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High resolution heat atlases for demand and supply mapping

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ABSTRACT

Significant reductions of heat demand, low-carbon and renewable energy sources, and district heating are key elements in 100% renewable energy systems. Appraisal of district heating along with energy efficient buildings and individual heat supply requires a geographical representation of heat demand, energy efficiency and energy supply. The present paper describes a Heat Atlas built around a spatial database using geographical information systems (GIS). The present atlas allows for per-building calculations of potentials and costs of energy savings, connectivity to existing district heat, and current heat supply and demand. For the entire building mass a conclusive link is established between the built environment and its heat supply. The expansion of district heating; the interconnection of distributed district heating systems; or the question whether to invest in ultra-efficient buildings with individual supply, or in collective heating using renewable energy for heating the current building stock, can be based on improved data.

Keywords:

Energy planning,
GIS,
heat demand,
district heating

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1. Introduction:

Renewable energy systems, based on 100% renewable energy sources such as wind, solar, biomass and geothermal, are an essential element of major strategies for the future Danish energy system by the middle of the century [1]. Most studies agree that the fluctuation of renewable energy, as well as the geographical limits of its use, pose major difficulties and make such systems economically challenging, technically demanding, and politically difficult. Hence, such energy systems need to be innovative in several ways. It is likewise accepted that the capability to incorporate higher shares of renewable energy is system dependent: nuclear energy and other "base load" electricity producing technologies reduce the ability to incorporate temporally variable wind energy; and geothermal heat sources may be severely limited by geology and the scale of operation, making them feasible to use only in centralised district heating networks. Similar technical, spatial and temporal nexuses between energy sources, energy supply and the final energy consumers can be found elsewhere in current and future energy systems.

Several studies [2, 3, 4] conclude that technologies are required that temporally separate production and consumption of energy to increase the share of temporally variable renewable energy sources. Such technologies are heat storages in combined heat and power (CHP) plants, large-scale heat pumps installed at CHP plants, or electrolysis plants to produce hydrogen. In future energy systems there is a need and a benefit to incorporate the transport sector as well [5]. Common to all these proposed technologies is that they, rather than aiming at the intricate storage of electricity, seek to

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convert excess electricity to easier storable heat at sufficient amounts, as heat storage losses are reduced with increasing volumes. This however requires that consumers of heat share a common heat distribution network. District heating therefore may be a prerequisite for larger shares of fluctuating renewable sources in national energy systems [6].

Thus addressing the matter of renewable energy sources and efficient energy supply, a 100% renewable energy system also is characterised by end-use efficiency [7]. This is imperative because renewable energy sources are limited and associated with higher production costs compared to known fossil technologies. Furthermore, efficient supply systems such as district heating require considerable investments in infrastructure. Energy efficient buildings therefore can save valuable renewable sources, save infrastructure costs, and reduce efforts needed to balance demand and production, while maintaining or even increasing comfort levels [8].

While the past decades have seen marginal developments in the fields of all three energy system subsystems: sources, supply and end-use, radical steps are required to achieve 100% renewable energy systems. A complete rebuilding of regional, national and global energy systems is without precedence and hard to imagine today. All our empirical knowledge of renewable energy systems relies on marginal, incremental steps. On the other hand, investments into energy systems are long term. Decentralised energy technologies may have a lifetime of 20 years, large-scale power utilities of 20–50 years, while the building stock may last for 50–100 years at least.

About 40% of energy end-use is found in the building stock. Its location is a result of the way human settlements are organised. It is a consequence of the geographical distribution on economic activity through times, and it determinant for other elements of the energy system such as the demand for mobility and transport. History, accessibility and land cost have all influenced the location, spatial distribution and quality in terms of energy of the current building stock, which for the next decades to come comprises the largest resource of energy efficiency gains. Age, use and property value of buildings determine the economic potential for energy savings. Heat demand density and distance to existing infrastructure define the potential for developing district heating. The availability of local renewable energy resources is also given by the local and regional geography. Hence all aspects of renewable energy systems relate to geography.

The spatial nature of renewable energy systems and the need to fundamentally change them with massive investments, new policies and change of behaviour requires geographical methods for their analysis. A geographical system for data storage, retrieval and analysis of location-based information is needed, which allows for getting answers for questions like 'where are buildings with district heating?', 'what is the heat demand within this area?' or 'how far is this area located from a nearby energy plant?' or 'who will be able to invest?'. A possible solution for this is a GIS, which incorporates a spatial database, a set of methods for spatial analysis, as well as the capability of supplementing energy system data with e.g. socio-economic or planning data. As the primary focus is on mapping heat demand and supply, this system is here called a Heat Atlas [9].

Legislation on the European scale [10] and in Denmark [11] clearly states the roles of energy efficiency and efficient heat supply. It is therefore imperative to address heat savings as well as identifying opportunities for district heating.

