Use of Danish Heat Atlas and energy system models for exploring renewable energy scenarios

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ABSTRACT

In the past four decades following the global oil crisis in 1973, Denmark has implemented remarkable changes in its energy sector, mainly due to energy conservation measures on the demand side and energy efficiency improvements on the supply side. Nowadays the optimal expansion of district heating networks in relation with significant heat saving measures that are capital intensive infrastructure investments require highly detailed decision - support tools. The Heat Atlas for Denmark provides a highly detailed database and includes heat demand and possible heat savings for about 2.5 million buildings with associated costs included. Energy systems modelling tools that incorporate economic, environmental, energy and engineering analysis of future energy systems are considered crucial for quantitative assessment of transitional scenarios towards future milestones, such as (i) EU 2020 goals of reducing greenhouse gas emissions, increasing share of renewable energy and improving energy efficiency and (ii) Denmark's 2050 goals of covering entire energy supply by renewable energy. Optimization and simulation energy system models are currently used in Denmark. The present paper tends to provide a comprehensive insight into the use of the Heat Atlas for Denmark in recent studies dealing with municipal strategic energy planning and main scientific papers addressing those issues. A literature review of current advancements and discoveries in linking the Heat Atlas and energy system models will be presented, while special attention will be given to treating competing investments between heat supply and savings using optimization models. Main scientific contributors, their methodologies and areas for future research will be identified.

KEYWORDS

energy system models; GIS; heat savings; district heating; heat atlas; demand and supply

INTRODUCTION

Before 1973, the time of first oil crises, Denmark was totally dependent on imported oil, with oil making for 92 percentage of total primary energy consumption. Almost entire transportation sector and residential heating was oil-based, while share of oil in electricity production was 78 percentages; the rest of electricity production was based on coal [1]. Sudden rise in oil prices forced Danish authorities to pursue different energy planning

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strategies than just building new production, transmission and distribution facilities and thus serving consumption that was increasing from year to year.
Denmark drastically changed appearance of its energy system during past decades – total primary energy supply remained unchanged while total energy used for heating buildings was reduced by 26%. In the same time period, total heated area grew up for more than 50 % [2]. This is done by constantly improving energy efficiency and introducing energy saving measures. Energy efficiency is mainly affected by large number of CHPs (Combined Heat and Power) in the system, which are using waste heat from electricity production as a heating source for residential buildings or industrial processes. Energy savings in buildings are achieved by using materials with smaller heat conductivity, mainly in building envelope. Along with reducing primary energy consumption and fighting the issue of resource depletion, energy savings and efficiency measures have decreased harmful environmental impact of energy systems. Also, use of oil for covering heat demand is reduced from more than 90% in 1972 to about 10% in 2011, thus improving security of energy supply and making complete energy system less prone to changes in oil prices.

Environmental impact of improved energy efficiency is even more evident when considering current Danish heating system: 52 % of total net heat demand in Denmark is covered by district heating, of which 76 % is produced in CHPs [1, 3]. One third of energy produced in CHP processes in 2007 was based on renewable energy [4] - this fact shows how the environmental impact is reduced by the use of CHPs and district heating technologies. In line with this, in 2008, Denmark, as one of EU members adopted long term targets in area of renewable energy and energy efficiency: 1) 20 % reduction in emission of greenhouse gasses by 2020 compared with 1990, 2) by 2020, 20% of final energy demand should be covered by renewable energy, such as wind, solar and geothermal energy and 3) 20 % reduction in total energy consumption by improving energy efficiency in whole chain production-transmission-distribution-end-use compared to business-as-usual scenario. Denmark went even further with renewable energy targets, setting the 2020 goal for share of renewable energy in final energy demand to 30% [5].

Although it is possible to see energy from many different sides, such as environmental, technical, technological, economical or behavioural, every segment of energy flow from production to end-use is spatially distributed and thus geographical in nature. Plants that produce energy can be described by its efficiency, type and amount of fuel used, maximum output and many more and put into the spatial context by assigning spatial coordinates. The same stands for other elements of energy systems, such as sources of energy, transmission and distribution facilities and consumers, such as households and industry - unique spatial coordinates could be assigned to all these elements. Spatial nature of energy systems is especially underlined in case of changes in the collective heat supply, such as expansion of district heating or the implementation of significant heat saving measures. Then, answers to spatial related questions, such as 'Where are existing DH areas?', 'How far away are these houses from existing DH areas?' or 'What is heat density inside this area?' represent starting point in energy system analysis.

Spatial aspect of energy planning played an important role in transition of Denmark's energy system from polluting and inefficient imported-oil based to modern, efficient energy system primarily based on renewable energy, CHPs and district heating. The first major policy statement was published in 1976 by Ministry of Trade and it declared aims for Danish energy policy. Energy efficiency was addressed by use of CHPs and district heating, energy savings by improving insulation on houses, while dependency on imported fuels was addressed by switching to use of coal, renewable energy, natural gas and nuclear power. Ideas about using nuclear power were abandoned later. Heat Supply Act, passed in 1979, required that communes, in cooperation with regional public utility companies, map present and future energy needs at the local level on the basis of small heat districts, the so called energy districts. A national, geo-based system for energy planning was created – information about number of houses supplied by different fuels and supply technologies was easily accessible. Then, on basis of energy districts, counties drew up heat supply plans for the county, which had to contain fuels that will be prioritised in the future, locations of future investment in collective heating and locations of specific activities that are producing or consuming large quantities of heat. For newly developed areas a collective heat supply was prescribed. Later, each commune had to draw up its own heating plan in agreement with the counties' heating plan [4]. Creation of heat plans and delineation of energy districts denoted beginning of regional energy planning. In the same time, due to geographical nature of energy districts, same process could be interpreted as first use of spatial decision support tool, a heat atlas. In 1970's and 1980's heat atlases were based on hand drawn paper maps, while in 1990's it started being incorporated in computerised GIS software. Today, heat atlas can be seen as highly precise, data-intensive decision support tool that provides huge possibilities for data storage, analysis and visualisation.

DANISH HEAT ATLAS

Current paper tends to describe a heat atlas developed at Aalborg University and presented in [3]. It is designed as File Geodatabase in ESRI's ArcGIS 10 software. This software has been chosen, because it is capable of efficiently storing and operating huge datasets and it offers variety of analytical tools and good connectivity.

The heat atlas contains spatially referenced data for about 2.5 million buildings in Denmark. Each building is represented as single point within GIS software. Heat supply data include heat installations (individual boilers, heat pumps, district heating), fuel used in individual heating (natural gas, wood chips, straw, etc.) and means of supplementary heating. Also not-energy related data, such as building age and type, heated area, conservation status, region, address, commune, postal and parish code, etc. are included in heat atlas and comprise a sound basis for computation of specific building parameters using empirical formulas. Further socio-economic parameters, such as level of income, education, property value, number of inhabitants or similar could be included in the future [4]. Even when taking issues of privacy into account, these data are publicly available with high resolution. With all-time progress of computer hardware and GIS software, storing and operating huge amount of data doesn't seem to be a problem either, but problem seems to be on empirical side. Heated area of buildings, age and type accompanied with empirical data about specific heat losses and domestic hot water consumption are used in spread sheet model developed by Wittchen [7] to calculate net heat demand for total of 175 types of residential buildings. Another approach, developed by Næeraa and Karlsson [8] is used for calculating net heat demands in commercial and public buildings. Net heat demand calculated in Heat Atlas was adjusted to Danish Energy Statistics data [1] and validated in study Heat Plan for Denmark [9]. It surely isn't matter of coincidence that GIS based heat atlas of such high detail was created for Denmark. Denmark has a relatively small population of around 5.5 million and about 2.5 million buildings. In the same time, highly developed statistical office (Danish Statistics) keeps track on people's residence, age, income, education or employment while national register of buildings and dwellings (BBR) maintains records about physical properties of buildings, their age, area and many more. Thus, publicly kept registers with high level of detail, containing data specified by geography, along with big experience in using heat supply plans, comprise a solid fundament for creation of GIS based decision-support tool – a heat atlas.

