP is implemented in Helsingør in 2050, making this technology choice the "business as usual" scenario. Norfors has a renewed capacity of the same type of energy units as in 2030. The Combi2050 scenario is based on solar heating, heat pumps, thermal storage and a small biomass boiler.

2.5 Building aggregation

In order to model the heat supply and heat savings in Helsingør, the buildings were aggregated according to their geographical location, age and use.

Geographical location defines the distance to existing district heating grids, thus the cost of district heating (DH). Therefore, we divided Helsingør into four types of areas: DH areas, Next-to-DH areas, Individual areas and Scattered buildings. In DH areas, the majority of buildings are supplied by district heating, but some are not connected to the DH network, requiring investments in connecting pipes and heat exchangers. Next-to-DH areas share a border with existing DH areas, but are not supplied by district heating. To connect the buildings located in Next-to-DH areas to the district heating network, investments in distribution and 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. To connect the buildings located in Individual areas to DH, investments in transmission, distribution and connecting pipes and heat exchangers are necessary. Scattered buildings represent individual buildings of low heat density, scattered across the municipality. We exclude the possibility of expansion of district heating to these areas.

Figure 1 depicts the location of DH areas and areas with expansion potential in Helsingør. Scattered buildings (not shown on the figure) are spread all across the municipality.

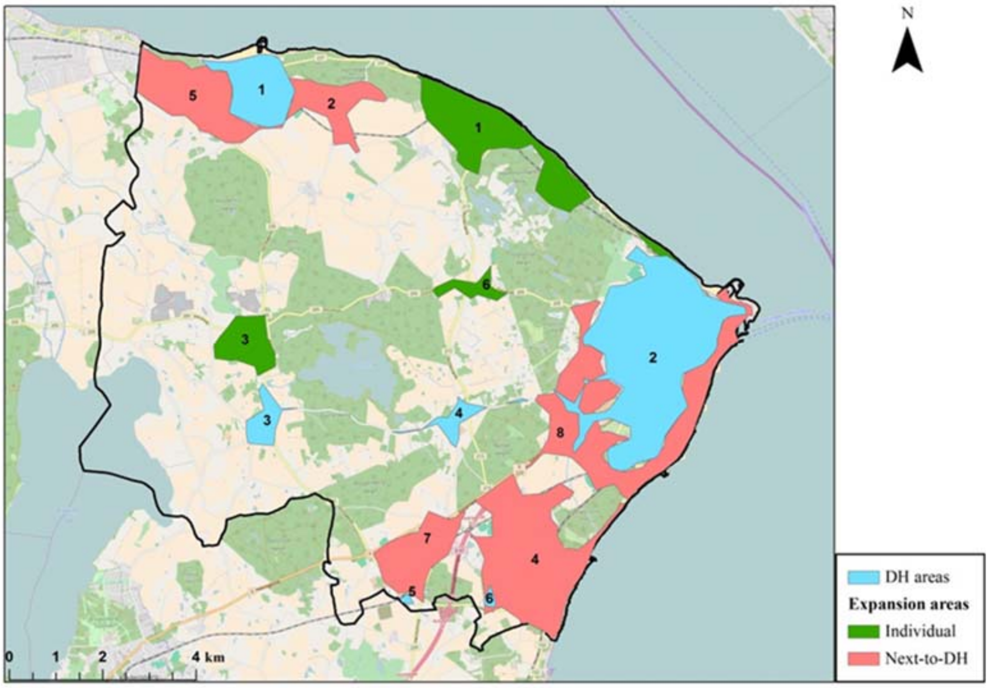

Fig.1 Administrative boundaries of Helsingør municipality and division into DH areas (blue) and expansion areas: Next-to-DH areas (pink) and Individual areas (green)

As Figure 2 shows, in Helsingør, the existing DH areas and potential DH expansion areas cover the majority of the building stock.

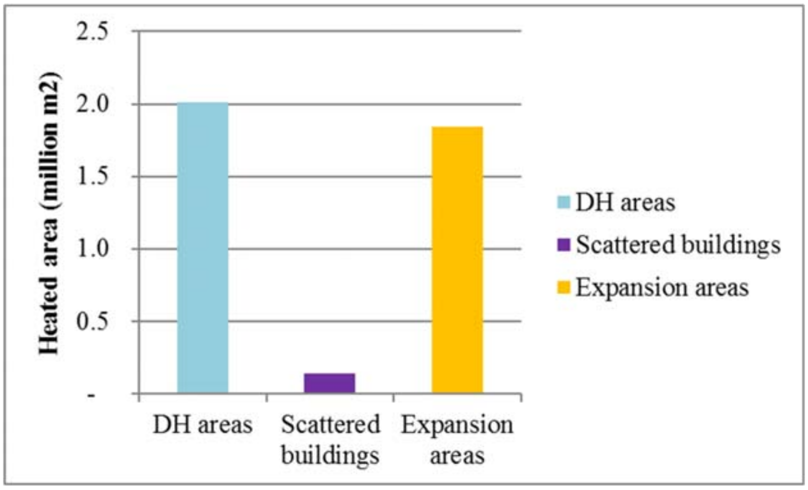

Fig. 2 Aggregation of building stock (heated area) per area type divided into: DH areas, expansion areas (Next-to-DH, and Individual) and Scattered buildings (million m^2).

The heat for buildings located within DH, Next-to-DH and Individual areas can be provided with DH or individual heating. Additionally, their heating demand can be reduced by implementing heat saving measures. The disconnection from DH is not allowed in our analysis. For the Scattered buildings only the individual supply and heat saving measures are possible.

The construction period (age) and the use of buildings determine the annual heating demand and subsequently the costs of heat savings. The aggregation of building stock according to construction period and use is adopted from the Invert/EE-Lab model [45] and presented in Figure 3.

