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Smart Energy Aalborg: Matching end-use heat saving measures and heat supply costs to achieve least-cost heat supply

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ABSTRACT

Energy efficiency improvements of buildings is widely recognized as an important part of reaching future sustainable energy systems, as these both reduce the need for energy and improve the efficiency of the heat supply. Finding the correct level of efficiency measures, depends on the type of measure, on the supply system typology as well as on the heat supply cost. As this information is often building-specific, most analyses related to energy efficiency in buildings are carried out in relation to specific renovation projects, while energy plans for larger areas make crude assumptions regarding levels of savings and costs. This article aims at improving the latter, by using a detailed heat atlas in combination with specific marginal energy renovation costs, in a study of Aalborg Municipality in Denmark. In the analysis, all buildings in the municipality are mapped at building level and both the marginal energy efficiency measure costs and the marginal heat supply costs are identified. The buildings are then sorted by their supply type, and marginal costs curves on supply and savings are compared to determine the feasible level of efficiency measures in each building. The results show that both the building type and the supply costs have a large influence on the feasible measures. Furthermore, the results show that a demand reduction of 30% in district heating areas, 35% for buildings with heat pumps and 37% for buildings with oil boilers, for the examined buildings, is socio economically feasible in a Business as Usual 2050 Aalborg Municipality scenario.

Keywords:

End-use;
Heat Demand;
Heat Planning;
GIS;
Energy system analysis;
EnergyPLAN simulation;

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1. Introduction

In 2016, the European Union made a strategy on heating and cooling [1], where energy efficiency measures like district heating and end-use heat savings are considered feasible measures. The main reason for considering district heating an efficiency measure is its ability to use excess heat from electricity production, industrial processes and waste incineration [2]. In the European Union alone, 10.2 EJ of excess heat are theoretically available from these three processes [3]. Other benefits of district heating are the relatively inexpensive heat storages [4], providing flexibility in relation to fluctuating renewable energy production and the integration of renewable energy sources through heat pumps [5], solar thermal collectors [6] or geothermal energy [7]. District heating can therefore play a crucial role in the transition to 100% renewable energy systems [8].

A key issue, when considering district heating as an energy efficiency measure, is that the technology needs to move towards fourth generation of district heating [9,10] where temperature levels are reduced to improve the efficiency of the supply system and enabling the exploitation of low temperature heat sources while simultaneously reducing grid losses. Furthermore, district heating is also an important technology in the Smart Energy System [11,12], where cross-sector integration is a central aspect.

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A central part of assessing the potential for district heating in an area is heat demand mapping, or the establishment of so-called heat atlases [13]. The main reason is that the economic feasibility of district heating is highly correlated to the density of the heat demand, where areas with a high density both reduce the network length and losses, when compared to less dense areas [2]. This also means that district heating will mostly be applicable within urban areas, while other heat supply solutions are needed in rural areas and areas with lower heat densities.

The recent acknowledgement of district heating, as a technology that has a crucial role in the transition towards smart energy systems, has sparked an interest in mapping heat demands. Heat demand mapping exists on different levels of detail, depending on the scope of the analysis, in which the mapping takes part. Some mapping is used for assessing district heating potentials on a national or regional level. Here, the Heat Roadmap Europe project [14] is a good example, where heat demands are assessed on a hectare level. In local studies, the mapping includes the specific building level. Such studies are typically used to examine district heating expansion potentials locally [15,16]. Additionally, mapping of the energy demand in buildings is also used by many cities in order to be able to assess building energy efficiency [17] with a view to targeting efficiency measures.

Much recent research deals with various aspects of energy efficiency in buildings, which is illustrated by a recent review article that focuses on energy efficiency in multi-family buildings [18] and identifies 234 relevant references dealing with this topic. The review shows that 50% of the articles deal with environmental aspects, 30% with economic and 25% with social aspects related to energy renovation. Many articles focus on efficiency measures from a technical perspective, by examining energy savings in relation to occupancy [19] or building characteristics [20].

A crucial part of assessing the feasibility of heat savings is the costs related to investing in the efficiency measures, compared to the savings in the heat supply. It is crucial to identify the right mix between renewable energy production and energy savings.

Previous studies have made such investigations on an overall national level, estimating the combination of heat production and heat savings in for instance a Danish 2050 energy system [21], and in four European countries (Czech Republic, Croatia, Italy and Romania) [22]. However, these studies do not consider the geographical aspects of how different building types are located throughout a country and how that compares with the available supply options. This link is necessary, as the individual building owners need to make decisions based on the available local heat supply options.

Furthermore, this article is a continuation of heating related topics already known to the journal. The editorial [23] from 2017, dealt with smart district heating and energy system analyses. Heat saving strategies were presented in [21] where the costs of energy renovation are compared to energy system costs for different district heating shares. The development of detailed heat demand maps were the main subject of [24] and [25], and their accuracy was discussed in [26]. Planning of heating systems using spatial methods and different scenario paths were investigated[27]. Other work concerned the barriers and policy recommendations for heat savings in Denmark [28] as well as building specific case studies on cost optimal level of heat savings [29].

1.1. Scope and structure of the article

Based on the problems presented in the introduction, the article aims to find the balance between end-use savings and supply costs within different areas. It seeks to combine geographical knowledge on energy supply systems and the location of specific buildings with an assessment of specific supply costs and heat demand reduction costs. This allows for a much more specific assessment of the coordination of heat savings and heat supply, which enables the discussion of the consequences for different buildings types and locations. This becomes relevant when assessing the difference in savings initiatives between buildings with access to district heating and buildings located outside district heating areas.

As the geographical distribution of buildings is site specific, this is shown for the specific area of Aalborg Municipality in Denmark. Aalborg is Denmark's third largest municipality and encompasses a variety of heat supply areas, including a large central district heating grid, some detached smaller district heating systems, as well as houses heated by individual solutions outside district heating areas. The analyses are done, with a focus specifically on end-use savings in existing buildings within the municipality. The energy demand for buildings where no renovation is implemented is included in the analysis. Furthermore, the analysis is carried out in relation to an Aalborg 2050 business as usual scenario for the municipality. The article focuses on the direct costs of the energy system including; investments, fuels and operation and maintenance, using costs from the IDA Energy Vision 2050 [30]. In the analysis, Aalborg Municipality is used as an example on how to apply the method proposed in this article. The method can be applied anywhere where the same information is available, but the results of the analysis are strongly related to the Aalborg example, as both the local heat supply systems and end-use demands are specific to Aalborg municipality. The modelling of the overall energy system in Aalborg Municipality is based on the work in the Aalborg Energy Vision [31].

2. Methodology

The basic principle of this article is to compare the marginal supply costs of heat with the marginal costs of heat saving measures. The scope of the article determines that the marginal supply costs and the marginal costs of energy savings are both measured in €/kWh. The first step is to identify the location of each building using Geographical Information Systems (GIS) and the supply type for each building (district heating or individual solutions). To identify the marginal supply costs in district heating, the principal methodology applied is similar to [21]. The heat production cost in district heating is highly dependent on the production units used. As such, it is necessary to identify the marginal changes in heat production for different units at different levels of heat savings. For this purpose, an energy systems analysis tool is used to calculate the production of district heating, which in turn is used to identify the marginal heat production costs.

In this article, EnergyPLAN [32,33] is used as the energy system analysis tool to identify the marginal costs of district heating supply. EnergyPLAN is well-suited since it simulates the entire energy system, and thus captures possible synergies across the heating, electricity and gas sectors (See Section 2.3).