GIS BASED HEAT ATLAS FOR CALCULATIONS OF DISTRICT HEATING EXPANSION AND HEAT SAVINGS

Relation between heat savings and DH expansion

Idea behind heat atlas, process of creation and applicability of heat atlas are described in [3]. Potential for analysis of heat saving measures and expansion of district heating networks are underlined as two main fields where this model can deliver a sound information base. Especially, heat atlas can be used for data storage and analysis of heat saving measures in areas with CO_2 intensive energy sources and for analysis of advanced heating technologies inside DH areas. In contrast with opinions that heat savings will reduce competiveness of district heating, there are multiple studies that claim that energy savings in buildings and industry, expansion of district heating in energy dense areas, introduction of 4^{th} generation of district heating with lower supply and return temperatures and use of heat pumps in individual areas represent optimal path towards renewable and sustainable energy targets. In following studies, heat atlas methodology is used for analysing technical, environmental and economic impact of heat savings and district heating expansion.

Moller and Lund [4] conclude that it is socio – economically feasible to expand district heating to somewhere in between 50% and 70%, mostly within energy dense areas such as towns and cities, and thus reduce CO2 emissions and fuel consumption. Scenarios with and without reduction in energy consumption in buildings were examined. Person and Werner [10] have calculated district heating distribution capital costs for European cities of various characteristics, sizes and heat demands and concluded that district heating can be expanded up to 60% at relatively low socio – economic costs. They also find the most suitable conditions for district heating within large cities and in inner city areas. However, they claim that district heating will lose competiveness in low heat density areas. Although heat atlas for Denmark isn't directly used in this paper, heat atlas methodology is applied. Lund at al. [11] describe district heating as technology that should be gradually expanded and accompanied by heat pumps in low energy areas, today as well as in future 100 % renewable energy systems. Sperling and Möller [12] have investigated short term ("transitional") energy scenarios for local energy system of Frederikshavn, where they assumed shares of district heating up to 92%, while in the same time investing in heat savings. In this study, data about building stock contained in heat atlas were adjusted to match local conditions. This was done by adjusting heat demand for normal degree days for Northern Denmark, comparing fuel types used for heating with local utility company and natural gas provider and comparing type of heat installation with local chimney sweeper data. Nielsen and Moller [13] went even one step further in describing future relation between district heating systems and heat savings in building stock by exploring NZEBs, buildings with small annual consumption of around 33 kWh/m^2 and similar amount of energy produced during summer months. They have concluded that NZEBs can benefit DH systems by substituting for production from combustible fuels, especially after adding seasonal heat storage in areas where excess heat from renewable sources is produced during summer months.

Calculation of costs of DH expansion

District heating is seen as very popular type of heating in Denmark and was covering 48 % of final energy consumption for space heating in 2011. Most of DH is produced in cogeneration plants, mainly from renewably sources, which significantly reduces environmental effects of heat production while improving overall efficiency. Main advantages of district heating in future Danish energy system that will be totally based on renewables are:

- Possibility of using waste heat with large scale heat pumps, solar thermal and geothermal plants to utilise excess electricity production form wind power. Wind power is expected to play major role in Danish energy system, as 50% of electricity needs should be produced from wind power by year 2020. This way district heating system will add flexibility to overall energy system.
- Capability of utilising waste heat from various sources, such as industrial and waste incineration facilities and power stations. Also, when coal and oil fired power plants switch to biogas and biomass, district heating systems will continue to utilise waste heat without need for expensive mechanical alterations.

Main disadvantages of district heating will be overcome on the road towards completely renewable energy systems:

- High investment costs will be partially compensated by using waste energy from various processes which is free of charge. High initial costs of district heating alternative will also be reduced by avoiding investments in individual heating equipment.
- Significant heat losses will be reduced by switching to low-temperature district heating with supply temperatures of around 55 °C and return temperatures of 35°C, along with reducing space heating demand.

If technical potential for expanding district heating is considered, it is possible to cover 100 % of heat demand with district heating. Economically feasible potential is lower, even when it is seen from socio-economic point of view. When private economical perspective is applied, economic feasibility might be further reduced. As mentioned earlier, after looking from socio – economic perspective, it is found that DH has potential of covering 55 [14] to 70 % [11] on national scale and even up to 92 % on local scale [12].

Due the major significance for current and future power system, research project related to Fourth Generation District Heating Technologies and Systems Research Centre was dealing with calculations of costs of expanding district heating systems and thereby separating economic from technical potential. Both authors of the current paper were involved in the project. Heat atlas methodology was applied and appropriate GIS analysis tools available in ArcGIS 10.1 were used. Costs of connecting all buildings within district heating (DH) areas, Next-to-DH and Individual areas with individual heat supply to DH networks have been calculated by using following procedure:

1. Layer containing boundaries of cities and towns is imported into ArcGIS.
2. Buildings that are connected to DH networks are grouped into polygons, called DH areas. Buildings that are not connected to DH systems and are geographically located within cities or towns are grouped into polygons called Next-to-DH areas. Buildings that are not connected to DH systems and aren't located within boundaries of cities are grouped in polygons called Individual areas.
3. Each DH and each Individual area had position of their centroid calculated. The distances from centroids of Individual areas to centroids of nearest DH areas were

measured. Distances from Individual to DH areas represent decisive parameter that determines costs transmission infrastructure. In this step, Individual areas are divided by total heat demand and placed into 9 groups. Each group was assigned different value for specific costs of transmission infrastructure (in millions of DKK per km).

4. Area (in km^2) is calculated for previously created Individual and Next-to-DH areas. After that, specific costs of distribution infrastructure (in millions of DKK per km^2) are assigned to every of these areas.
5. All buildings spatially located within 3 types of areas are divided into 3 groups (Small, Medium and Large buildings) based on their calculated annual heat demand (in MWh annually). Number of buildings within each group is counted and costs of connecting pipes and heat exchangers are assigned to each group of buildings.
6. Investment costs of connecting certain areas to existing district heating infrastructure are calculated using following expression:

$$C = C_{TR} + C_{DIST} + C_{CONN} = c_{TR} \cdot d_{DH-IND} + c_{DIST} \cdot A + \\ + (c_{CONN,s} + c_{HE,s}) \cdot n_s + (c_{CONN,m} + c_{HE,m}) \cdot n_m + (c_{CONN,l} + c_{HE,l}) \cdot n_l \quad (1)$$

where used symbols have following meaning:

C – Total investment costs of connecting one area to existing DH system; in case of DH areas these are the costs of switching all buildings inside DH area to district heating.