The objective of this paper is to describe the development of heat atlases in Denmark, which allow for the assessment of efficiency measures in the building mass, the expansion of district heating, and the use of renewable energy sources for existing buildings. These heat atlases are to be used for spatial analyses of the choice between these different efficiency opportunities on the pathway towards 100% renewable, sustainable energy systems. After a historical account for the development of such systems in an energy-political context, the core methods of producing a heat atlas for Denmark are described. Several cases on the national, regional and local scales are referred to, and existing applications for Denmark are presented. The paper intends to describe the development and application of heat atlases in Denmark. Recent research in this field is done for the EU in Connolly *et al.* [12] the USA in Gils *et al.* [13], South Korea in Yeo *et al.* [14] as well as for the UK in Finney *et al.* [15].

2. The history of Heat Atlases in Denmark

The first oil crisis of 1972–1973, together with the UN Conference on the Human Environment (the Stockholm Conference) and its scientific predecessors have triggered the interest in acting on the waste of energy resources, issues of pollution, scarcity and socio-economic risk of the energy system, which at this point was highly reliant on oil, increasingly polluting and progressively less efficient. In Denmark, nearly all the heat supply was based on oil, predominantly oil-based district heating or electric heating using electricity made to 90% from oil. This left the country in a state of crisis and vulnerability: high costs of energy affected households and companies, and a negative currency balance had an impact on socio-economy.

The country subsequently managed to ridden itself partly of its dependency of imported oil; the power and heating sectors being forerunners. The former Ministry of Trade and Commerce published an energy plan in 1976, aiming at nuclear power and the conversion of oil-fired power stations to coal. The heating sector was addressed by the expansion of district heating, which in the larger cities was to be based on the co-generation of heat and power. In the years after this first energy plan, regions and towns began to look into heat planning. With the Heat Supply Act of 1979 a legal basis was laid for municipalities, together with the former counties, to develop heat plans, which describe the heat supply in a given area. Heat plans were to be formulated for given built-up areas, parts of towns or the like, with homogenous building mass and with similar supply opportunities, the so-called energy districts. For each energy district, there was made an account for the buildings located within, their means of heating, as well as their estimated heat demand. A priority heat supply was defined for existing areas, and for newly developed areas a collective heat supply (district heating, later also natural gas) was prescribed. District heating systems had their fuel and technology prescribed by means of these heat plans [16]. Hence, the Heat Supply Act was a rigorous and effective means to create many local monopolies for heat supply, to be utilised by publicly or cooperatively owned district heating companies.

Because of its geographical nature, the heat plans required a spatial basis of information and decision-making, and the phrase Heat Atlas was coined. The early heat atlases were based on paper maps and punch-card registers, and converted into computerised planning tools with the advent of GIS in the 80s. The spatial entities were linked to legally binding planning documents, prepared by the municipalities and reported to the Danish Energy Agency. Each year the heat plans were to be revised [17]. By means of heat planning, based on spatial data and spatial zoning, district heating grew to be the most popular means of heating, which in 2012 covered 50% of the Danish heat demand, connecting 60% of all buildings. In the period from 1972 to 1990, the specific heat demand of the Danish dwelling stock was reduced by 25%, while the fuel demand fell by 29%. The importance of oil in the heat supply shrank from more than 90% to less than 10% today. This had not been possible without the combination of decentralised spatial planning of heat supply using heat atlases; the introduction of stricter building codes; the introduction of energy taxes; as well as the general energy awareness triggered by the oil crises.

Since 1990, however, municipalities were no longer obliged to prepare heat plan documents, but could develop heat supply by means of a project-based negotiation between administration and utility. The liberalisation efforts in the energy sector further reduced interest in heat planning [18], and currently municipalities are left without the means to strategically plan local energy systems. This is critical in a situation, where municipalities become engaged with so-called strategic energy planning, which encompasses the mapping of heat demand and supply. Municipalities currently have no tools to map continuously and coherently at a high geographical resolution the heat demand by supply type, and to assess the potentials of energy efficiency and efficient supply by energy and cost.

The present and future role of district heating and strategic energy planning in the Danish energy system comprises three main aspects: fuel savings, incorporation of fluctuating renewable energies, as well as utilisation of renewable energy sources otherwise out of reach, such as geothermal, waste heat and large scale solar heating [19]. Hence the present paper describes how Heat Atlases can be developed further to meet such challenges, and be applied to meet current and future challenges of strategic energy planning.

3. Materials and methods

3.1. Design principles for a heat atlas for Denmark

Heat atlases must represent the geographical heterogeneity of heat demand and supply. That means, that data must reflect the distribution of real world phenomena such as the spreading of the building stock or the distance to infrastructure. Urban and rural environments grow increasingly diverse, and the boundary between public utilities and individual heating solutions is a matter of metres. A heat atlas must therefore aim for the smallest possible geographical entity, which yields the highest available level of detail: ideally the single building. The single occupied building houses the smallest socio-economic entity to affect energy demand, the household, which also is the broadest basis for decision making on consumption, investment in the building stock, and energy-related behaviour.