As the aim is to identify the potential differences in heat saving potentials due to the geographical placement of each individual building and individual building characteristics, it also must consider the marginal production cost of heating for individual buildings. These costs differ due to building type and building age and that different locations enables different supply options. Here, the study assumes that the marginal cost of individual heating is equal to the fuel costs including handling costs divided with the efficiency of the heating technology.

To identify the heat savings potential for each building, geographic data of the current heat demand at the individual building level is combined with heat saving cost data on different building categories associated to different level of savings. This allows for the identification of marginal savings costs for each building. By comparing the marginal supply cost with the marginal savings costs, it is possible to identify the feasible level of saving in each supply area where the supply area is characterised by the specific heating infrastructure applied. This can be district heating, or an individual heating technology situated at the individual household.

An overview of the approach is illustrated in Figure 1, and each step is described more in detail in the following sections.

3. Case study

In this chapter the methodology from Chapter 2 is applied to the case of Aalborg Municipality. First, the mapping of heat demands and supply areas is explained. This is followed by an explanation of the heat saving measures used, their implementation in the energy system as well as general cost assumptions of the Aalborg energy system.

3.1. Maps of case and description of end-use heat demands

This section describes the geographic scope of the analysis, as well as the data used to assess end-use heat demands, heat supply costs as well as end-use heat saving potentials.

3.1.1. Supply areas in Aalborg

Aalborg Municipality has 76,179 buildings with a total end-use heat demand of 2,027 GWh/year [34]. Within the municipality the heat supply systems are divided into the central area of Aalborg District Heating, other district heating areas and buildings with individual heating, these are shown in Figure 2 and the percentage distribution is shown in Figure 3.

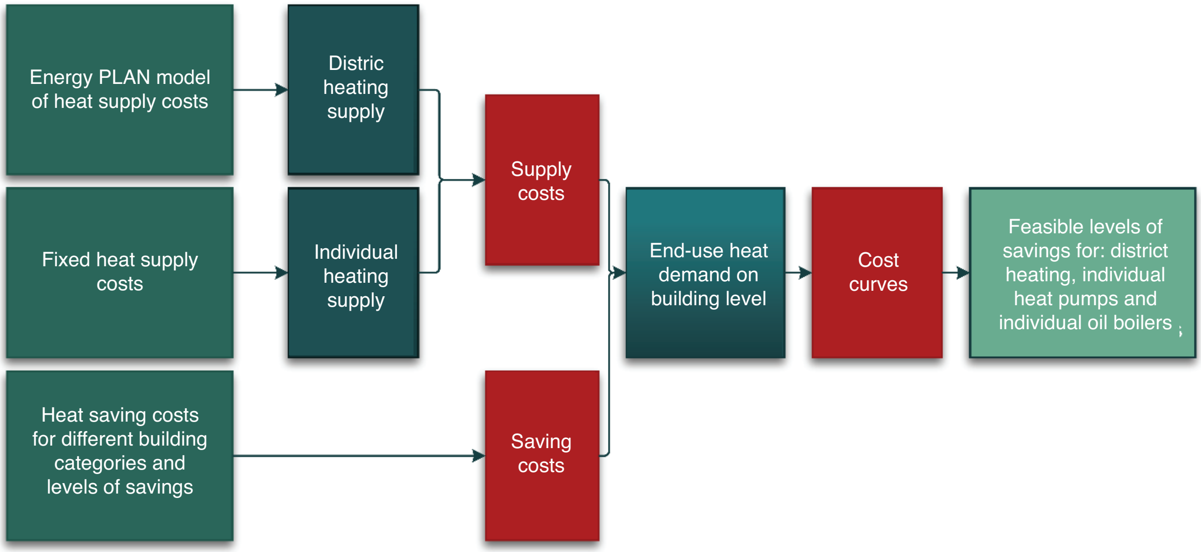

Figure 1: Methodological framework for identifying feasible end-use heat saving costs in different heat supply areas