C_{TR}, C_{DIST}, C_{CONN} - Costs of transmission, distribution and connection infrastructure for all buildings in specific area within 3 groups of areas, respectively.

c_{TR} – Specific costs of district heating transmission infrastructure in $\frac{mill\ DKK}{km}$; c_{TR} is dependent of heat demand that is supplied by specific transmission line.

c_{DIST} – Specific costs of district heating distribution infrastructure in $\frac{mill\ DKK}{km^2}$.

A – Area of specific Next-to-DH or Individual area in km^2,

$c_{CONN,s}$, $c_{HE,s}$, $c_{CONN,m}$, $c_{HE,m}$, $c_{CONN,l}$, $c_{HE,l}$ – costs of connecting pipes and heat exchangers for small, medium and large buildings in $10^3 \frac{DKK}{building}$, respectively.

d_{DH-IND} – Straight-line distance between centroid of one Individual area and nearest centroid of one district heating area.

n_s, n_m, n_l – Number of small, medium and large buildings within one geographical area.

As can be seen from expression (1), division of areas by their position relative to previously defined DH areas on DH, Next-to-DH and Individual areas reflect physical and economical nature of district heating expansion:

- In order to expand DH to buildings within DH areas, investments in connecting pipes and heat exchangers must be made, as transmission and distribution infrastructure already exists in these areas.
- Expansion of DH into Next-to-DH areas, which are sharing a border with DH areas, needs to be accompanied with investments in distribution and connection infrastructure, including heat exchangers. It is assumed that transmission infrastructure already exists in the close vicinity of Not DH areas and that these investments are not needed.
- Investment costs for expanding DH into Individual areas are composed of costs for transmission, distribution and connection infrastructure and heat exchangers, since

there is no existing infrastructure that could be used to supply these areas with district heat.

Investment costs of expanding DH are calculated for each area and presented in Figure 1. Costs were discounted with 3 % interest rate over 30 year period, as recommended in [15,16]. It can be observed from Figure 1 that the highest socio-economic potential for DH expansion lies within already existing DH areas, usually towns and cities, where transmission and distribution infrastructure already exist. It is more expensive to expand district heating to neighbouring areas, as distribution infrastructure is needed. These areas have highest technical potential, but big part of that potential comes with a price greater than 0.1 DKK/kWh, the price needed to connect 95 % of all DH areas. Parts of technical potential were omitted from the figure 1 in order to make all curves fit same scale of magnitude. Buildings within Individual areas have high technical but low socio - economic potential, due to high investment costs of transmission infrastructure. It is most likely that these areas will remain supplied by individual means of heating and this is where heat pumps as efficient and environmentally friendly source of heating could prove to be very effective, especially with increasing amount of wind energy in Danish energy system.

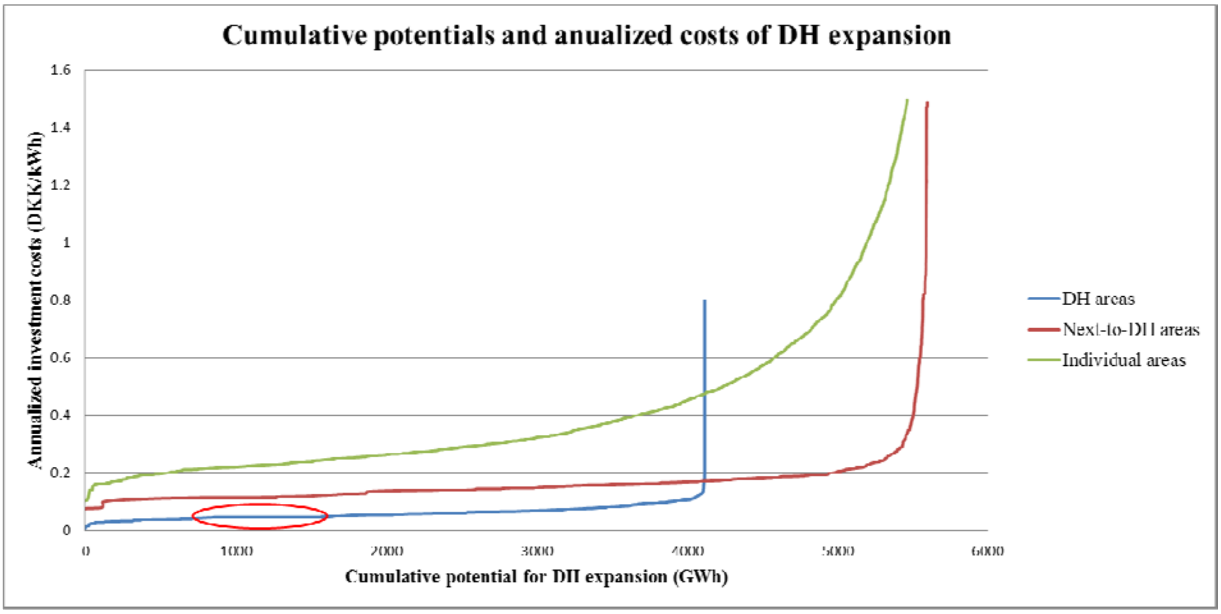

Figure 1. Cumulative potential for expansion of district heating and associated annualized investment costs

In order to highlight level of detail provided by heat atlas, part of the curve that represents Copenhagen-Frederiksberg DH area in Figure 1 is circled in red and data about buildings inside the area is presented in Table 1.

Table 1. Number and properties of buildings in Copenhagen-Frederiksberg district heating area

size	range ($\frac{MWh}{year}$)	number of buildings	total heated area (1000 m^2)	total heat demand (GWh)	average annualized costs of connection (DKK/kWh)
Large	0-50	278	1519.8	189.5	0.076
Medium	50-350	2067	2088.5	272.4	0.008
Small	>350	14430	1722.5	241.7	0.023

High-detail spatial database of heat atlas was already been used for examining socio-economic feasibility of expanding DH in previous studies [4, 11, 14]. The difference with this approach is that DH areas, which have the biggest potential to be fully converted to district heating, are formed within GIS software and haven't been taken from administrative databases. Using administratively created DH areas could be a potential source of two types of errors: administrative databases could be outdated, which means that DH has already been expanded to certain area, but that wasn't recorded in heat supply plans; administrative databases could contain areas designated as future DH area, but it possible that DH was never physically expanded to that region.

Although used approach geographically clearly defines areas and costs of connecting them to DH, there is still room for refinement of this method:

- Distances d_{DH-IND} are measured using Near tool in ArcGIS and represent straight line distances. As this length represents length of supposed transmission pipeline, it would be good addition to introduce a coefficient greater than or equal to 1 that will multiply measured distance to include differences in terrain that supposed pipeline will pass through. Introduction of this coefficient will increase expenses of expansion of DH systems to Individual areas.
- Results of this analysis provide costs of connecting all buildings inside one area to district heating. Of course that it's possible that not all buildings inside one area will decide to do the same. Based on equation (1), cost of connecting single building within DH area to DH grid doesn't depend on number of buildings that will connect. On the other hand, cost of connecting single building within Next-to-DH and Individual areas is greatly increased with decrease in total number of connecting buildings. Graph presented in Figure 2 represents this fact for Individual areas – the smaller number of buildings dividing the costs of transmission and distribution infrastructure, the bigger average costs are for buildings that are connecting. Building-level detail provided by heat atlas gives possibility to include each building separately in equation (1) and thus calculate connection costs per building for any combination of buildings within certain area.
- Certain buildings are characterized as DH supplied, but on the map these appear as an "island" of DH users, usually as group of 5 to 20 buildings. After projecting plants from Energy Producers Count [17] on the map within ArcGIS, it has been noted that there is no plant in close vicinity of these buildings. It is likely that these buildings are supplied by "Blokvarme", small engines usually placed within one of buildings. In reality it is not possible to connect to these in the same way as to other DH systems. The solution could be to identify and group these areas into separate group from DH areas and thus forbid ArcGIS software to measure distance to these areas. Due to current lack of valid data, this effect is left for further examination.