Heat atlases must furthermore allow for decisions on “how far to go”, reflecting the significant difference between theoretical, technical, economic and socially or environmentally acceptable potentials of a technology. On a spatially sourced curve of supply costs by supplied amount, each fraction of the potential amount comes at a specific, marginal cost. The heat atlas must be able to represent these marginally increasing costs of utilising a technology in a continuous way, using the marginal costs as a decision parameter. The marginal costs of a resource, however, are not the same for the whole country as potential resources are geographically distributed in space and with different density or availability and therefore different specific costs of utilisation. We consequently must speak of a spatially continuous model, which maps fractions of the total resource base by geographically determined costs, technical constraints, environmental impact or social consequences.

Heat atlases finally must provide a better basis for making energy systems analysis with computer models. This means that the heat atlas must be able to deliver consistent data on the potentials of a resource, its costs and impact. In contrast to most of the newly emerged heat atlases for parts of the UK [20, 21], Germany [22, 23, 24] or even the European level [25, 12], the present heat atlas must contain quantitative data on heat demand and supply in terms of energy and costs, which can be extracted for any geographical or other entity to be used for energy systems analysis.

3.2. Elements of a heat atlas

Heat atlases become very data intensive if they require the single building as the smallest computational and mappable unit. In contrast to most other countries, where data availability is a severe hindrance for bottom-up models of heat demand [26], in Denmark there is a national system of public databases, which describe individual buildings, businesses, agriculture and the civic population using unique address and geographical locators. This greatly facilitates the development of heat atlases, which in most other countries only can be based on aggregated statistics, surveys, aerial imaging or detecting, remote sensing in combination with spatially coarse statistics, census data or even 3D-models of urban areas. Using the national register of buildings and dwellings (BBR), it is possible by address coordinates to locate each individual building by age, use, area, heat demand and supply and up to 60 other individual data. The register is updated daily. In addition, an increasing proportion of Danish buildings have been subject to energy audits in recent years, which can be used to perfect a stratified model of the current and future heat demand. A great challenge however is the accuracy of the BBR, which is based on house owners’ input. It can be observed, e.g. that the number of oil boilers is overestimated by a factor 2, since not all house owners have reported the replacement of such by a biomass boiler or the like. Also, a higher confidence level can be observed for urban areas compared to rural municipalities, which may reflect the effort made in public administration to achieve accurate registers. Another uncertainty is that the heat demand of a building in many cases still needs to be validated using national averages of specific heat demand for types and age classes of buildings, as the reporting of actual heat demand only has been mandatory for a couple of years. These problems are about to be addressed though, as the registration of heating means and annual heat demand improves [27].

Hence comprising an error-prone but possibly the best available basis world-wide for mapping the heat demand for single buildings on a national scale, these large scale empirical and register data need to be organised in a way, which allows access to the smallest entities (the single building) as well as its geographical relation to other phenomena such as district heating networks, energy supply units, local renewable energy sources, or plain administrative units. In other words, a heat atlas must represent the complete supply chain of primary energy to end-use heat demand. This is imperative because buildings of the same characteristics may receive district heating from different sources, or vice versa.

Another central feature of a heat atlas is the ability to carry out spatially explicit analyses for actual locations, for spatial distributions, distance between phenomena or a spatial overlay of occurrences, all at the highest possible degree of detail. Therefore the heat atlas is implemented using GIS databases and technology, where the spatial dimension allows for the location of single entities such as buildings relative to other entities such as infrastructure, administrative or planning zones. This spatial hierarchy in a GIS makes possible to quantify and qualify geographical interaction by means of location, distribution and distance.

Finally, the heat atlas must be able to map costs of heat supply, district heating installations, renewable energy or energy savings. Costs can be defined as direct or marginal costs, as well as operation and investment costs, and should be associated to actual amounts or fractions of resource utilisation. This requires the link between the models that describe the energy performance of buildings with scenarios for efficiency measures and the connection to district heating grids, with economic analysis of these, for individual buildings.

For the present version of the heat atlas, which is version 3.0 after versions 1.0 [9, 28, 29] and 2.0 [8, 30, 31, 32], a BBR extract was purchased for the date 31-12-2012 containing all tables, which can be obtained under a public license. It comprises the largest possible database of the Danish building mass that can be handled outside the public administration system.

3.3. Technical implementation

Technically, the heat atlas has been implemented as an integrated spatial database with associated analysis tools. As software for the GIS database and analysis ESRI's ArcGIS version 10.1 has been chosen, which offers good analytical capabilities and data connectivity [33]. The integrated spatial database is designed using the File Geo-database, which allows for efficient handling of large datasets in the ArcGIS 10.1 environment. An open-GIS interface can be programmed for software like Quantum GIS [34] or MapWindow [35], so that the Heat Atlas can be made available for project partners without means and skills to operate expert GIS.