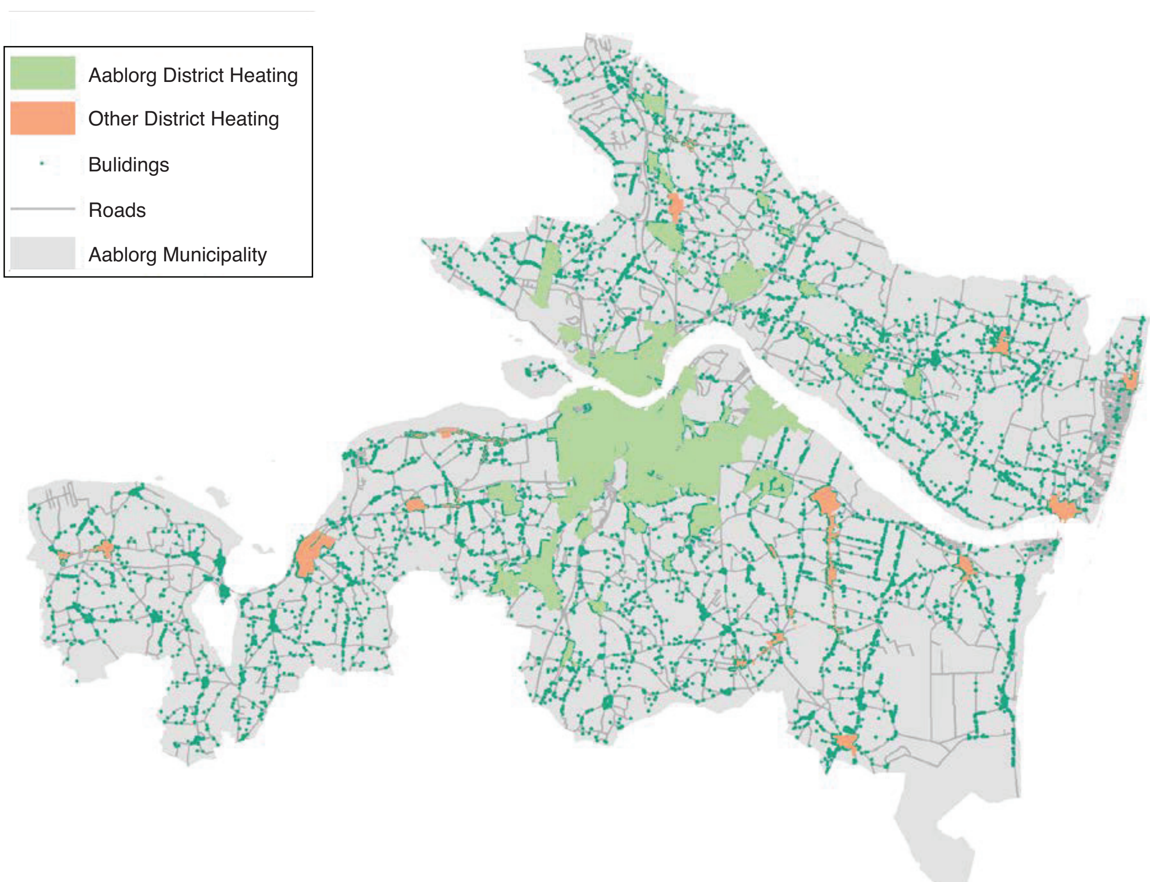

Figure 2: Heat supply areas in Aalborg Municipality

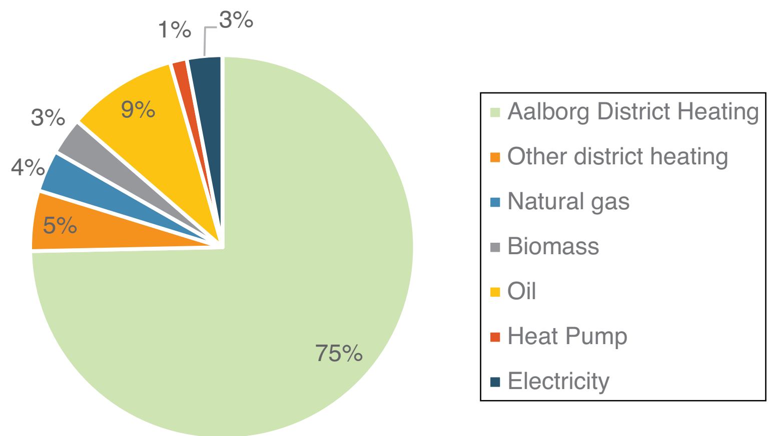

Figure 3: Percentage share of end-use heat demand by heat supply type

3.1.2. The Danish Heat Atlas

To find the end-use heat demand of the existing buildings in Aalborg, the Danish heat atlas is used. It was first published in [35] and has been updated in several versions since. The atlas has been used in various scientific publications [24,36–41].

The heat atlas provides an estimate of the annual end-use heat demand as well as other relevant information such as heat supply, construction year, building type and floor area. All this information is recorded in the Danish Building Register [42], which is a national registry covering all Danish buildings.

Building owners are obliged to update the information, when new buildings are built, or when major renovations are carried out. However, the Danish Building Register does not provide information about the end-use heat demand in the buildings, so this must be estimated based on other sources.

The current version of The Danish Heat Atlas estimates the end-use heat demand based on another database named FIE [43], which includes annual heat consumption from most Danish district heating, natural gas and fuel oil providers on individual building level. The data extract from the FIE data base covers the years 2010-2014, and has 5,578,433 registered heat demand measurements, however, it only covers half of the heated Danish buildings, as some buildings are not supplied by district heating, natural gas or oil or due to lacking information from some of the heat providers. As the FIE database does not cover all buildings, the end-use heat demand is estimated based on a statistical analysis of the FIE data, where buildings are classified by age (9 construction periods) and type (24 buildings types) and for each combination an average demand (kWh/m2 of floor area) is found. These averages are multiplied with the total floor area of each building in The Building Register to create The Danish Heat Atlas. A more elaborate explanation of the methodology can be found in the documentation of the heat atlas, where the uncertainties of the estimates are shown for each building category [34].

In this article, only buildings from Aalborg Municipality are used. Figure 4 illustrates the level of detail, showing different building types in a part of the municipality. The example shows that the Danish Heat Atlas operates at a building level, where each point represents a building, and that the main types of buildings are single-family, terrace and multi-storey.

3.2. Heat saving costs

The heat savings potentials for the study are based on Wittchen, Kragh and Aggerholm [44], who assess them for the Danish building mass. The study defines a number of renovation measures as steps of activities to be taken in each individual type of building. Each level of saving is a marginal increase in energy savings with a marginal increase in costs associated to it. Table 1, Table 2 and Table 3 show the level of savings, a qualitative description and examples of the actual measure implemented.

Figure 4: Example of building types from the Danish Heat Atlas

Table 1: Energy savings measures and concrete initiatives in walls [45]

Level	Energy savings measure	Cavity walls	Massive walls	Light Walls	Basement walls
0	Point of departure	Nothing	Nothing	Nothing	Nothing
1	Basic renovation (building code)	Nothing	25 mm if bad	75 mm	Nothing
2	Cavity wall insulation	Filled	25 mm if bad	75 mm	Nothing
3	Windows (A level)	Filled	25 mm if bad	75 mm	Nothing
4	Insulation of ceiling and roofs	Filled	25 mm if bad	75 mm	Nothing
5	Good practice for insulation	Filled	125 mm if bad	100 mm	100 mm
6	Energy saving focus when insulating	Filled	125 mm if bad	100 mm	100 mm
7	Level 6 fully implemented	Filled	125 mm if bad	100 mm	100 mm

Each of the seven steps has a key focus in terms of renovation, meaning that some of the steps deal with outer wall insulation while other deals with more energy efficient windows. Step 1 implements basic renovations, that brings the building up to current Danish standards. This focus on more insulation and energy label B windows. Step 2 is only cavity wall insulation in buildings without. Step 3 goes from energy label B windows to energy label

Table 2: Energy savings measures and concrete initiatives in roofs and windows (based on Danish window labelling) [45]

Level	Energy savings measure	Ceiling	Flat Roofs	Windows
0	Point of departure	Nothing	Nothing	Nothing
1	Basic renovation (building code)	75 mm	100 mm	Energy label B
2	Cavity wall insulation	75 mm	100 mm	Energy label B
3	Windows (A level)	75 mm	100 mm	Energy label A
4	Insulation of ceiling and roofs	200 mm	150 mm	Energy label A
5	Good practice for insulation	250 mm	200 mm	Energy label A
6	Energy saving focus when insulating	350 mm partly	300 mm partly	Energy label A
7	Level 6 fully implemented	350 mm fully	300 mm fully	Energy label A

Table 3: Energy savings measures and concrete initiatives in floors [45]

Level	Energy savings measure	Ground deck	Crawl space	Basement floor	Ground deck w/ floor heating	Crawl space w/ floor heating
0	Point of departure	Nothing	Nothing	Nothing	Nothing	Nothing
1	Basic renovation (building code)	100 mm	75 mm	100 mm	100 mm	75 mm
2	Cavity wall insulation	100 mm	75 mm	100 mm	100 mm	75 mm
3	Windows (A level)	100 mm	75 mm	100 mm	100 mm	75 mm
4	Insulation of ceiling and roofs	100 mm	75 mm	100 mm	100 mm	75 mm
5	Good practice for insulation	200 mm	150 mm	200 mm	200 mm	150 mm
6	Energy saving focus when insulating	300 mm partly	200 mm	300 mm partly	300 mm partly	200 mm
7	Level 6 fully implemented	300 mm fully	200 mm	300 mm fully	300 mm fully	200 mm

A. Step 4 increases insulation of ceilings and roofs. Step 5 increases insulation across the entire building, with step 6 and step 7 implements the highest levels of insulation to all buildings.

An important precondition to achieve cost-efficient energy savings is that the energy saving initiatives are performed at the same time as the general renovation of the building. This pre-condition is assumed for all costs in the study [45]. Wittchen, Kragh and Aggerholm [45] assume that a certain level of savings can be achieved at a marginal cost of zero, since this will be the basic renovation house owners would do as part of the general refurbishment of their buildings. Thus Level 1 does not have a marginal cost, as shown in Figure 5. Overall, this means that the costs used in this study are based on the additional costs associated to the increased performance of each activity to achieve the energy saving. Since Wittchen, Kragh and Aggerholm [45] do not take into account potential savings in summer houses, and other minor building categories, not all building types are included in the analysis. However, the large majority of the demand is analysed.

Wittchen, Kragh and Aggerholm [45] use a discount rate of 4% for their initial calculations. As the Aalborg Energy Vision's results are based on a 3% discount rate, these had to be aligned. In this study, the marginal saving costs have been recalculated to be based on a 3% discount rate, to align cost assumptions between the two studies.