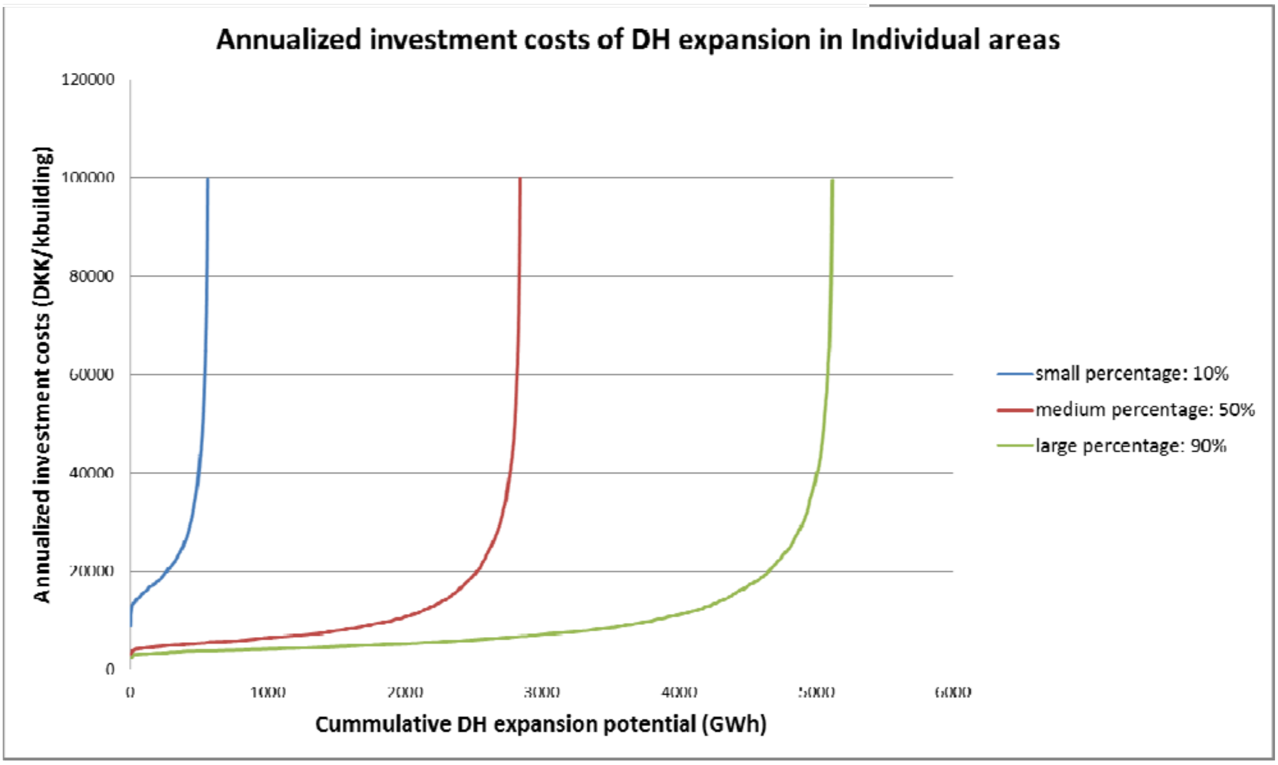

Figure 2. Annualized investment costs for different shares of buildings connecting to district heating within Individual areas

Heat savings in existing and new buildings

As mentioned earlier, Denmark successfully followed the road from dependency on imported oil towards self-sufficiency in terms of energy supply by following two main directions: energy savings and efficiency improvements. Energy savings are mainly addressed by reducing energy demand in building environment. In 2011, gross heat consumption for space heating amounted to around 202 PJ, which corresponds to approximately one third of final energy consumption in Denmark in the same year. Despite significant heat demand reductions through successful saving policies and regulations, this amount of energy still represents large part of total demand and thus a potential for demand reduction measures. Net zero energy buildings with total heat demand of around 33 $\frac{kWh}{m^2}$ of heated area (with domestic hot water making more than half of demand), described in [13] could serve as indicator how far we could go with heat savings. The aim of this section is show how heat atlas accompanied with simple physical model of building's thermal characteristics can be used for answering questions such as "How big are heat losses in specific building?", "How much energy can be saved by replacing windows in specific area?", or "How much would it costs to save specific amount of energy within certain area in East Denmark?".

Simple physical model is used for calculating heat demand, possible heat savings and associated costs [18]. Heat demand in single building, which represents smallest entity contained in Heat Atlas, can be described by following equation:

$$H_{dem} = H_{env} + H_{ven} + H_{dhw} - H_{sol} - H_{int}, \quad (2)$$

where used symbols have following meaning:

H_{dem} – Total demand for heat inside single building that should be covered by heat source.
H_{env} – Heat loss through different elements of building envelope, such as windows, walls, floors, roofs and doors.
H_{ven} – Heat losses caused by ventilation.
H_{dhw} – Heat demand needed for domestic hot water preparation.
H_{sol} – Solar heat gains caused by solar radiation entering through windows.
H_{int} – Internal heat gains as a result of waste heat produced by electrical appliances and heat produced by human bodies.

H_{env} is a consequence of building elements' property to transfer heat from warmer to colder place and is directly proportional to heat transfer coefficient (u values), temperature difference between warmer and colder place and size of transmitting surface. It is assumed that heat savings or reduction of heat loss through different elements of building envelope are achieved by replacing building elements with new elements with lower u values, as can be seen from following equation:

$$SAV_{env} = \sum_m \sum_{elem} \left(u_{elem}{}^{old} - u_{elem}{}^{new} \right) \cdot A \cdot f_{elem} \cdot \left(t^{ind} - t_m^{out} \right) \cdot d_m \cdot k_{24} \cdot k_{elem}{}^{t} \quad (3)$$

where used symbols have following meaning:

m – Months of year.
Elem – elements of building envelope: walls, floors, windows, roofs.
$u_{elem}{}^{old}$, $u_{elem}{}^{new}$ – heat transfer coefficient of specific building's envelope elements before and after renovation (in $\frac{W}{m^2 \cdot K}$)
A – Heated area of building (in m^2), obtained from Heat Atlas [3].
$f_{elem} = \frac{A_{elem}}{A}$ – Coefficient that relates area of specific element of building envelope with heated area of building [8, 19].
t^{ind} - Indoor temperature, assumed to be 20 ˚C.
t_m^{out} - Outdoor temperature in month m.
d_m – Number of heated days in month m.
k_{24}=0.024 – Constant used as multiplier with 24 (hours in one day) and divider by 1000 (Wh in one kWh).
$k_{elem}{}^{t}$ – Correction factor that takes into account that floor is conducting heat to area with temperature greater than t_m^{out} [20].