Various thematic data are contained, such as building points, network lines, and supply or planning areas. For each of these themes there is a geometrical representation (point, line or polygon) as well as associated attribute or descriptive data. The spatial database also comprises a geographical structure by means of hierarchy (administrative or supply boundaries) or by describing vicinity or neighbourhood.

Regular updates are crucial. The updating rate depends on the budget, but yearly updates should be aimed for. The main component is the BBR extract, which comes at a cost of 1,300 €. Other components are either available from the public planning database PlansystemDK [36] or from the National Mapping and Cadastral Agency [37] by means of the Open Data initiative of the Danish Government.

3.3. Modelling heat demand and energy saving potentials

Heat demand is calculated using a typology of the existing building mass [38] prepared by Kragh and Wittchen [39], Wittchen [40] and Nielsen et al. [41]. Each building type by use and age class has a typical specific heat demand and a specific savings potential at a given investment level. The heat demand model used in the heat atlas is based on a top-down distribution of annual heat demand as registered in the national energy statistics [42] to a number of main consumer categories such as households (single and multi-storey buildings) and service (public and private). The further distribution by particular building types and age classes is done using empirical data collected in more than 300,000 building audits. Hereby a general ground proofing of total heat demand as well as heat demand by building categories is made, which however does not include regional and local differences due to climatic as well as socio-economic conditions. Table 1 shows the attribute, or descriptive, data for the basic heat atlas, which describes buildings as points.

4. Validation of the heat atlas by means of actual consumer data

4.1. Means of validation

In several studies the calculated heat atlas data was validated against local statistics, e.g. by means of recorded heat demand data from utilities. The results of these validations were quite different for each of the studied areas. A study carried out for Aalborg municipality [8] found excellent agreement between the heat atlas and the recorded district heat demand in Aalborg for the year 2007, where the difference was a mere 0.3%. A study carried out for the region of Mid-Jutland [43] did however show great differences of calculated and recorded district heating demand for some towns, where calculated district heating demand was up to 40% lower than actual demand. This may have several reasons. Firstly, the BBR data may not have been updated in terms of heat supply installations to buildings, which is typically the case in newly established district heating areas, where house owners show certain inertia in their behaviour while keeping

Table 1: Attribute fields of the Heat Atlas database, their format and brief description. This information is stored for each building point.

Field name	Format	Description
OBJECTID	Object ID	Unique object identificator
Shape	Geometry	Geometry content
x_utm	Long Integer	UTM Easting coordinate [m]
y_utm	Long Integer	UTM Northing coordinate [m]
e_type	Text	Heat demand type identifier
muni	Integer	Municipality code
use	Integer	Building type
build_year	Integer	Year of construction
tot_area	Long Integer	Total heated building area [m2]
heat_inst	Integer	Type of heat installation
heat_means	Integer	Means of heating
cons_code	Text	Building conservation code
suppl_heat	Text	Supplementary means of heating
demand_orig	Integer	Current heat demand [MWh/yr]
demand_50	Integer	Demand for -50% scenario [MWh/yr]
dir_cost_50	Integer	Costs to insulate, -50% scen. [1000 DKK]
margcost_50	Integer	Marginal ins. costs, -50% scen. [1000 DKK]
KOMED	Long Integer	Municipal energy district identifier (old)
HEATPLAN	Long Integer	Municipal heat plan identifier (current)
Region	Text	Regional district code
Cons_cat	Text	Type of consumer
PARISH	Text	Parish district code
KN1 kmDK	Text	Reference to Danish Square Grid, 1 km
Within_urb	Text	Location within/without urban boundaries
Placename	Text	Name of town or city
Within_DH	Boolean	Location within/without town with DH
Post_code	Integer	Postal district code
Post_place	Text	Place name as in postal district
Address	Text	Address text (road name, house number)
Land_parcel	Text	Cadastral land parcel code

public record data updated. Second, socio-economic factors such as income, property values or ownership may influence the specific heat demand for each of the building types, which are based on use and type rather than behavioural factors. Finally, the heat atlas does not include demographical data; hence deviations in the number of people per dwelling area would cause further differences. It shall here be mentioned that the heat atlas based on heat demand calculations can never replicate the heat demand in individual buildings. Studies have shown differences in the recorded heat demand by a factor 10 for exactly the same buildings, which have to be attributed solely to behavioural factors [44].

Earlier studies [45, 28] have indicated that the mean error of calculated heat demand in areas has to do with the type of buildings. Single-family houses, large in number, show the smallest error in average and the highest statistical significance. Public institutions, hotels, industries etc. on the other side, are fewer in numbers and show a greater diversity, hence low statistical significance and high mean error. One would therefore expect that a heat atlas could be improved significantly by adding actual consumption data for large consumers in particular, while the majority of buildings could be represented by a model using averages. This was tested during a study prepared for the municipality of Ballerup in the vicinity of Copenhagen.