Based on the data from [45] it is possible to calculate the percentage reduction of heat demand associated with each level of savings. Figure 5 shows a situation of diminishing returns where most of the heat savings are associated with the initial levels of savings, while the later steps do not save as much. Figure 6 plots the level of heat savings with the costs, which furthermore shows that the first levels of savings have lower marginal costs than the later levels, in total giving a situation where the cost efficiency is highest in the first levels and lowest in the last levels.

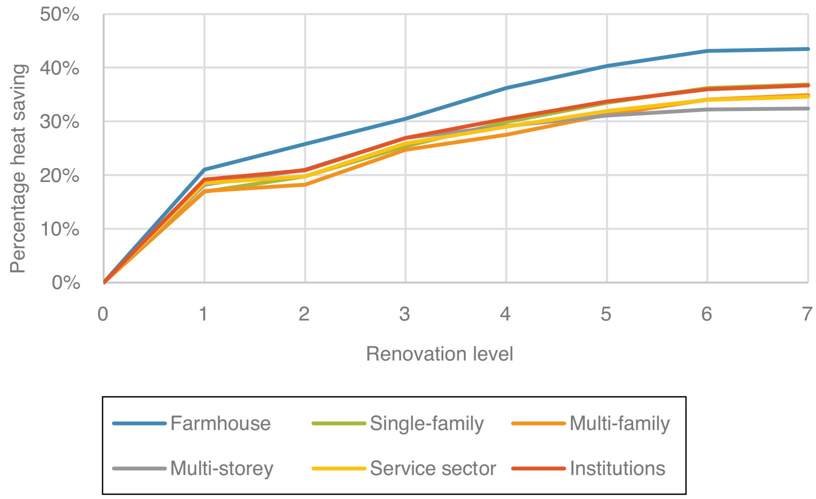

Figure 5: Total heat savings percentage by increasing the renovation level on an overall level [45]

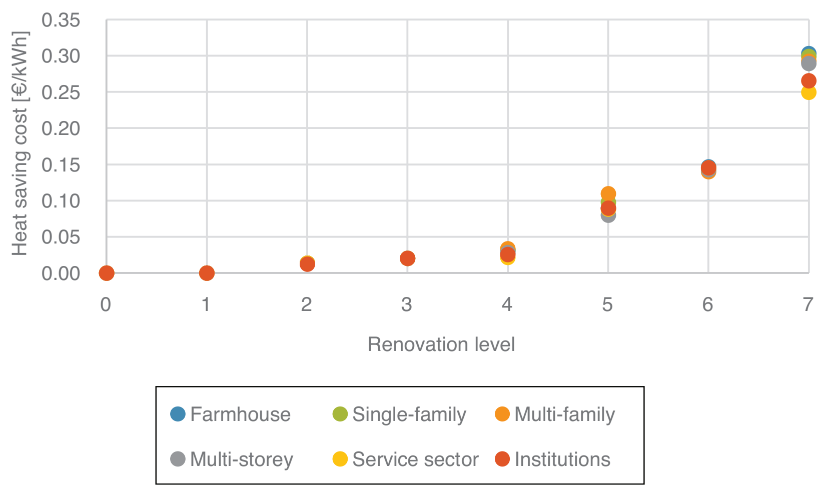

Figure 6: Marginal heat saving costs by increasing the renovation level [45]

3.3. Heat supply costs assessment using EnergyPLAN

EnergyPLAN is an advanced energy system analysis tool capable of analysing the hourly operation of an entire energy system over a year [46].

EnergyPLAN is chosen to simulate the operation of the energy system to identify the marginal heating costs due to its capability of investigating the entire energy system. It includes industry, transport, electricity, heating and gas demands, and potential links between these sectors. It is therefore possible to include benefits of waste heat from industry in the district heating grid and combine this with the consequences of changes in heat demand. Furthermore, due to EnergyPLAN being based on hourly operation it allows for detailed analysis of the operation of storages, including thermal storages. This again increases the details of the modelling, taking into account the flexibility of the energy system. Figure 7 illustrates the overall elements of the sectors included in EnergyPLAN and highlights the links in the district heating system. EnergyPLAN have been used in similar studies, for assessing the link between energy savings and energy production [21,22,47], has previously been applied to model e.g. countries [30,48–53] and local areas [54–57] with district heating, and has been applied in more than 100 peer-reviewed journal articles [58].

EnergyPLAN is used for modelling the energy system of Aalborg. The scenario used in this paper is a 2050

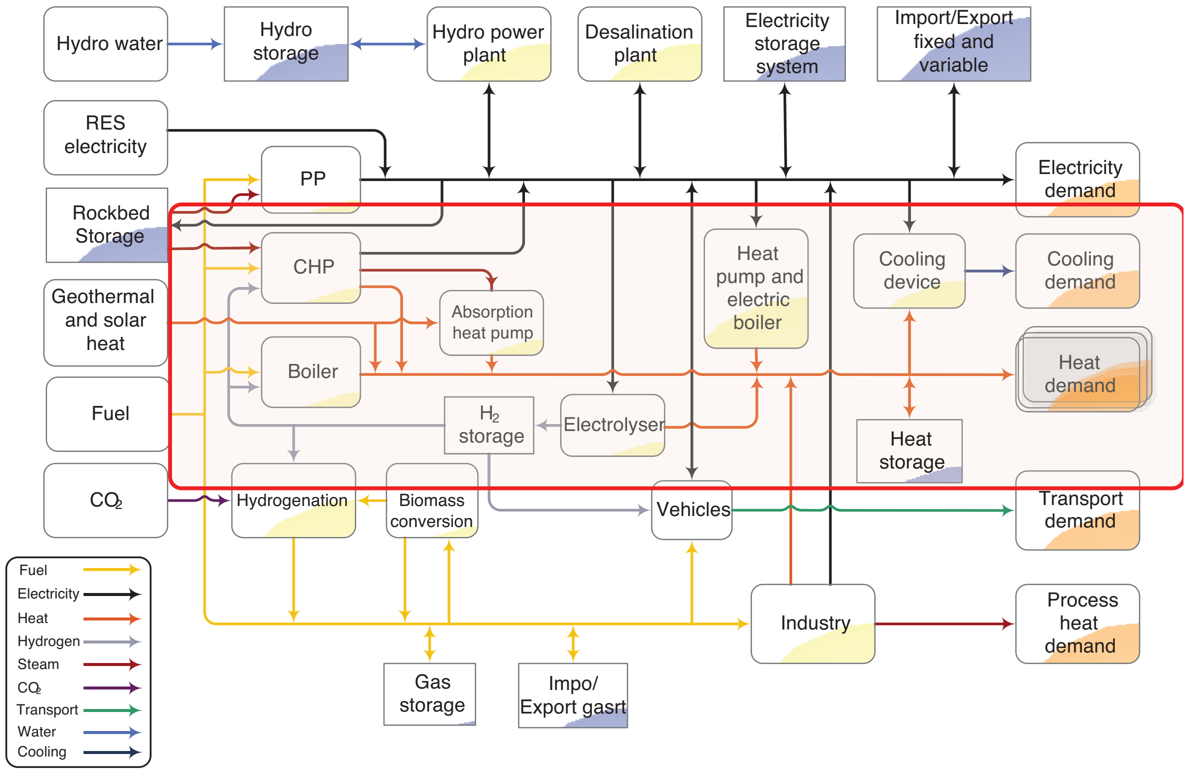

Figure 7: EnergyPLAN structure [46]. Within the red square the district heating sector can be found

business as usual scenario (BAU). The 2050 BAU scenario is created by extrapolating current energy demands in Aalborg based on a 2016 energy account of Aalborg [51]. The increase in demands is based on the overall expectations for Denmark and Aalborg based on the Danish Society of Engineer's energy vision of Denmark [59]. Thus the assessment of savings is taken into account in a scenario for 2050 for Aalborg Municipality.