H_{ven} is a result of natural ventilation or mechanical ventilation without heat recovery. In that case, efficiency of heat recovery, $\eta_{old} = 0$. It is assumed that reduction of ventilation heat losses is achieved by installing ventilation systems with heat recovery that have efficiency of heat recovery of $\eta_{new} = 0.9$:

$$SAV_{vent} = \sum_m \eta_{new} \cdot 0.34 \cdot n \cdot H \cdot A \cdot \left(t^{ind} - t_m^{out} \right) \cdot d_m \cdot k_{24} \quad (4)$$

where $n(h^{-1})$ represents air exchange rate and H(m) represents average room height. Exact numerical values for n and H are obtained from [21].
Reduction of heat losses are calculated using equations (3) and (4), but not all losses are covered by heat supply, some are covered by solar and internal heat gains. Share of heat savings that is covered by heat supply can be calculated as:

$$SAV_{env,supply} = S \cdot SAV_{env} \quad (5)$$
$$SAV_{vent,supply} = S \cdot SAV_{vent} \quad (5'')$$

where $S = \frac{H_{env}+H_{ven}-H_{sol}-H_{int}}{H_{env}+H_{ven}} = \frac{H_{dem}-H_{dhw}}{H_{env}+H_{ven}}$ represents share of heat losses that is covered by additional heat supply to a building (district heating, gas , electric heating, etc,…) and is different for buildings built in 7 analysed time periods [22].

When heat savings are accomplished, reductions in heat supply occur, as described in (5') and (5"). For each heat saving measure (replacement windows, improving insulation on floors, roofs, walls, introducing mechanical ventilation systems with heat recovery) marginal and full costs per m^2 of building element are used for different levels of heat savings [21, 23]. In total, 10 different levels of heat savings are assumed – 3 for improving insulation on floors and walls, 2 for replacing low energy efficient windows and 1 for insulating floor and installing ventilation systems with heat recovery. Marginal costs are used if heat savings are implemented when buildings are subjected to scheduled renovation and reflect additional expenses of heat saving measures. In case of building's renovation is done solely with aim of saving energy, than full costs are considered. Calculated costs are annualised with 3 % socio-economic interest rate over lifetimes obtained from [20, 23] – 40 years for roofs, floors and roofs, 30 years ventilation systems and 20 years for windows. Ventilation systems have also O&M costs assigned.

Results of calculation of cumulative heat saving potentials and additional marginal costs are presented in Figure 3 for Copenhagen – Frederiksberg DH area, the same area circled in red in Figure 1.

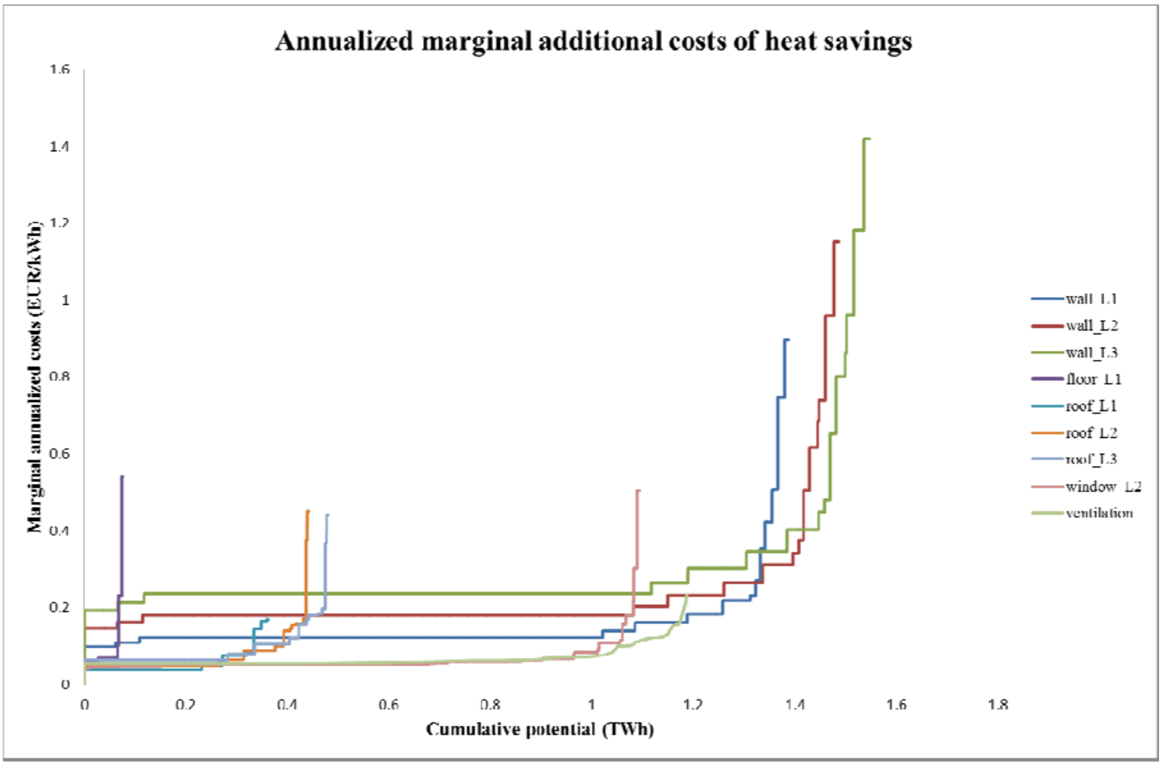

Figure 3. Cumulative heat saving potential and associated marginal annualized costs for different heat saving technologies

Due to procedure for creating DH areas, Copenhagen – Frederiksberg DH area is somewhat different than actual administrative area. Costs are called additional marginal because they are additional and marginal for 2 reasons: they are expressing additional costs of heat savings while scheduled maintenance is taking place, while in the same time denoting price of additional saved kWh. If heat saving potentials and associated costs aren't disaggregated by used technology, than curve presented in Figure 4 is obtained.