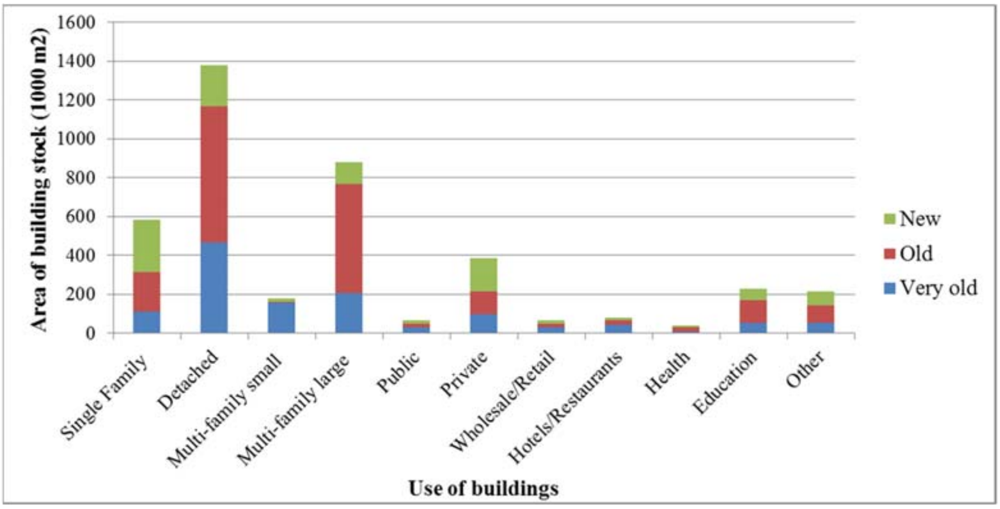

Fig. 3 Building stock aggregated according to use and construction period (1000 m^2). "Very old", "Old" and "Normal" buildings were built before 1950, between 1951 and 1978, and after 1979, respectively.

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 type of 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 in Helsingør.

3 Methods

Two main methods are used in this study: district heating modelling with energyPRO and iterative modelling of heat supply and heat savings costs with a purposely-developed spreadsheet-based Least Cost Tool (LCT). The cost-optimal heat supply mix is found by comparing costs of heat savings, DH and individual supply within the LCT, considering the specific heating demand and the average heated area. The process is dynamic, because if individual or DH supply increases or decreases, new costs are calculated and the iterative process continues until definitive results are found, as shown in Figure 4 and explained further in section 3.2.

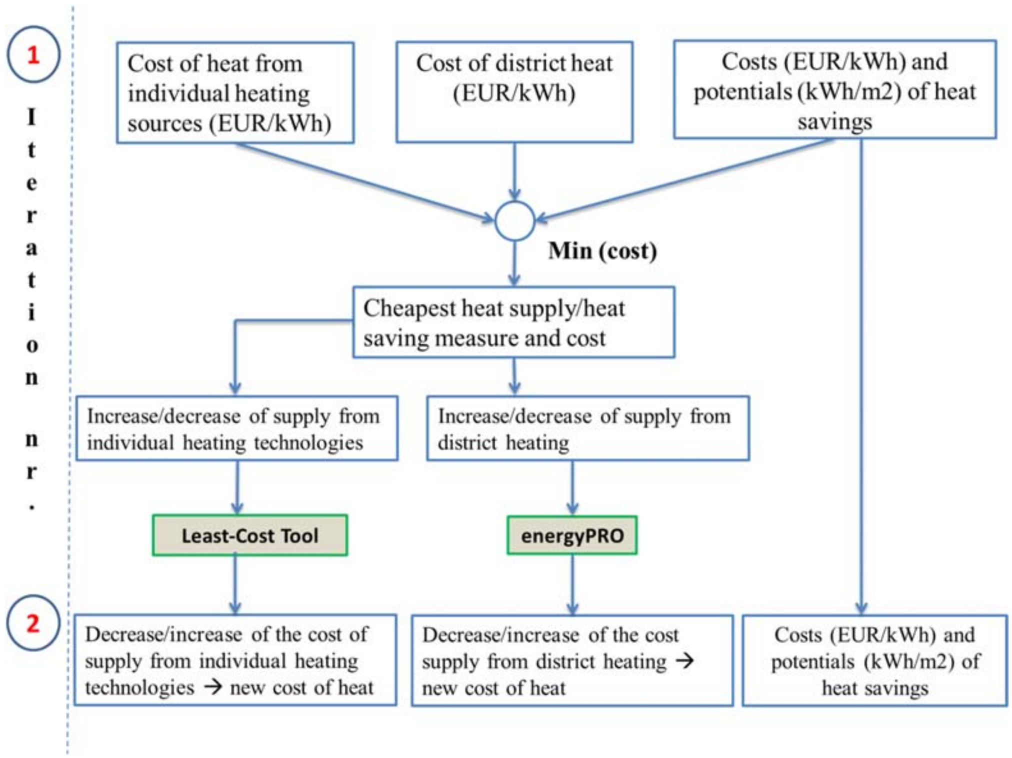

Fig. 4 Least-cost calculation iterations between the Least Cost Tool and energyPRO

The energyPRO tool (see section 3.1) is used to calculate the costs of district heating (DH) production, depending on changes in the heat demand, which can increase if DH expansion takes place or decrease if heat savings are implemented. The potentials and costs of heat savings in buildings are adopted from the Invert/EE-Lab model (for its description and methodological details see Refs. [45] and [46]).

3.1 Modelling with energyPRO

In this study, energyPRO is used to calculate the costs of district heating production, depending on changes in the heat demand caused by heat savings. The tool, developed by EMD International [47], is a commercial software for techno-economic analyses of energy projects, which can conduct an operation optimization, accounting for e.g. technical properties of units, maintenance costs, fuel prices, taxes and subsidies etc. [48]

The model only optimizes operation, not investments. Investment capacities were derived by authors in an iterative process of system cost comparison, considering the renewable resources available in Helsingør. The operation optimization is conducted via flexible operation strategy - calculated as in Eq. (3):

The objective function for energyPRO is to minimize *NHPC*, where:

$$NHPC = FC + FIXOM + VAROM - ELSAL \tag{3}$$

The operation strategy is flexible, because additional components can be added to the *NHPC* function, such as those exemplified in Eq. (1) and Eq. (2) in section 2.4. *NHPC* is calculated for each calculation step of 1 hour; the length of the optimization period is 1 year. The production units operate non-chronologically within a year, until the heat demand is fulfilled, under constraints such as minimum operation time and capacity of thermal storage [48] [49].