4.2. Comparing calculated with recorded heat demand

The 11,000 buildings of Ballerup are primarily heated with individual natural gas; however large consumers increasingly connect to district heating. In order to compare calculated heat demand from the national average model with actual heat demand, data from the natural gas utility HMN and from the district heating utility Vestforbrænding for the year 2009 were collected, geo-referenced to the heat atlas and compared after compensation for deviation for standard climate (5 year moving average) and assuming efficiencies for gas boilers (90% in average). The graphs in figure 1 show the deviation by means of a linear relationship as well as the correlation factor.

While industrial and private service buildings show the best fit on average with only 1% mean error, while heat demand in multi-storey dwellings is underestimated by 15%. Public buildings for research and education show a great underestimation by 50%. The coefficient of correlation R^2 shows that calculated and recorded values correlate reasonably well except for research and education buildings, where correlation was very small, which also could be accounted for the small number of buildings and their great diversity. From this basic comparison we can conclude that: 1) even in a small geographical area the mean error is sufficiently low to assume that calculated heat demand in large industrial, office and hotel buildings is close to reality; 2) heat demand in multi-storey dwellings is underestimated, probably because many of these buildings are poorer energy performers compared to national average and 3) some types of buildings like schools, universities, sports halls, kindergartens and nurseries show great deviations, which require further work. The coefficient of correlation is on a level, which for most buildings can confirm that heat demand is a function of floor area and hence surprisingly simple. This also shows the crucial role of the building typology, which is used to calculate typical heat demand in types of buildings, which in the Danish case represent the use of buildings. The reasons why education and research buildings fail to fit into the typology is probably that the building mass is too diverse here to be represented by a single building type.

As table 2 shows, Ballerup municipality is only partly representative for the Danish building mass, as most of the buildings were built in the 1960 s to 1980 s and older urban and rural buildings in particular are absent. In a few important categories, however, such as detached houses, multi-storey dwellings and industrial buildings, building age and share is comparable, while private service buildings are younger and summer houses are absent in Ballerup municipality. It has to be kept in mind, however, that age is taken into account in the heat

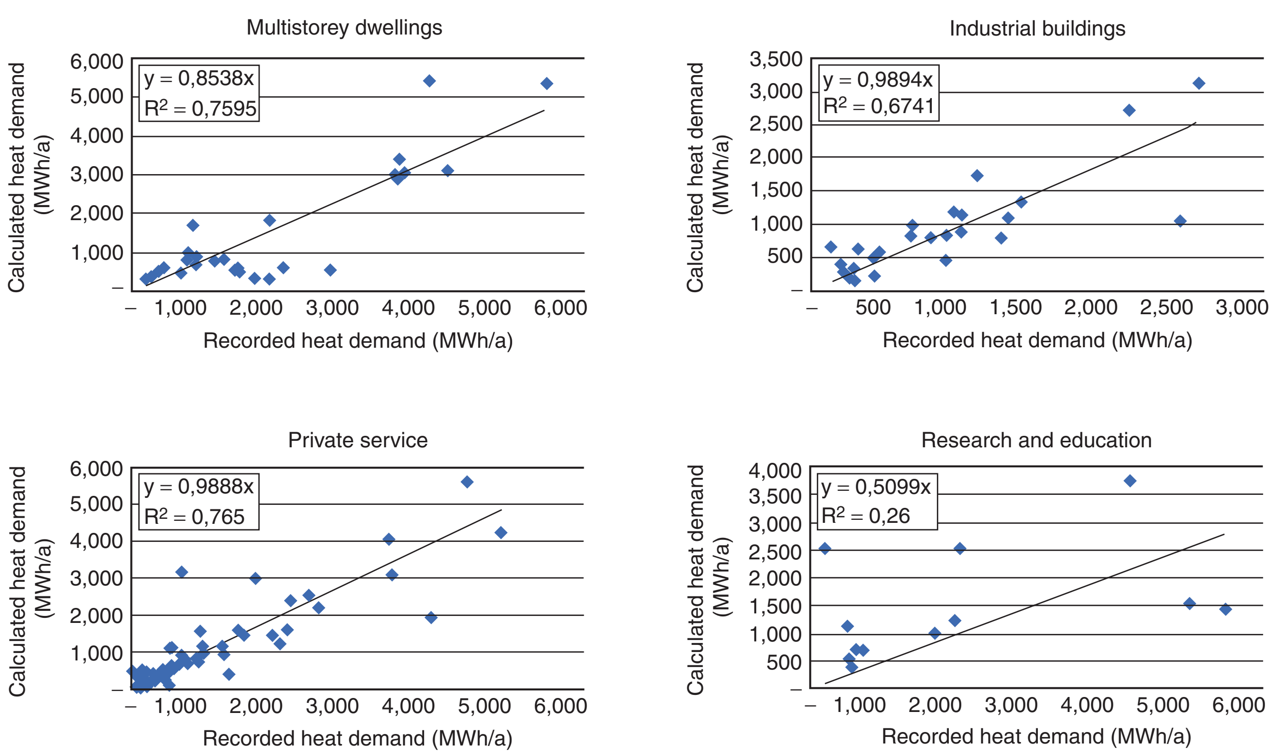

Figure 1: Comparison of calculated and recorded heat demand for large consumers in Ballerup municipality.