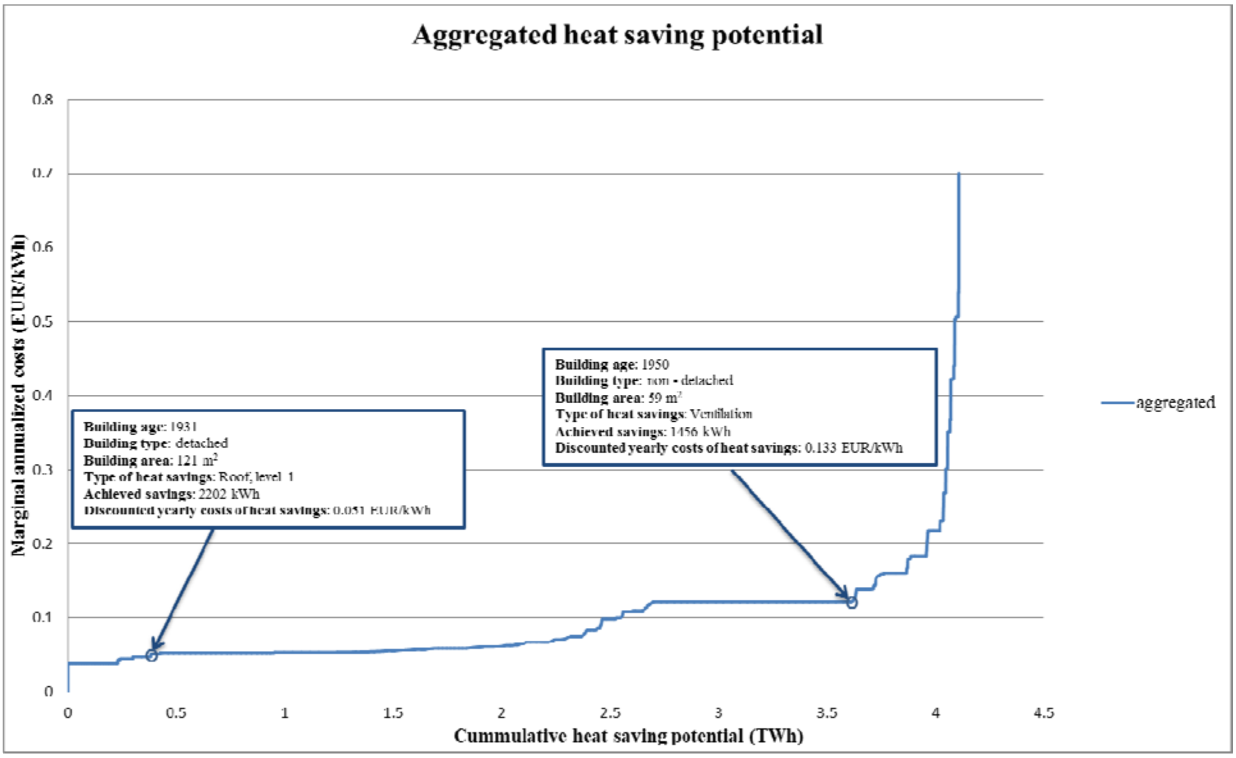

Figure 4. Cumulative heat saving potential and associated marginal annualized costs for different heat saving technologies aggregated into single curve

Highly-detailed and data-intensive spatial database, which serves as the foundation for heat atlas, is considered crucial for calculations of potentials for heat savings and associated costs. Heat Atlas contains, among others, information about buildings' spatial coordinates, age, heated area and building type. These information are used in the following way:

- Buildings' type is used to divide buildings into 5 type-groups: farmhouses, multi-storey, detached, non-detached, and public/office buildings.
- Buildings' age is used to group buildings into 7 age-groups.
- Each building had a value for $u_{elem}{}^{old}$, f_{elem} and $n(h^{-1})$ assigned depending on which type and age group specific building is belonging to; these variables are mentioned in equations (3) and (4)
- Values for S used in equations (5') and (5") are assigned to buildings according to age group that they are belonging to.
- Heated area of buildings, $A(m^2)$ is used directly for calculating heat saving in equations (3) and (4).
- A number of factors used for calculating H_{sol} and H_{int} had values assigned according to membership to one of age or type groups.
- Coordinates of buildings are used for visualising of results; as an example, Figure 5 shows selected multi-storey buildings in Copenhagen-Frederiksberg DH area with

annualized marginal costs of second level heat savings in windows less than 0.05 EUR/kWh.

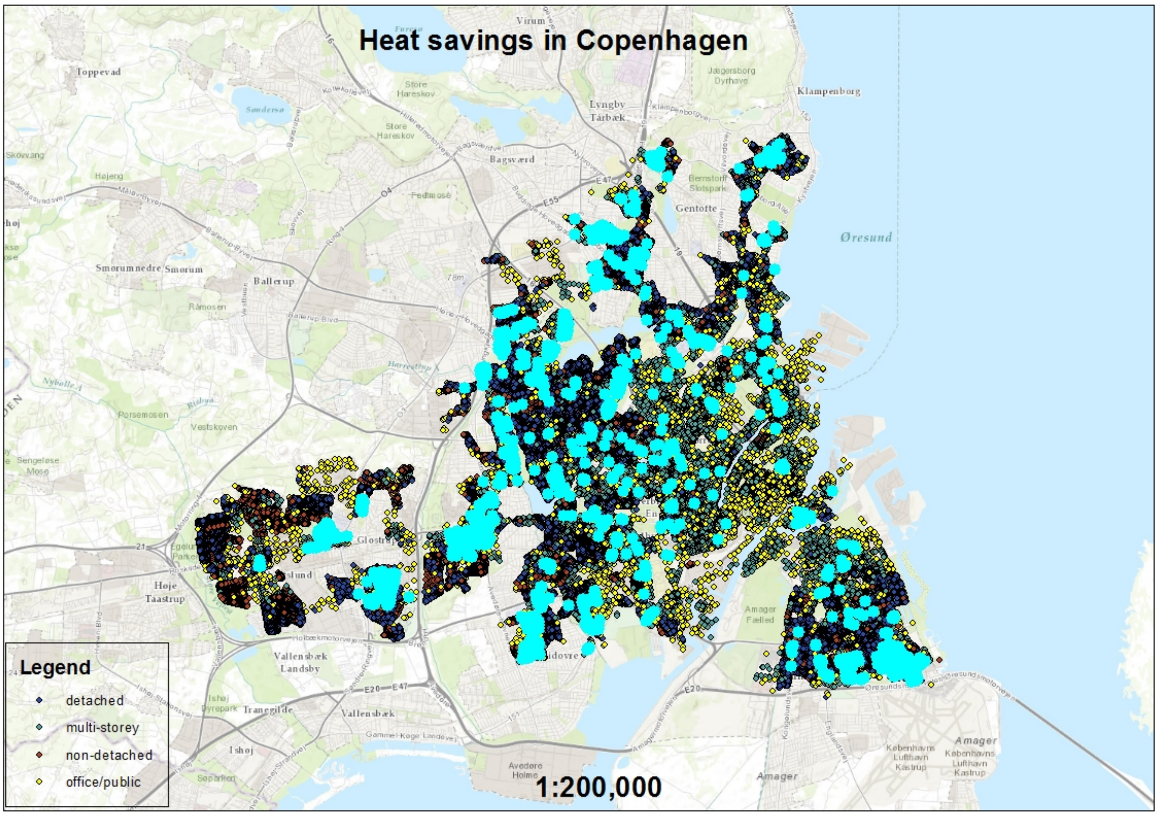

Figure 5. Selected (light blue) buildings in Copenhagen – Frederiksberg district heating area have annualised marginal costs of second level heat savings in windows less than 0.05 EUR/kWh

Lack of reliable data about air ventilation systems in public/office buildings, especially about efficiency of heat recovery, has caused these buildings to be omitted from calculations of heat savings in ventilation. Also, effect of heat savings by improving insulation in floors has been calculated only for buildings with cellar. Level 1 heat savings in windows were omitted from Figure 3, because it is assumed that these heat savings have marginal price of 0 - these will be done when scheduled renovation takes place. Process of grouping 35 types of buildings originally contained in Heat Atlas into 5 groups made spread sheet calculation of heat savings computationally less difficult, but has resulted in the fact that some buildings are omitted from consideration. However, in case of GIS created Copenhagen-Frederiksberg DH area, buildings not being subjected to calculation account for about 9 % of buildings and about 7 % of total heated area, which doesn't bring substantial inaccuracies to results.