3.2 Least Cost Tool (LCT)

Technically, every building can be supplied with heat and domestic hot water either from an individual heating source or from district heating (DH), but when we consider economy, a certain heat density is needed for DH to achieve cost-effectiveness (see also [50]). Similarly with heat saving measures: space heating demand can technically be reduced to very low levels, but the cost of the measures vary greatly within the building stock. With the exception of natural gas boilers, which require grid connection, the cost of heat from individual heating sources does not vary much depending on the geographical position, construction period and the use of building.

Moreover, the 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 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 DH 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.

Due to these complexities, it is necessary to take into account DH, individual heating options, heat savings and even combinations of heat savings and heat supply to find the least expensive heat supply alternative. To solve this task, we have developed Least Cost Tool (LCT), which calculates the cost-optimal heat supply configuration through an iterative procedure. The iterations are driven by the cost of heat supply, i.e. when the average heat supply cost in the municipality stays below a certain threshold between two consecutive iterations, the iteration procedure stops. The resulting heat supply configuration is optimal, considering the costs and potentials discussed above.

The heating cost is calculated according to the following Eq. (4):

$$HC^{(i)} = \frac{\sum_a \sum_c \sum_u \sum_h HD_{a,c,u,h}^{(i)} \cdot AR_{a,c,u,h} \cdot \left(INV_{a,c,u,h}^{(i)} + O\&M_{a,c,u,h}^{(i)} + FUEL_h\right) \cdot (1 + VAT)}{\sum_a \sum_c \sum_u \sum_h HD_{a,c,u,h}^{(i)} \cdot AR_{a,c,u,h}} \quad (4)$$

where the criterion for stopping the iteration is: $HC^{(i)} - HC^{(i-1)} < 0.001 \frac{EUR}{kWh}$

The components of the Eq. (4) can be expressed with the following Eqs. (5) - (8):

$$INV^{(i)}{}_{a,c,u,h} = \frac{\sum_a \sum_c \sum_u \sum_h INVC_{a,u,h} \cdot CAP_{a,c,u,h}^{(i)} \cdot CRF_u}{\sum_a \sum_c \sum_u \sum_h HD_{a,c,u,h}^{(i)} \cdot AR_{a,c,u,h}} \quad (5)$$

$$O\&M_{a,c,u,h}^{(i)} = FIXOM + VAROM = \frac{\sum_a \sum_c \sum_u \sum_h FIXOM_{u,h} \cdot CAP_{a,c,u,h}^{(i)} \cdot CRF_u}{\sum_a \sum_c \sum_u \sum_h HD_{a,c,u,h}^{(i)} \cdot AR_{a,c,u,h}} + VAROM_h \quad (6)$$

$$FUEL_h = \frac{FC_h}{eff_h} \quad (7)$$

$$HD_{a,c,u,h}^{(i)} = HD_{a,c,u,h}^{(i-1)} - HS_{a,c,u,h}^{(i)} \quad (8)$$

3.3 Calculation of CO_2 emissions from heating production

The CO_2 emissions calculated concern only the heat production (including electricity consumption of heat pumps). For each scenario, they are a sum of emissions from district heating relative to the size of production (calculated with energyPRO) and emissions from individual supply, depending on fuels used. The CO_2 emission factors used are shown in Table 5.

Table 5. CO_2 factors [32]

Fuel	CO_2 factor
Natural gas	56.95 t/TJ
Oil	77.4 t/TJ

We allocate emissions from CHPs proportionally to their heat output. Given the Danish and regional goals for implementation of renewables, we assume that electricity already in 2030 will be 100% based on renewable fuels - thus heat pumps are also assigned no emissions. Moreover, biomass is considered a CO_2-neutral resource.

4 Results

4.1 Heat supply mix

Figure 5 shows the heat supply mixes in the base year and cost-optimal heat supply mixes for the six analysed scenarios in 2030.

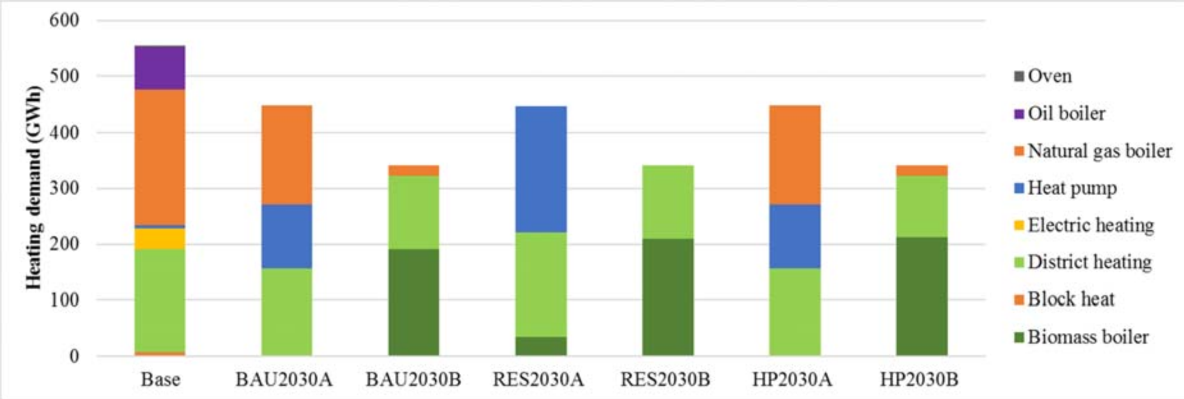

Fig. 5: Heat supply mix in the base and all the 2030 scenarios (GWh)

The difference between the total heat supplied in the base year and in the alternative scenarios originates from heat savings. In none of the scenarios are oil boilers chosen, due to their high cost.