3.3.1. Assumptions for the Aalborg Municipality energy system

The Aalborg 2050 BAU is modelled as the entire energy system, and thus includes industrial, transport, electricity, heat and gas demands. The electricity demand is modelled as Aalborg's share of the entire Danish electricity demand, identified in [59] before savings. A large coal-fired CHP unit, as well as renewable energy, supplies this demand. All parts outside the heating system are unchanged in the analyses, but changes to the heating system affect the overall operation of the entire system. For instance, that changes in heat demand can affect the production of electricity in a combined heat and power plant. The overall system operation and layout is described in [60].

The heating demands are identified using the aforementioned GIS data. The GIS analysis also identifies supply methods for each demand, thus allocating the heat demands to different boilers, heat pumps or district heating areas. The inputs for heat demands are found in Table 4.

Table 4: Final energy for end-use heat demands by supply type [60]

	Heat demand [TWh]	Energy demand [TWh]
Heat demand (central district heating)	1.80	2.28
Heat demand (decentral district heating)	0.07	0.10
Individual heat demand (oil)	0.11	0.14
Individual heat demand (natural gas)	0.02	0.02
Individual heat demand (biomass)	0.06	0.09
Individual heat demand (electric boiler)	0.06	0.01
Individual heat demand (heat pumps)	0.03	0.06

Table 5: Capacities and investment costs for district heating [60]

	Capacity [MW]	Specific investment [M€/MW]	Fixed O&M [% of investment expenditures]	Lifetime [years]
CHP unit	323 el / 422 Th	1.78	1.64	40
Boiler unit	800	0.05	3.4	25

Table 6: Capacities and costs for individual heating [60]

	Capacity [1000 units]	Specific investment [M€/1000 units]	Fixed O&M [% of investment expenditures]	Lifetime
Indv. fuel boiler	10	2.7	6.7	20
Indv. electric heat	3	3.0	0.8	30
Indv. heat pump	2	7.6	2.22	15

Table 7: Fuel prices [60]

Fuel type	Basic Fuel price [€/kWh]
Coal	0.010
Fuel oil	0.042
Natural Gas	0.029
Biomass	0.022

The associated costs for the system are based on the EnergyPLAN cost database [61] using 2050 prices. Important for this study are the fuel costs and the costs for the units being changed with the re-design of the district heating system due to changes in demand. The costs do not include taxes as the analyses are conducted with socio-economic feasibility in mind rather than business economic feasibility. The fuel costs are found in Table 7 and the investment costs and capacities for the heating system in Table 5 and Table 6.

To investigate the marginal changes in heat production costs at lower heat demands in the district heating areas, three parameters were changed.

1) The actual heat demand was lowered to the new value as identified by implementing the levels of savings.
2) The hourly heat demand load profile was changed to reflect that the hot water consumption and grid loss remained constant, thus the heat savings only affect the space heating demand in line with [21].
3) The capacity of the peak-load boilers in the district heating network is adjusted to reflect the heat savings and reduced demands. This reflects that with lowered heat demands due to better insulation, less peak capacity is needed.

Table 8: Changes to the district heating system as consequence of space heating savings in Aalborg in a 2050 scenario

Savings rate in space heating	Heat supplied to the district heating grid [TWh]	Resulting heat demand in buildings [TWh]	Peak-load boiler capacity [MW]	Heat and electricity system cost [M€]
0%	2.28	1.80	800	668
15%	2.02	1.54	689	656
30%	1.76	1.28	578	646
45%	1.50	1.02	467	637
60%	1.23	0.75	357	631
75%	0.97	0.49	246	628

Therefore, several potential energy systems are designed that can supply the reduced energy demands. The difference between these heating systems represent the marginal changes in production costs. The demands that the energy systems need to supply represents a percentage reduction of the initial heat demand in the district heating system in Aalborg. Table 8 shows the resulting changes to the district heating system, with a changed demand. Based on these changes it is possible to calculate the marginal heat production costs with increased savings. These can be seen in Figure 8. It should be noted that this calculation only is done to determine the marginal production costs with increased savings level. To identify the actual savings rate, the marginal production costs must be compared with the marginal savings costs.

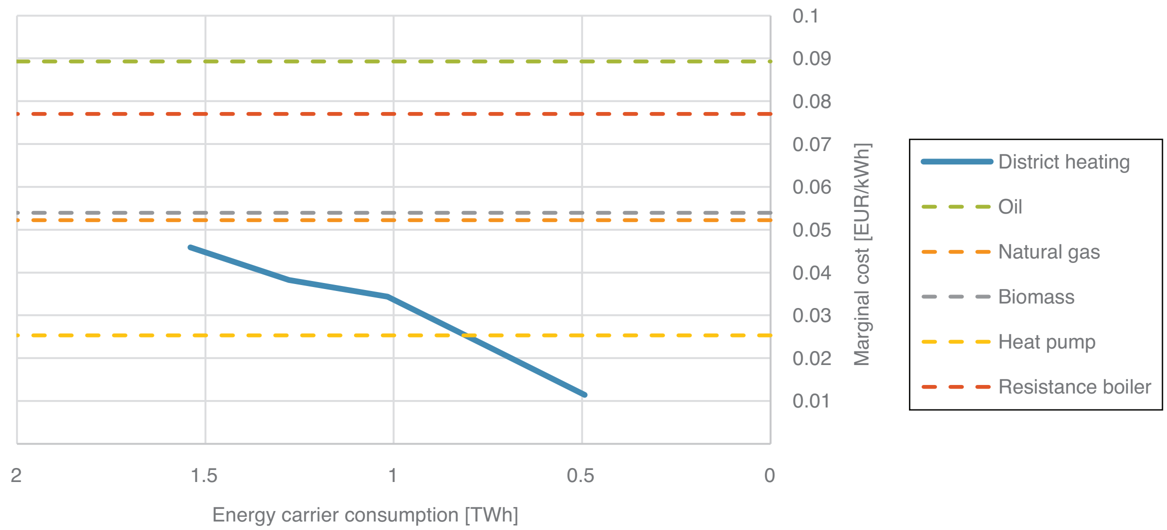

Figure 8: Marginal heat production costs for reduction in heat production. The solid line is the district heating supply with different levels of demand, while dashed lines are marginal supply costs for individually heated buildings

Table 9: Marginal costs for changing the heat demand in individual heating

Fuel type	Heat efficiency	Fuel price for indv. heating incl. handling costs [€/kWh]	Resulting heat price [€/kWh]
Oil	0.80	0.071	0.089
Natural Gas	0.85	0.044	0.052
Biomass	0.69	0.037	0.054
Electricity (boiler)	1.00	0.077	0.077
Electricity (heat pump)	3.10	0.077	0.025

To investigate the marginal heat production costs of changes in the individual heat supply, this study assumes that it is reflected in the fuel costs for individually heated buildings. The assumed fuel costs are found in Table 9. Figure 8 shows the marginal heat supply costs as the heat demand is reduced in Aalborg Municipality.