Curves presented in Figures 3 and 4 represent good addition to heat atlas and can serve as a good approximation of reality for wider geographical region or whole Denmark or as a first estimate for smaller geographical region. However, these costs are calculated from a system perspective and annualized using 3% socio-economic interest rate, which could be a problem in some cases. It could be a case that in buildings with high u values, where significant heat savings could be achieved, it is not feasible from private economic perspective. Buildings with high u values have poor energy standards, what is usually related with low property value. Further on, low property value is usually related with low income of building's inhabitants, which makes investments in heat savings impossible, even though they are socio-economically cost-effective. To confirm or disprove this relation between possibility for heat savings, property value and earnings of its inhabitants, data about later two would comprise valuable addition to Heat Atlas. It would be ideal for understanding of this phenomenon to analyse the data on single building level, but privacy issues could comprise a firm obstacle in getting access to these data. However, data averaged inside 1 km square would also make valuable addition for further research without compromising privacy of inhabitants, even inside areas with low population density.

Ownership of buildings is also one of social parameters that should be included in Heat Atlas, as it could possibly become a substantial barrier in achieving significant energy savings [3]. For example, if heat prices are to be elevated in order to promote heat savings, this will usually be passed over to tenants, without efficiency improvements and reduced environmental impacts. Policy makers would greatly benefit from such addition, as this would give them an opportunity to explore spatial aspects of their policies; for example, it would be possible to analyse whether to promote (or not to promote) loans with lower interest rates for installing energy efficient windows for multi-storey buildings built before 1973 where over 95 % of inhabitants are also owners of apartments in certain neighbourhood in coastal area of West Denmark.

Heat atlas as basis for energy system models

Highly detailed database of physical building characteristics contained in heat atlas comprises a solid foundation for calculating heat demand and possible heat savings. Location of each building relative to heat supply technologies is used for the assessment of heat supply strategies by potentials, costs and environmental consequences. Thus, heat atlas can be used as a tool for distinguishing between theoretical, technical, purely economical and economical potential when environmental and political constraints are taken into account. It is able to represent increasing costs of utilising next portion of energy, the marginal costs, as presented in Figures 3 and 4. These curves are continual; they have no breaks, seen from mathematical not geographical point of view. Mathematical continuity means that function describing costs has no breaks and gives valid results for any valid input parameters, while geographical continuity implies that there is no "wholes" in representing space, there are no buildings, cities or geographical areas left out. This fact also reflects important geographical aspect of renewable energy systems: energy resources, demand and supply are geographically distributed, this being the reason way spatially continual model is needed to mark the parts of these resources by technical, environmental and economic constraints.

Important property of heat atlas that goes hand-in-hand with calculating marginal cost curves is use of heat atlas' outputs as inputs to energy system analysis models. Beside costs, heat atlas is also capable of delivering information to energy system analysis models about amount of available resources and impacts of used energy technologies.

Energy system analysis models can be seen as computer tools for exploring scenarios, preferably renewable energy scenarios. For given inputs, such as current consumption and export/import of electricity and heat, projections of future consumption and associated costs, amount of available resources and similar, models optimize energy systems by finding the best "mix" of technologies to satisfy demand for each discrete time step during the given period, taking availability of resources into account. The optimizing is done by minimizing sum of operation and investment costs, while satisfying all technical and non-technical constraints. Technical constraints mean that power system should work with high levels of safety and reliability. The best example of non – technical constraint is Danish goal of being fossil fuel free apart from transport sector by 2025 – even though coal power plant could be the cheapest technology to invest in 2025 even when taxes on coal are taken into account and there is still enough resources, models won't base their future energy supply on coal, because it's use is constrained in the model.

There are 2 main types of energy system analysis models used in Denmark in recent years: optimization and simulation models. For given curves describing marginal costs of utilising certain technology, optimization models are finding "optimal mix" for each period within analysed time frame. Simulation models depend on experts' best guess which technology will be used in the future and in what amount. As an example, input to optimization model could contain marginal costs of utilising a solar resource by installing PVs, along with prices of solid and liquid fuels and competing technologies and amount of available resources. In this case, model will decide how big part of solar resource should be utilised from socio-economic point of view. On the other hand, utilisation of solar resource will be given as input to simulation energy system models; in other words, experience, vision and great knowledge of experts making analysis with these models substitute for optimisation procedure done in optimisation models. This claim can be well observed by looking at main representatives of two types of models used in Denmark when identical task is put in front of them – discover role of district heating in future Danish renewable energy system. Balmorel [24], as a representative of optimisation energy system models is used in [14], while EnergyPlan [25] was used in [11]. Both approaches agree that thorough energy system analysis is needed to discover optimal role of district heating in future renewable energy system, even though they are exploring different time frames – year 2025 in the first and year 2060 in the second paper. In both papers, heat atlas is used to identify potential scenarios and associated costs of expanding DH, while energy system analysis tools are used for modelling current and future Danish energy system. The main difference between two approaches is that optimization model Balmorel chooses investment strategies in order to minimize the sum of operation and investment costs, while in simulation model Energy PLAN investments are fed in as exogenous inputs; 10 different heating technologies are compared. This is the reason why outputs from Balmorel can claim optimality, while EnergyPLAN's outputs rely on experts' vision of future energy system and can only claim to be a proper framework for analysing whether current opinions about district heating will be accurate in the future. Despite differences, results from both models conclude that gradual expansion of district heating in areas with high heat density, heat pumps in low density areas along with heat savings in buildings are important components of future energy system.

Beside creating and storing marginal cost-curves, GIS-based heat atlas can serve another role, as a data container. In the process of creating a Danish version of TIMES energy system model, data contained in heat atlas are directly used to input data into household module. All buildings are divided into 240 groups depending on age when buildings were built, type of buildings, geographical and DH areas in Denmark where buildings are located and type of heating being used. Sum of calculated heat demands and heated areas within each of these groups of buildings is imported into the model and will serve for describing the base year. In order to account for buildings that will be built in the future, 120 groups of "New buildings" are created. Because of that, model will be able to distinguish buildings built, for example in 1963 and 2015, even though they belong to same geographical area and have the same use. Since inputs to the model and outputs from the TIMES energy system model doesn't have the same aggregated form, it is not possible to directly input outputs from the model into Heat Atlas, but an disaggregation procedure for converting aggregated outputs from energy models into heat atlas should be addressed within further research. Even in the aggregated form, results from energy system models can be spatially referenced and projected in GIS software or imported as separate layer into heat atlas.

Visualizing outputs from energy system analysis models could be seen as another major benefit of GIS based heat atlas. Main inputs into previously mentioned energy model Balmorel are capacities of existing electricity and heat generation units, electrical power transmission capacities, heat and electricity demand, accompanied with fuel prices, CO2 costs, policies and taxes. Main outputs are productions, transmissions and demands for electricity and heat, fuels used and emissions. Both heat and power sector are geographically referenced. Heat sector is divided both by geographical location and technology used to produce heat. Information about which buildings are connected to district heating grids and their heat demand is also contained in heat atlas; registered production from heat plants and district heating grid they are delivering heat to is contained in [17]. Analysis of spatial distribution of heat power plants and their annual production led to the conclusion which building is supplied from which heat power plant. Later, unique relation between district heating grid and geographically referenced heating areas is used to place each building within one district heating area (Balmorel area). Geographical appearance of district heating areas in Balmorel is shown in Figure 6. Due to high number of areas, only areas in East Denmark are presented. When outputs from the model are calculated, it is possible to present them in geographical manner.