In the analyses from a simple socio-economic perspective, the heat supply mix is composed of individual natural gas boilers (about 30%), individual ground-source heat pumps and district heating (based on biomass or heat pumps and thermal storage). In the RES2030A scenario the use of individual boilers running on fossil fuels is forbidden, so instead of natural gas, the buildings are supplied mainly by heat pumps and district heating. The reason for the high cost-competitiveness of ground-source heat pumps lays in their high efficiency. In the present analysis, it is assumed that residential heat pumps operate with the average annual electricity price. However, if heat pumps are operated flexibly they can achieve even higher cost-effectiveness.

In the private-economic scenarios, the optimal heat supply mix is dominated by individual biomass boilers, which cover around 56%. The main reason for the high competitiveness of biomass boilers is that biomass is not taxed in Denmark, whereas natural gas and electricity are. The price of biomass for the final consumer can increase in the future, either due to taxation or due to an increase in the world market prices. The influence of increased biomass prices is analysed in Section 4.5.

The results show that in general, individual heat pumps and district heating are more viable from the simple socio-economic perspective, but individual biomass boilers are more viable from the private-economic perspective.

Figure 6 shows the heat supply mixes in the base year (results from 2030) and cost-optimal heat supply mixes for the two analysed scenarios in 2050.

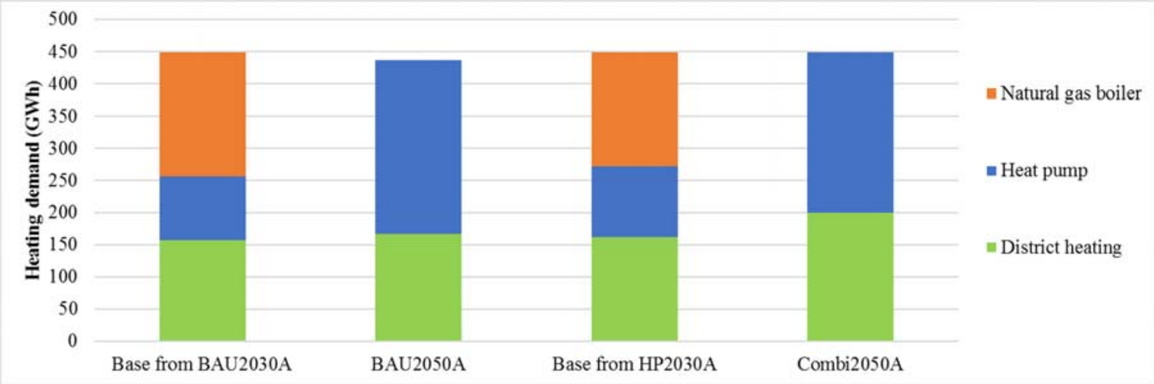

Fig. 6: Heat supply mix in the base and the 2050 scenarios (GWh)

The cost-optimal heat supply mix in both socio-economic scenarios is composed only of individual heat pumps and district heating (based on biomass or heat pumps, thermal storage and solar heating) - natural gas boilers are not part of the mix. This is the result of the policy restriction that fossil fuels cannot be used in the longer time frame, which corresponds with the Danish target of becoming independent of fossil fuels by 2050 [51].

4.2 Heating costs

Figure 7 depicts the calculated average heating costs per area type in Helsingør in analyses from the socio-economic perspective in 2030.

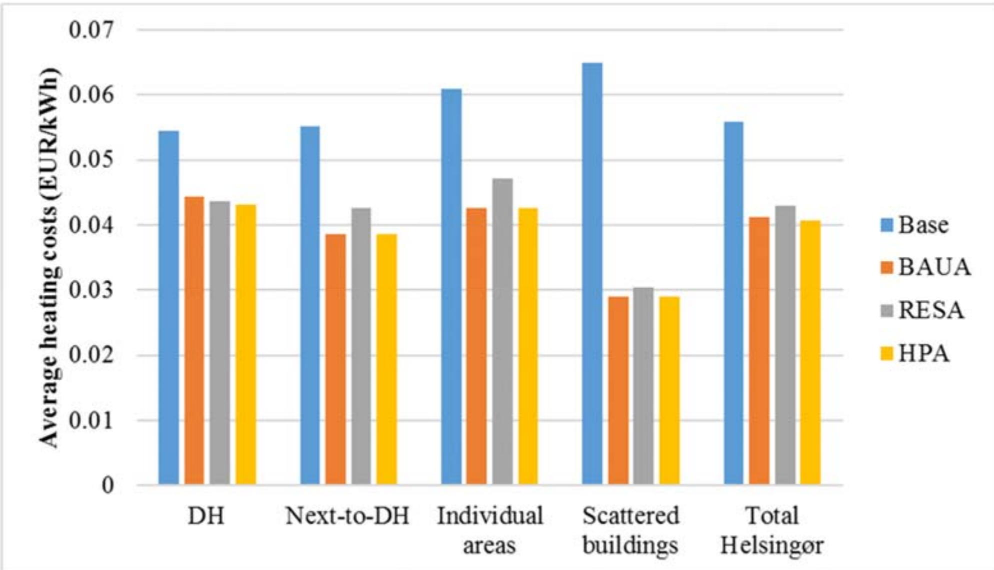

Fig. 7: Average heating costs in the base and in the socio-economic scenarios BAU2030A, RES2030A and HP2030A (EUR/kWh)

The average heating costs represent the average costs for all the buildings located in an area. Heat savings are included in the same way as the heat supply technologies, i.e. annuitized cost of saving 1 kWh of heat is included in the average in the same way as the annuitized cost of supplying 1 kWh of heat. In all areas and all scenarios, costs decrease compared to the base.

The largest decrease in the heating cost occurs within the Scattered buildings due to implementation of around 40% of heat savings. Scattered buildings are relatively old compared to the average age of the building stock in Helsingør. Therefore, the heat savings implemented in Scattered buildings appear to be least expensive. While the difference among 2030 scenarios is minor, the difference between current average heating price (Base) and the average heating price in renewable scenario is rather substantial.

Figure 8 depicts the calculated average heating costs per area type in Helsingør in the private-economic scenarios in 2030.