Table 2: Age and share of buildings by building type in Ballerup municipality and Denmark as a whole. Only the six most important out of 25 building types are shown.

Bulding type	Ballerup municipality			Denmark		
	Avg. year of constr.	Count	Share	Avg. year of constr.	Count	Share
Detached house	1964	6,381	59.46%	1952	1,075,346	55.11%
Terrace house	1975	1,944	18.12%	1968	228,447	11.71%
Multi-storey dwelling	1968	446	4.16%	1930	88,081	4.51%
Trade and commerce	1971	475	4.43%	1946	57,125	2.93%
Hotel and service	1968	39	0.36%	1939	11,457	0.59%
Education and research	1974	117	1.09%	1955	17,044	0.87%

demand model, and the number of buildings is represented with great accuracy in the heat atlas, which has the single building as the smallest unit.

5. Using the heat atlas database for spatial analysis of heat demand and supply economy

5.1. Inclusion of spatial entities for planning

Spatial entities such as administrative boundaries (regions, municipalities, parishes etc.), zoning (urban planning, heat plans etc.) or other can be added to the Heat Atlas database by means of spatial joins. A spatial join appends descriptive, or attribute, data to a GIS layer based on the location of features relative to another. Two ways of spatial joins are interesting; firstly to join to the Heat Atlas point theme the attributes of a spatial entity, e.g. the name or code of a zone; and secondly, to aggregate the data of all Heat Atlas points within a zone, e.g. the sum of heat demand in all buildings, the major means of heat supply, or the average year of construction. This allows either to incorporate administrative or zoning information to each building, or to summarize data on heat demand and supply within each such zone. A join from a spatial entity to the building point is important for defining the geographical structure of heat demand and supply, so that the supply chain from primary energy to end-use can be mapped for each building, or important planning information, such as the mandatory connection, can be added to data on heat demand and current supply. On the other hand, a join of all building points to spatial entities may be used for mapping at a larger scale, for the production of statistics by area, or for the characterisation of neighbourhoods etc. Both ways, the inclusion of spatial entities by means of attribute transaction adds data content and functionality to the heat atlas database.

5.2. Data retrieval and visualisation

Two of the strengths of GIS are its functionality as a database management system, which can be used to input, manage and retrieve data in various form; as well as the visualisation by means of digital maps. In terms of database management, the heat atlas in its present form is a so-called “flat” database, where all information is stored in a single attribute table, which is linked to a spatial point theme. While input of data is left to the import of large tables rather than inputting data manually, the management of data refers to regular updates, in case new BBR registers are to be incorporated, or new spatial heat planning becomes available, for instance. The remaining important database functionality is data retrieval, which may be used in different ways. First, data can be extracted by means of spatial and non-spatial queries. This may be used to prepare extracts for a given municipality or other geographical entity, or to identify all buildings within a given distance of district heating areas, which also have gas heating. Second, statistical interpretations of larger amounts of data can be made by cross-tabulation, or pivot-tables, after the entire heat atlas database has been exported or linked to a MS Access database or MS Excel spreadsheet; the latter though for a fraction of the total amount of buildings only as Excel only can hold 1,048,576 rows in a single sheet. These pivot tables, see table 3 for an example may be used to e.g. summarize heat demand by municipality as well as by current means of heating, something that is not possible in the national statistics. They may further be used to produce easily accessible representations of the heat atlas data, which, because of the large amount of records and fields, is impossible to grasp at a glance. An important role here is the cross-validation of data.

The map interface and medium allows for visual interpretations of geographical phenomena. There is a large variety of methods in cartography, of which a few

Table 3: A pivot table generated from the Heat Atlas allows for a quick overview to facilitate data validation and data extraction.

Heat Demand in Denmark by heating installation and consumer category [GWh/a]

Heating installation	Total heat demand	Dwellings	Industry	Public service	Trade and commerce
District heating	26,262.914	18,351.199	1,382.982	3,017.657	3,511.076
Central heating	20,527.100	12,636.541	4,462.141	1,243.008	2,185.410
Stoves	929.388	593.653	216.008	40.322	79.405
Heat pumps	330.022	284.023	27.435	6.123	12.441
Large central heating	587.813	432.770	128.713	8.687	17.643
Electric heating	3,451.480	2,903.874	197.300	159.011	191.295
Gas stoves	30.864	10.573	12.930	1.382	5.979

are interesting for visualisation of heat demand. Point data of the heat demand may be aggregated to choropleth maps using administrative or other geographical area units as the defined basis for showing graded colours for properties and quantitative or qualitative phenomena such as heat demand or type of supply. Figure 2 shows an example of average heat saving potentials in Copenhagen, based on data from the heat atlas.