Room for improvement of heat atlas

GIS based heat atlas proved to be very useful tool for supporting planning of energy systems, especially in areas of heat savings in buildings and expansion of district heating systems. It contains large amount of spatially referenced data about building stock and population, which are part of extensive public registers that are being kept in Denmark. Measuring distances and densities and overlaying layers on top of each other are done with ease in heat atlas, while it is much more difficult to do it in any other way. Although it can serve well as a data container, heat atlas has possibilities for successful data retrieval and analysis. It works well with energy system analysis tools, by serving as a pre-analysis tool as well as for visually representing results. Despite all that, there is still room improvement of heat atlas – improving level of details of current data, improving models of heat savings and district heating expansion, adding new types of data and making automatic connection between heat atlas and energy models:

- More detailed values for u, f and t^{ind} used in equation (3) depending on age, use, type of heating and geographical location instead of values representing national averages will give more accuracy to results.
- Adding social parameters, such as population age and density and type of building to empirical model will yield better representation of domestic hot water consumption; currently heat demand for domestic hot water preparation is based on national average of 800 $\frac{kWh}{cap \cdot year}$. Work presented in [26, 27] could possibly serve as solution.
- Data about measured heat demand would be a good addition to heat atlas and will eliminate any uncertainties with regard to accuracy of calculated heat demands, which match reality on national but not always on local level.

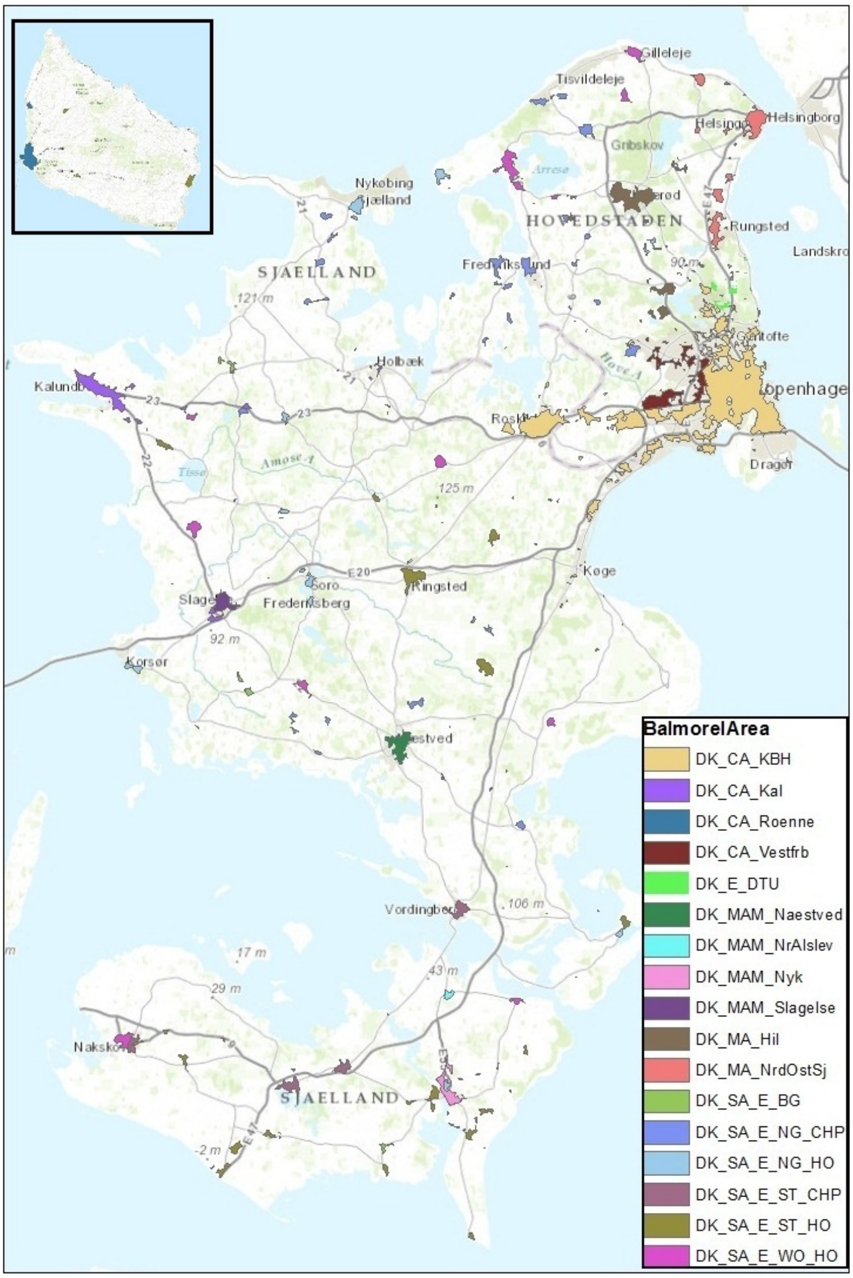

Figure 6. District heating areas in East Denmark suitable for representing results from Balmorel

- Information about ownership, average income, property value, level of education would provide possibilities to investigate energy end-use and possibilities for analysis of heat saving investments on more detailed level.
- Incorporation of industrial consumers into models, especially ones that are currently seen as consumers but actually produce large amounts of waste heat, would yield much better representation of energy system.
- Adding geographical data about solar, wind, biomass or geothermal resources, power, gas and electricity transmission lines and generation facilities would strengthen the role of heat atlas as a data storage for energy system analysis models; this atlas would contain much more than just heat related data, so it could be called Energy Atlas.

- Creating standard input and output forms in order to facilitate better communication (fully or partly automatic) between heat atlas (or energy atlas) and energy system modelling tools.

CONCLUSION

This paper addressed the issue of heat atlas for modelling of Danish energy system on its way towards 100 % renewable energy future. First, transition of Danish energy system from inefficient imported oil-based to efficient renewable energy based was put into historical context. Extensive use of CHPs and introduction of heat saving measures in building stock have been identified as main contributors to the transition. Importance of continuous geographical mapping of demand and supply was denoted as important precondition for energy planning on municipal level. Development of heat atlases from paper based maps to modern GIS-integrated software tool was described. This paper then gave detailed description of heat atlas developed at Aalborg University and presented in [3], its functionality and contained elements. Expansion of district heating systems and heat saving measures in building stock are presented as competing trends that will both be present in future renewable energy system. Emphasis is put on spatially explicit analyses that produce cumulative potentials and marginal costs as output from the analysis. Examples of marginal costs calculation are shown for Copenhagen – Frederiksberg district heating area and put within general idea of this paper. Analytical models used for these calculations were presented in compact form, while underlining high level of detail provided by heat atlas. Use of heat atlas with energy system analysis tools was investigated and it was concluded that it can serve in multiple roles – as data-container, pre-analysis tool or as tool for spatially presenting results from analysis. Similarities and distinctions between simulation and optimization energy system models were underlined based on two studies of district heating expansion; heat atlas was extensively used for spatial analysis in both studies. Finally, it has been discussed how heat atlas could be improved – how heat saving model in heat atlas can be expanded and refined, current data made more detailed, new thematic layers added and connection with energy models established.

To conclude, heat atlas for Denmark has proven to be useful tool for strategic energy planning on national, regional and local level. Although it can serve multiple roles, strategic energy planning can't be based solely on heat atlas. In order to fulfil all aspects of energy planning, such as economic, environmental, energy and temporal aspects, heat atlas is often paired with energy system analysis tools. Joint analyses of this type give the possibility of perceiving future Danish energy system in the light of taken actions. Outputs from these analyses are providing answers to fundamental questions of the kind "What will happen to our energy system if we undertake these actions?" and "What actions to take to achieve optimal energy system?".

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