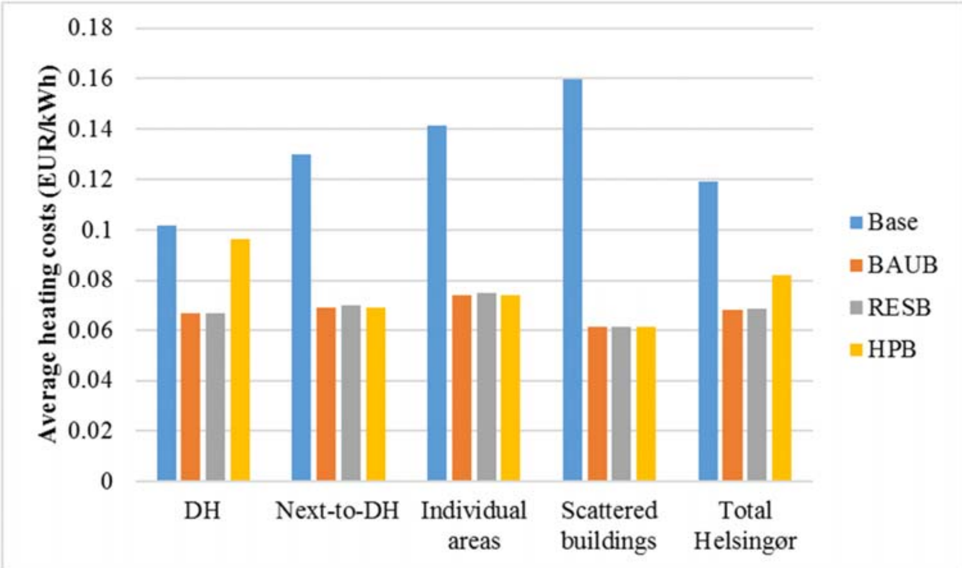

Fig. 8: Average heating costs in the private-economic scenarios BAU2030B, RES2030B and HP2030B (EUR/kWh)

The decrease of the average heating cost (except in the HPB scenario) is even higher than in the socio-economic scenarios and is around 40%. Moreover, the cost in the RES scenario is almost the same as the BAUB scenario; i.e. forbidding natural gas and oil boilers does not result in a higher cost compared to the BAU scenario. Furthermore, the HP scenario is more expensive than the other alternative scenarios and cannot be recommended from a private-economic perspective with the current taxation in place.

Figure 9 shows the calculated average heating costs per area type in Helsingør in 2050.

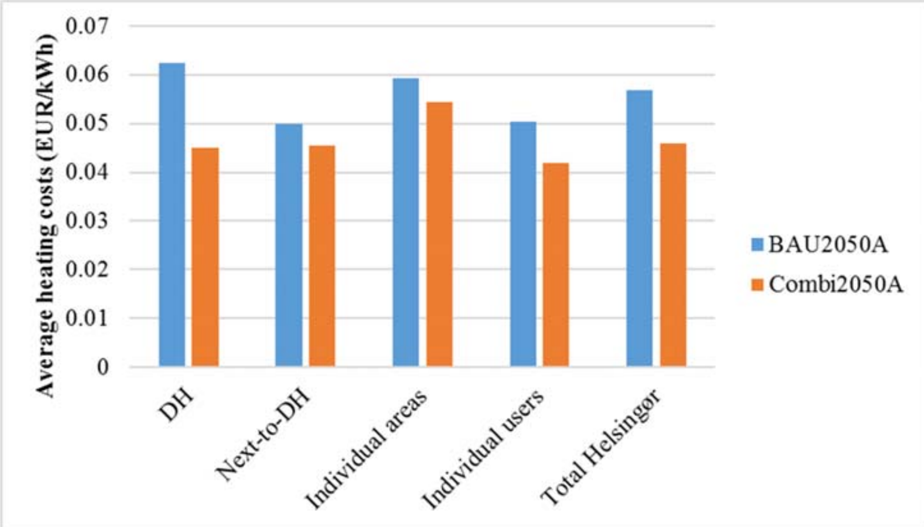

Fig. 9: Average heating costs in the socio-economic scenarios BAU2050A and Combi2050A (EUR/kWh)

The Combi2050 scenario is less expensive both in total in Helsingør and in all areas, mainly because the district heating cost is lower in this scenario, resulting in a higher DH share.

4.3 Share of district heating and heat savings

The share of district heating in Helsingør in the base year is 33%, which corresponds to the current share marked in Figure 10. The figure shows the resulting cost-optimal shares of district heating in 2030 in the BAU, RES and HP scenarios from the simple socio-economic and private-economic perspectives.

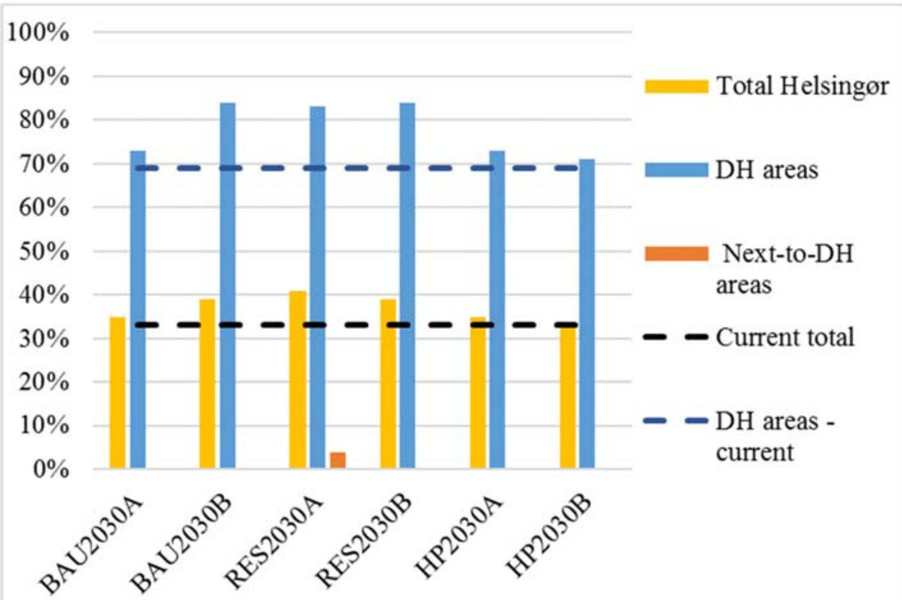

Fig.10: Share of district heating in the 2030 scenarios (%)