5.3. Generation of cost-supply curves

Cost-supply curves, see figure 3, establish a relation between a quantity and its marginal cost. For any point on the graph the corresponding costs for a given amount can be determined. The main principle of the cost-supply is that in economic theory, the least cost amounts of a commodity are the most attractive, and the actual amount useable is a function of the marginal cost at the

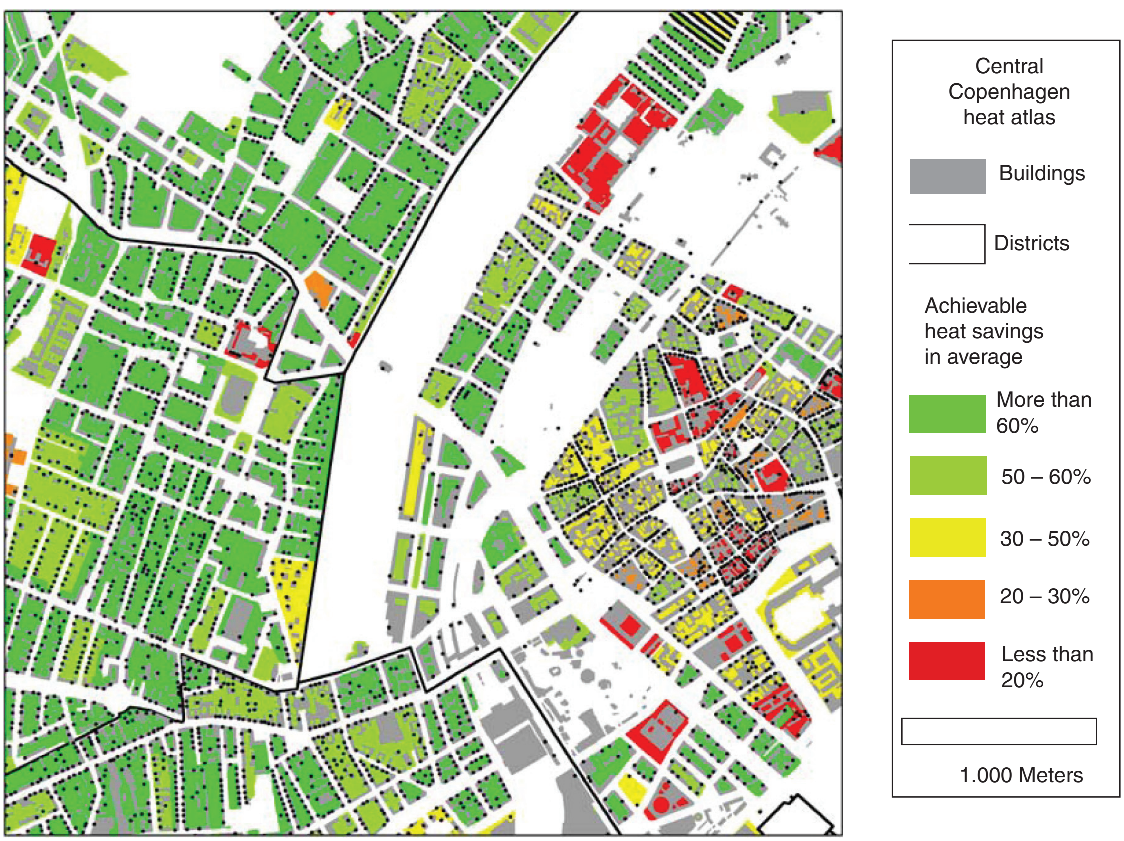

Figure 2: Extract from the heat atlas for Copenhagen, which shows the data basis as points as well as a visualisation of achievable heat savings per building block as a choropleth map.

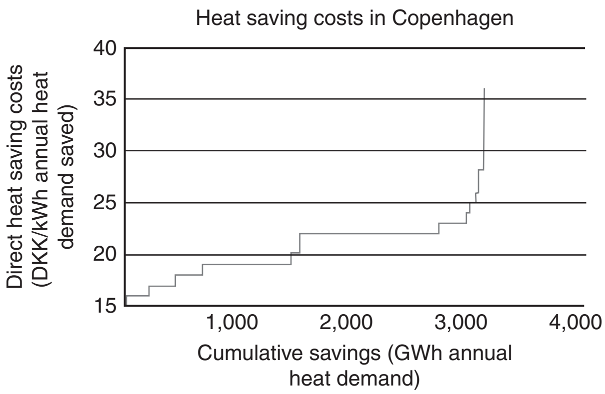

Figure 3: The cost-supply curve relates the marginal costs of supply (in this case heat savings) to the cumulative potential supply. It can be seen that some heat savings can be achieved at low costs, while some may be too costly to be feasible.

intersection between the supply and the demand curves. By organising cost data in such a way, that all costs are sorted from the lowest to the highest, while aggregating the cumulative amounts, a cost-supply curve can be drawn for every commodity, which comes at different costs. In the present context of energy systems this comprises heat demand, potential for district heating, energy savings or renewable energy. The idea is here that one should harvest the potentials by utilising the least cost options first, and only after the exhaustion of a resource priced at this rate, the next instance should be used, as it comes at a higher cost. For spatially distributed resources and costs, the supply or utility curve is a function of the geographical availability and the spatially determined costs. The costs typically follow geographical patterns, such as the development of a city, the urban density, socio-economy or distance to central features. Hence the heat atlas allows for the identification of economically feasible shares of a total potential by cost, amount and location. Further characterisations, e.g. by ownership, current technology or other geographical or statistical units are practical.