4. Results

Based on the GIS analyses and costs presented in the methodology, it is possible to identify marginal cost curves for both production of energy in the Aalborg energy system and the energy saving in each individual building. The buildings and renovation levels are aggregated based on supply. Figure 9 shows the marginal cost curves for supply and savings for the central district heating area, where Figure 10 shows the curves for the individually heated buildings.

From the intersection between the two curves in Figure 9, the socio-economically feasible renovation level in each supply area is identified, associated to the specific buildings that need to be renovated and the extent of this renovation. The overall energy efficiency increase for each supply area can be seen in Table 10. It is important to note that not all buildings in Aalborg Municipality are included in the analysis. Table 10 therefore includes both the specific savings in the buildings included, and the influence on the total energy demand. One example is that the electric heating category contains many summer cabins that are not renovated, which means that even though the modelled buildings have to reduce the heat demand with 33%, it

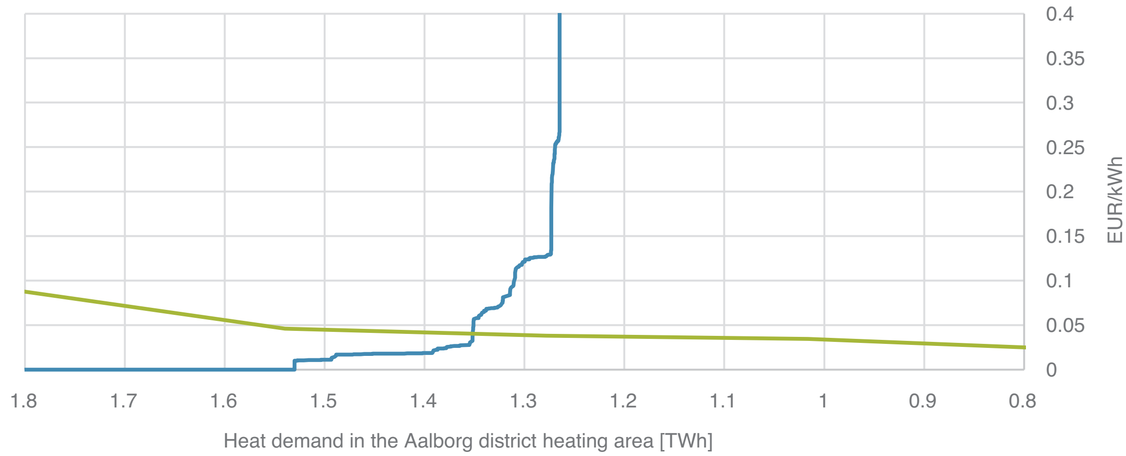

Figure 9: Heat saving costs and heat supply costs in district heating

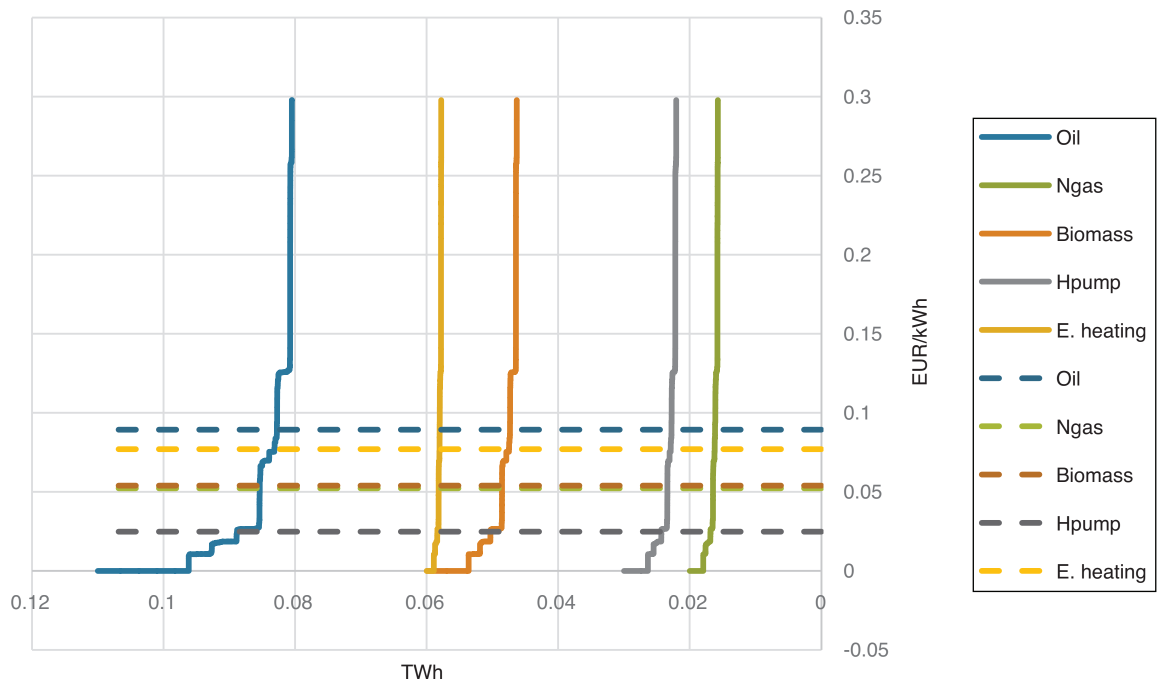

Figure 10: Heat savings costs and heat cost for individual heating. The dashed lines indicate marginal heating costs and the bold lines the marginal saving costs

Table 10: Specific savings in modelled buildings and influence on total heat demand

	GWh savings	Savings in modelled buildings	Total heat demand reduction
Central district heating	450	30%	25%
Individual oil	27	37%	24%
Individual gas	4	36%	20%
Individual biomass	11	34%	18%
Individual heat pumps	6	35%	23%
Invididividual electric boiler	2	33%	3%

only affects the total heat demand for electric heating with a 3% reduction since most buildings with electric heating won't be renovated. For the central district heating area, however, the 30% savings potential can reduce the overall heat demand by 25% due to the large share of houses connected to the central district heating system.

It is now possible to identify results for each building type in all supply areas. For this analysis, the paper focuses on the district heating area, and the most and least expensive individual heating technology respectively, oil and heat pumps.

Figure 11 and Figure 12 show the amount of energy reductions at each level, dependent on the construction year of the building. For district heating and heat pumps, savings up until Level 4 are feasible, whereas for the most expensive heat source, oil, the buildings can be renovated up until Level 5. The results show that Level 1 savings can achieve savings in all buildings, just as well as installing Energy label A windows (Level 3). However, Level 2, and Level 4 and 5 primarily achieve a significant amount of energy reductions in buildings constructed before 1973, since these steps are already implemented in newer buildings in Denmark.

Furthermore, the figures also illustrate that the building mass is newer in the district heating area, compared to the buildings with individual oil boilers and heat pumps. Figure 11 shows that it is feasible to conduct savings in the newer building mass, but since most buildings already have better insulation standards there is less feasible savings to make. In both the oil and the heat pump-heated buildings, most of the savings can be achieved in buildings older than 1930. For oil-supplied buildings it also seems feasible to refurbish to level 4 or level 5, which is not relevant in the heat pump-heated houses. However, here it might be more feasible to change to a different supply technology.