The share of district heating in district heating areas increases in all scenarios. It increases slightly in the BAUA, RESA and RESB scenarios, while the growth of around 10% occurs in the remaining scenarios. The RESA scenario is the most favourable scenario for district heating and this is the only scenario where an expansion to the areas next to existing DH areas is observed. The expansion of district heating within district heating areas was expected, since the investment needs to cover only the substation and connecting pipes. Further expansion, even within district heating areas is limited by the cost of competing technologies. For the municipality as a whole, the share of district heating increases in all scenarios, but only in RESA does it surpass 40%, which is significantly below the Danish average of around 50% or e.g. 98% in the Danish capital, Copenhagen. However, if we consider the population density as a proxy for heat density, Helsingør has a rather small population density, compared to cities like Copenhagen (see section 1), which is why reaching high shares of district heating may not be as cost-optimal as in bigger cities.

Figure 11 depicts the share of district heating in the 2050 scenarios.

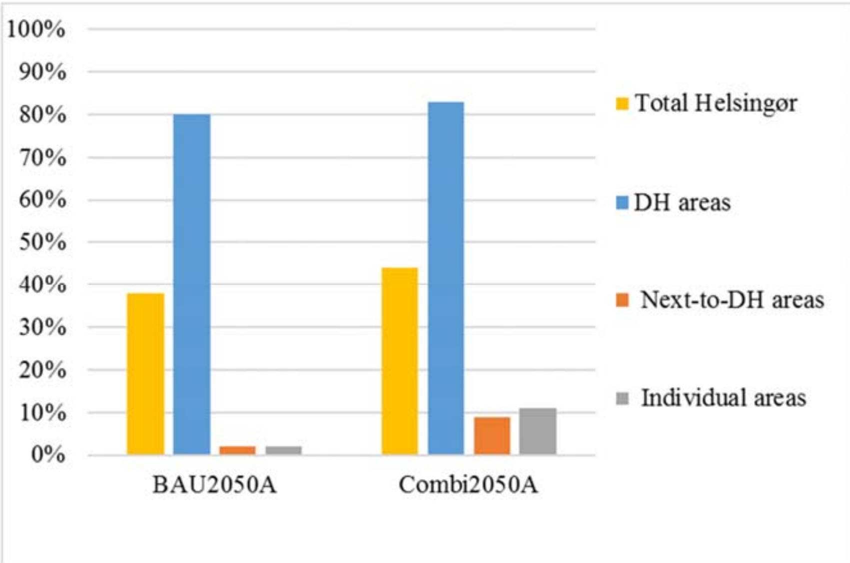

Fig.11: Share of district heating in the 2050 scenarios (%)

Due to the lower district heating cost, Combi2050 results in higher shares of district heating than the BAU2050 in each type of area and overall in Helsingør.

The heat savings in 2030 compared to the Base year are presented in Figure 12 for the six analysed scenarios.

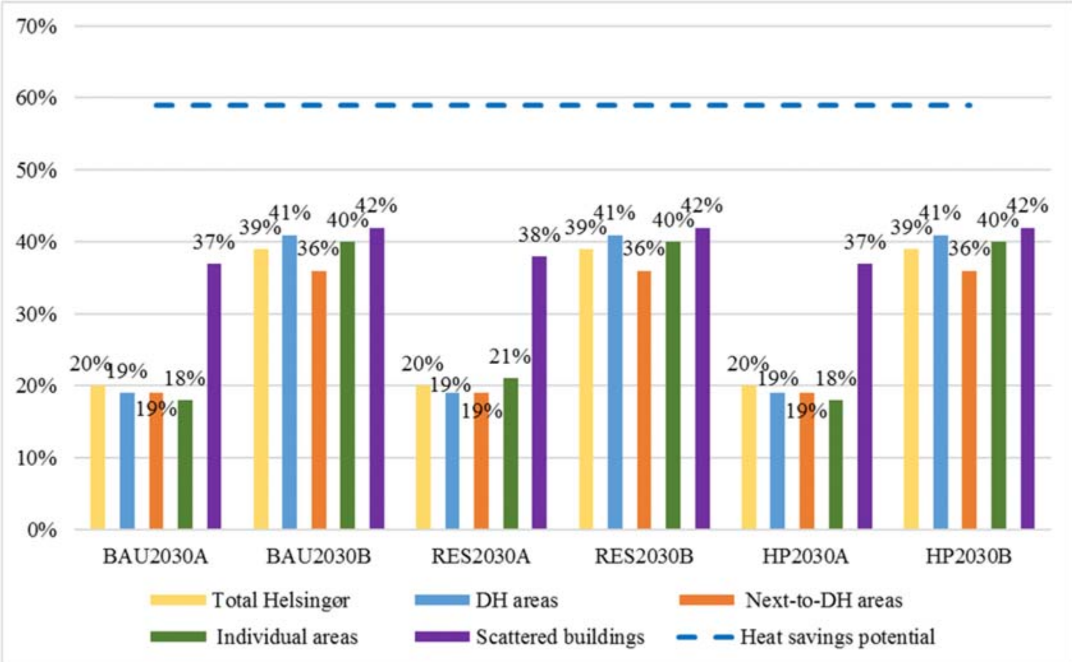

Fig.12: Share of heat savings in the 2030 scenarios (%)

Heat savings occur in all scenarios – in the socio-economic ones (BAUA, RESA and HPA) they are around 18%, while in the private-economic scenarios (BAUA, RESA and HPA) the heat savings are around 40%. The maximum heat savings potential of 58% (blue line in Figure 12) refers to the share of heat demand that can be reduced in the whole municipality on average; not in every individual type of areas. Two general observations can be drawn from the Figure 12. First, due to the fact that VAT is the only tax applied on heat savings, while the heat supply technologies (except biomass boilers) are also taxed on the input fuel (natural gas, oil, electricity, etc.), heat savings are more cost-competitive from a private-economic perspective than from a simple socio-economic one. Second, scattered buildings are the buildings most affected by heat savings. This is an expected result. On the one hand, these buildings cannot be supplied by district heating and natural gas boilers. On the other hand, these buildings fall into groups of "Very old" and "Old" buildings, i.e. heat savings are relatively cost-effective there.

4.4 Heating-related CO_2 emissions

The resulting CO_2 emissions in the heating sector in 2030 compared to the Base year are shown in Figure 13.

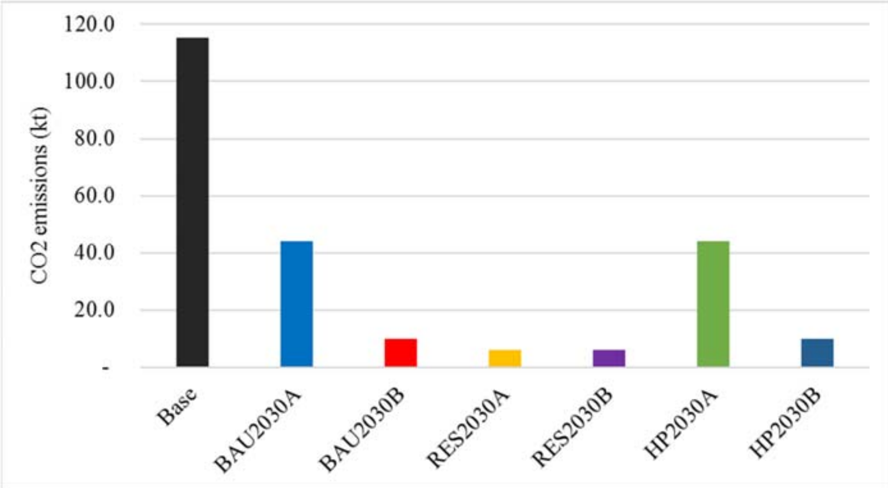

Fig. 13: CO_2 emissions in the 2030 scenarios (kt)

Substantial reductions occur in all scenarios; however, RES2030 is the optimal, emitting only 6 kt (95% reduction). The only CO_2 emissions originating from heat supply in this scenario are related to the fixed amount of district heating coming from Norfors area, which is based on natural gas and MSW. These results correspond with the heat supply mixes shown in Section 4.1.

The resulting CO_2 emissions in the heating sector in 2050 amount for 6 kt and are the same in both scenarios, because we assume a constant amount of district heating supplied from the Norfors area. This is also the reason for no further emission reductions compared to e.g. scenario RES2030.

4.5 Sensitivity analyses

Biomass and electricity price are chosen for sensitivity analysis, since the future prices are highly uncertain and the examined scenarios are expected to be highly dependent on these resources. We discuss substantial changes in: district heating and heat savings share, heating costs and CO_2 emissions.

4.5.1 Increase and decrease of the price of woodchips and wood pellets

Table 6 shows the results of the sensitivity analysis on the woodchip price for district heating plants and wood pellet price for individual boilers in the scenarios with a high share of biomass.

Table 6. Changes (%) in DH share, heat savings share, heating costs and CO_2 emissions due to biomass price increase or decrease of 50% in relation to the price used in the main scenarios. Additional heat savings are not implemented in 2050 scenarios.

Scenario	Biomass price change	Change in total DH share	Change in total heat savings share	Change in total heating costs	Change in CO_2 emissions
BAU2030A	+50%	-1%	0%	+11%	+1%
	-50%	+5%	-19%	-10%	-84%

BAU2030B	+50%	-7%	+1%	+12%	+264%
	-50%	-5%	-22%	-15%	-37%
RES2030A	+50%	-5%	+3%	+8%	0%
	-50%	-1%	-19%	-12%	0%
RES2030B	+50%	+11%	+2%	+17%	0%
	-50%	-5%	-22%	-15%	0%
BAU2050A	+50%	-1%	n/a	+18%	0%
	-50%	+8%	n/a	-25%	0%

Changes in the total district heating share are minor in all scenarios. In the socio-economic scenarios BAU2030A and BAU2050A, a decreasing biomass price causes the district heating share to increase, the overall heating cost to decrease and the heat savings share to decrease as well. This is due to district heating based on biomass being less expensive than other options including heat savings.

In the case of a biomass price increase, both the district heating cost and individual biomass boiler heating cost increase, resulting in selecting natural gas and heat pumps in this scenario and thus higher average heating cost. A 50% biomass price increase does not cause substantial changes in district heating, heat savings share or heating costs, except for BAU2050 scenario, where additional heat savings are not modelled. A remarkable increase in CO_2 emissions occurs in BAU2030B scenario, caused by the large share of individual natural gas boilers.

4.5.2 Increase and decrease of the price of electricity

Table 7 presents the results of the sensitivity analysis on the electricity price in the scenarios with a high share of heat pumps.

Table 7. Changes (%) in DH share, heat savings share, heating costs and CO_2 emissions due to electricity price increase or decrease in relation to the price used in the main scenarios. Additional heat savings are not implemented in 2050 scenarios.

Scenario	**Electricity price change**	**Change in total DH share**	**Change in total heat savings share**	**Change in total heating costs**	**Change in CO_2 emissions**
HP2030A	+50%	0%	0%	+6%	+56%
	-50%	+5%	-10%	-7%	-67%
HP2030B	+50%	0%	0%	+2%	0%
	-50%	0%	0%	-2%	0%
Combi2050A	+50%	+3%	n/a	+12%	0%
	-50%	-5%	n/a	-10%	0%

The total DH share does not substantially change due to the electricity price. However, changes in the socio-economic scenarios HP2030A and Combi2030A are more pronounced than in the private-economic scenario HP2030B, where electricity price changes are almost insignificant compared to the taxation levels. In HP2030A, the CO_2 emissions are highly sensitive to the price - an increasing electricity price makes district heating produced using heat pumps and individual heat pumps less profitable, causing more investments into natural gas boilers.