Figure 13 and Figure 14 show the achievable saving in each building type based on the level of renovation, Figure 13 shows the results for district heating, while Figure 14 shows for individual oil and heat pump heated buildings.

First, it is clear from the comparison that the individually heated buildings are almost exclusively single-family houses and farmhouses. In the district heating area, the type of buildings is much more diverse. The potential for saving energy is largely split between apartment buildings and single-family houses, with some amount of savings achievable in schools, universities, offices and terrace houses. Apartments and offices together account for almost 33% of the feasible potential for heat savings. It should also be noted that, even though the district heating is in denser urban areas with a more diverse building stock, 33% of the heat savings potential is still in single-family buildings.

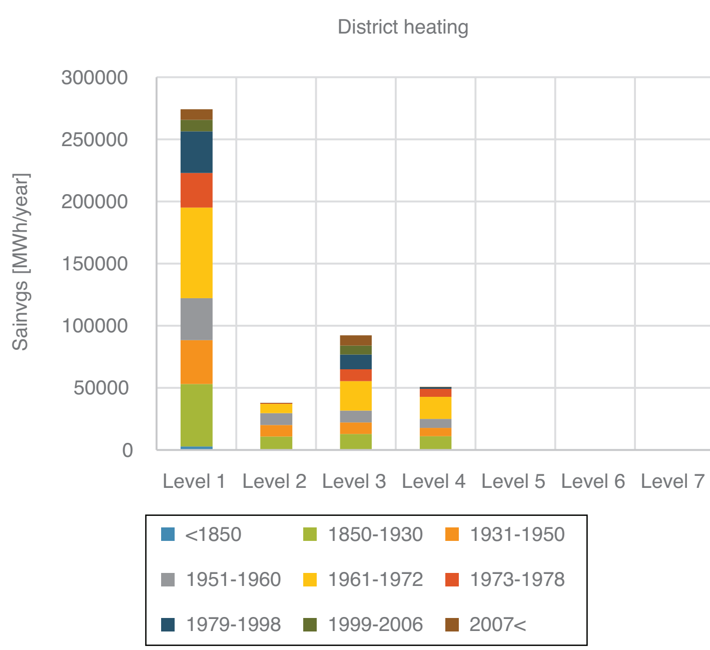

Figure 11: Heat savings by construction year for buildings using district heating

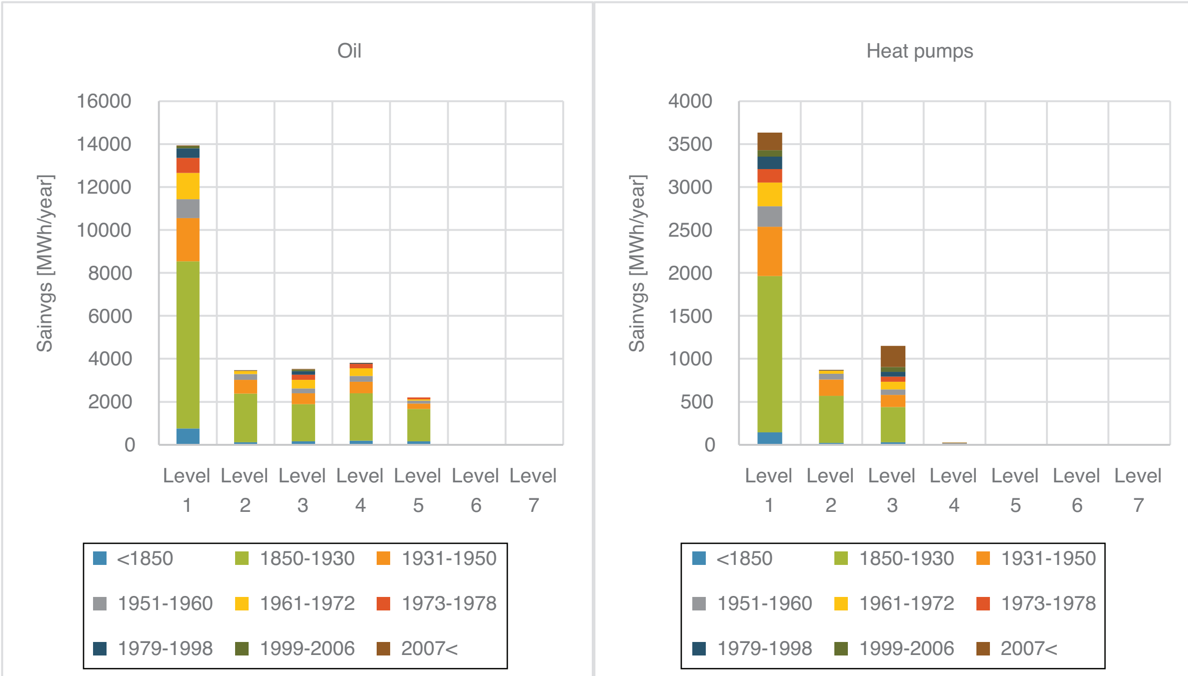

Figure 12: Heat savings by construction year for buildings using oil and heat pumps

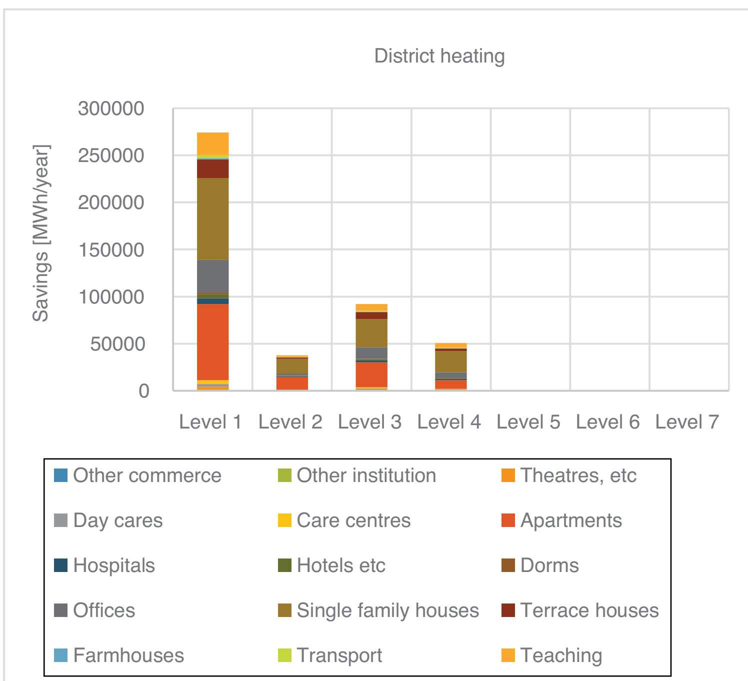

Figure 13: Heat savings by building type for district heating

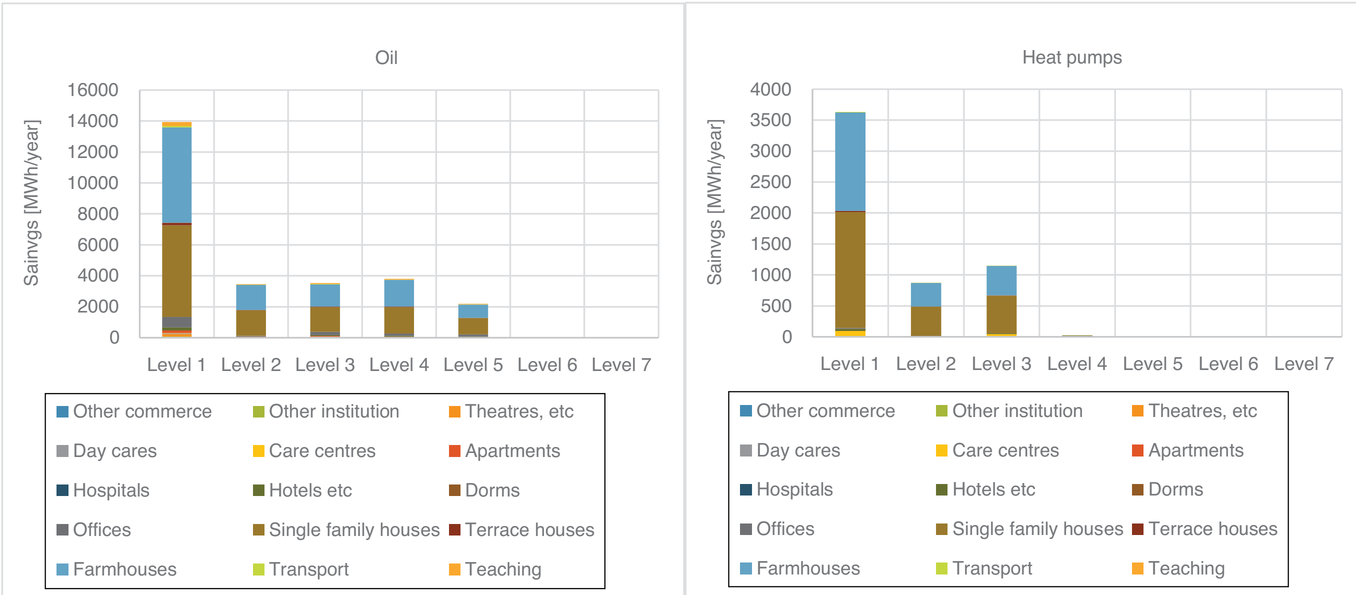

Figure 14: Heat savings by building type for oil and heat pumps

5. Discussion

Usually, the detailed building level perspective is only used for specific buildings and not on a municipality scale. With this type of detailed analysis on a municipal scale, it is possible to provide insights into the costs difference of end-use heat savings in relation to both the type of buildings and the heat supply. Another strength of the methodology is that it examines energy savings at an aggregated level for district heating, where the savings in individual buildings influence the production costs of the system, which again is valuable information from a planning perspective. In the analysis, the focus is on the feasibility of savings with the current heat supply, however, the analysis could also be expanded to look at future renewable energy systems. Overall, with the suggested approach it becomes possible to identify feasible levels of heat savings in buildings on a concrete level, and considering the specific supply system.

It is, however, possible to further the analysis, as some generalisations have been made. This is mainly due to the simplifications necessary when analysing the buildings of a whole municipality. One of these simplifications is that even though the data is presented at a building level, both the heat consumption and the renovation costs are based on averages for the building classifications. It would be more precise if the heat consumption and costs collected specifically for each building. However, this type of data is not available on the scale of this analysis. The data used for the current end use heat demands in the buildings are based on a statistical model of measured data from the supply companies. As such, this model is best in the building categories, where much data is available, which is also why the analysis only focuses on some building types. Thus, the heat saving potential in the municipality could be higher if other buildings were included. Similarly, the model used for the heat savings estimates only deals with specific types of savings, where other types of saving measures are not present e.g. mechanical ventilation or A+ windows. Including more types of saving measures could potentially increase the feasible saving potential, while on the other hand these might be more expensive than the ones already included. Thus, the results do depend on what energy savings are seen as part as the general refurbishment and what are extra initiatives. On the more technical side, some parts of the system are not adjusted when implementing the heat savings, e.g. introducing a higher co-efficiency of performance for heat pumps. The same could be said for the district heating systems, where lower building temperatures, potentially reduce network losses, increase supply efficiencies and enable lower temperature heat sources as part of the supply.

Another important aspect in the analysis, is that all the costs used are socio-economic costs, where the current tax and tariff systems are neglected. In other words, the analysis does not look at the conditions for the individual building owner, and the saving measures that are feasible in this analysis are not necessarily feasible in a private economic context. Also, the building owner gets additional benefits of improving the energy efficiency of the building, such as improved comfort, indoor climate and a higher property value, which has not been included in this analysis. This is a crucial aspect towards implementation, as both taxes, subsidies and tariff structure can have a significant impact on the feasibility for the individual building owner. Another relevant topic related to the feasibility of heat savings, could be related to the ownership of the buildings [62], which is only indirectly touched upon, by looking at building types. Typically, it is easier to implement heat savings in buildings with only a single owner, as this owner will get the full benefit of the heat saving measures. However, in other cases, e.g. in some social housing projects, it is actually a benefit that the owner can renovate larger building blocks with feasible loaning options available, as opposed to privately owned multi-storey buildings without the same options. This becomes relevant as a large part of the savings potential in the district heating area is found in apartments.

6. Conclusion

With the focus on the importance of energy efficiency in buildings in relation to the renewable energy transition, and the availability of more detailed data on both building demands and energy efficiency measures, this article focuses on developing a new method for analysing the heat demands in a regional context. The article uses the Danish municipality of Aalborg as a point of departure. The article uses the Danish Heat Atlas, which includes building level information, to estimate the heat saving potentials as well as the cost for seven different heat saving levels, for the whole municipality. The levels of savings used are:

1. Basic renovation (building code)
2. Cavity wall insulation
3. Windows (A level)
4. Insulation of ceiling and roofs
5. Good practice for insulation
6. Energy saving focus when insulating
7. Level 6 fully implemented

The saving costs are further compared to the supply costs, which are modelled in the hourly energy system analysis tool EnergyPLAN. In the analysis, buildings with the same supply costs are aggregated together and the feasible point between energy efficiency measures and supply is found. The analysis only focuses on energy efficiency measures in six building types, but to find the supply costs of district heating, the energy demand from other building types are included in the analysis.

The overall result shows that a demand reduction of 30% in district heating, 35% for heat pumps and 37% for oil, for the examined buildings, are feasible. Furthermore, it shows that Level 1 and 3 savings are feasible in almost all buildings, while Level 2, 4 and 5 are mainly feasible in buildings older than 1973. Buildings of this age and older are also the ones with the largest efficiency potential energy wise. For district heating it is feasible to go to Level 4 energy savings, while for the buildings with oil-boilers, it is feasible to go to Level 5 savings and for heat pumps it is only feasible to go to Level 3. For buildings older than 1930, efficiency measures to Level 5 is relevant, no matter if the supply is heat pump or oil, however, the buildings supplied by oil boilers would probably be better off changing supply. In addition, there is a difference between the building types of the district heating and the individual heating, where the district heating area has a substantial share of offices and apartments, the individual heating is mainly in single-family building and farm houses [42].

The article shows an example of Aalborg Municipality, but using the same methodology in other places would most likely show that it is very important to be able to distinguish different building and supply types, when assessing the level of heat savings that should be implemented as the renovation decisions have to be made on the individual household level and we need to support them with the correct information. It is important to note, that this article is based on socio-economic costs, and that it would be necessary to supplement it with private economic analysis, to determine if the savings measures are feasible in a given setting.

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