5 Discussion

A number of limitations occur in this study. The costs of heat saving measures adopted from the Invert/EE-Lab model are based on the assumption that heat savings will be implemented when the building is renovated anyway. In this way, the cost only includes the additional renovation costs related to energy savings, not the full costs. While for 2030, this assumption needs to be analysed further, for 2050, it is in line with the Danish experience. Moreover, due to the system boundary definition, we assume the Norfors DH system to remain the same; however, the possibility of new developments (renovations, changes in energy plant capacity) cannot be excluded. Thus, there may not be enough capacity in the system to expand DH as much, due to expansion in the connected system. 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 electricity prices.

In all the analysed scenarios, the value of investments in new capacities is based on the assumptions about inflation and discount rates, thereby making these parameters crucial for the analysis (see also section 2.4). Our assumptions are based on current rates available for loan-takers, but the possibility of them changing in the future cannot be excluded. Higher rates than assumed would increase the cost of borrowing, which could theoretically discourage investors from taking loans and as a result could e.g. decrease or delay the investments in heat supply options, leading to different supply setups than those resulting from our assumptions.

Since no further implementation of fossil fuels is planned in the municipality, a substantial decrease of CO_2 emissions in the heat supply is very plausible, no matter which scenario will be chosen. However, in the case of the biomass CHP the feasibility of district heating expansion depends very much on which prices the future district heating will be able to offer and how taxation (including tax exemption for biomass) will be shaped. The importance of energy taxation is also significant in our results concerning e.g. heat savings. Other examples are: future fuel and technology prices, as well as policies including CO_2 targets.

The viability of the scenarios proposed depends also on the availability of the locally available renewable energy resources. Scenarios not based on biomass may benefit from better security of supply and from avoiding the risk of biomass price increases. Besides, looking from an overall sustainability perspective, it could be argued that biomass should rather be used in sectors such as heavy transport, which currently does not have other CO_2-free solutions.

Since the possibility of DH disconnection is excluded in this study, high shares of heat savings are implemented even in district heating areas. However, allowing disconnection could affect these shares. Furthermore, the lack of a limit on the speed of implementation of new individual heating technologies also influences the results. We assume that all of the technologies are implemented in the year of focus, while in practice certain implementation delay will occur e.g. due to people's behaviour or technical obstacles.

The sensitivity analysis conducted shows that the change of electricity and biomass prices influences mainly the heating costs and CO_2 emissions, which in turn is linked to different fuel mixes than in the main scenarios.

The goals of Helsingør reaching a level of one tonne of CO_2/inhabitant in 2030 and becoming CO_2 neutral in 2050 are achievable in the heating sector, independently from scenario - but certainly, choosing scenarios with lowest emissions such as RES2030 will allow faster transition to sustainability or offsetting emissions from other sectors, e.g. transport. This will in turn require that a ban on fossil fuel-based individual heat supply is implemented, which may be difficult to get political support for in practice.

6 Conclusions

In this study, we developed a methodology for deriving an optimal mix of heat savings, district heating expansion and individual heat supply, using the spreadsheet-based Least Cost Tool (LCT) and energyPRO modelling tool. We applied this methodology in the municipality of Helsingør, Denmark.

In general, our results show that in Helsingør individual heat pumps and district heating are more feasible from the simple socio-economic perspective, but individual biomass boilers are more feasible from the private-economic perspective - similar conclusions have been presented for several Danish locations by Ref. [52].

From the simple socio-economic perspective, the highest district heating share for the municipality as a whole (41%) and lowest CO_2 emissions (6 kt) occur in the RES2030A scenario, where a policy of forbidding individual oil and natural gas boilers is applied. This share is still below the current Danish average of around 50%. RES2030A is also the only scenario where an expansion to the neighbouring areas is observed. Moreover, the RES2030A scenario has the same low average heating cost as the BAU2030 scenario. From the private-economic perspective, the scenario resulting in the highest district heating share (39%) and the lowest CO_2 emissions is the RES2030B scenario - it also results in a low average heat cost equal to the BAU2030B scenario. Thus, under our assumptions, RES scenarios are most feasible for Helsingør in 2030, considering both economic and environmental aspects. In 2050, the Combi scenario is more viable than BAU when accounting for the district heating share and the heating cost.

The overall heat demand reduction due to heat savings is the same for each 2030 scenario. However, it is higher from the private-economic perspective, where it is feasible to save almost 40% of the heat demand in each area.

A possibility for substantial CO_2 reduction exists in Helsingør, contributing to fulfilling the municipality's aspirations of reaching the level of one tonne of CO_2/inhabitant in 2030 and becoming CO_2 neutral in 2050. A 95% CO_2 emission reduction occurs in the scenarios RES2030A and RES2030B. Both 2050 scenarios: BAUA and Combi achieve the same CO_2 level as RES2030, due to the assumed fixed amount of heat supplied from the Norfors area, which is based on MSW and natural gas.

Since the Combi2050 scenario is from the simple socio-economic perspective an optimal solution for Helsingør in 2050, we recommend that the operation of an already decided biomass CHP plant is closely monitored and new technologies such as heat pumps and heat storages are considered in the 10-15 years' perspective. The uncertainty connected to future biomass taxation is rather high. If electricity taxation changes in the future, considering large heat pumps is also important. Many district heating companies in Denmark are investing in solar thermal installations now and this technology should be examined as well.

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 iterative method for calculating the optimal heat supply configuration can be useful in energy planning of any heating system type, geographical region and scale. Furthermore, the paper displays solutions that may encourage other cities to conduct local energy planning.

Future work will concentrate on policy analyses such as the influence of tax alternation and subsidies on the profitability of heat supply and heat savings options in Helsingør. It will also address some of the behavioural aspects, such as the practicality of using residential biomass boilers versus e.g. heat pumps and district heating and the rate of implementation of individual heating technologies.

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