Cost-supply curves therefore allow for the identification of the least cost options, the potentials at a given cost level, as well as the separation of the feasible from the non-feasible. If future cost data are available, they may also be used to develop cost-supply curves for the future. Here it is necessary to combine the current cost and potential data with an annual utilisation rate and future costs, both of which can be borrowed from learning curve theory. Future cost-supply curves produced in this manner assume that every year a given quantity of the least cost potentials of a resource are used, at the current cost. The use of the resources results in a quantity, which influences the costs of a given technology e.g. by economy of scale. The depleted resource is excluded from the potential map. It will depend on the depletion rate versus the technological learning efforts whether the costs decline or rise.

Cost-supply or utility curves may be used for system models, which include price elasticity to cater for the fact that resources do not come at the same costs. They may also be used to limit the theoretical potential from a practical potential by excluding the share of resources, which are located after the second cost rise at the far right of the curve.

6. Application of heat atlases in the development of renewable energy systems

6.1. Expansion of DH systems and conversion of natural gas areas

District heating emits now marginally less CO_2 than individual natural gas, and can most often be supplied by existing district heating networks at a lower cost to the consumer. In a project funded by the Danish Board of District Heating, in 2008 Aalborg University and Rambøll engineering consultants prepared a project “Heat Plan Denmark”, which by means of a heat atlas described potentials, costs and the overall feasibility and policy requirements for such a conversion at a massive scale, which could bring the share of district heating from 46% of the net end-use heat demand to 60 – 70%. The study found good feasibility of doing so, and it pointed out possible synergies between modern district heating networks and low-energy buildings [46]. The heat atlas used the existing heat supply areas from former municipal district heat and natural supply planning in combination with a building-sharp heat demand model based on the BBR. Potentials and investment costs of saving 20% and 50% of the current heat demand in average were calculated for each building, leaving newer buildings with lower saving potentials than older. Based on empirical cost data for the expansion of district heating, a cost model for the expansion of district heating systems into neighbouring natural gas areas was developed, separating the economically attractive potentials for new district heating form the larger technical potential [28].

Figure 4 shows an extract of the spatial database developed for the project Heat Plan Denmark. The map

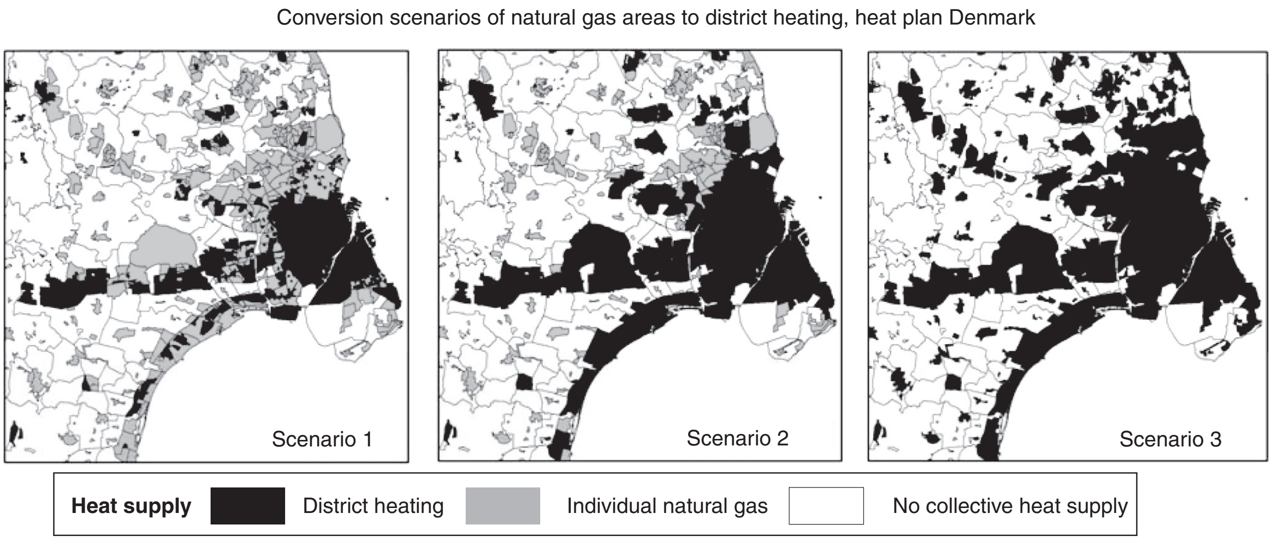

Figure 4: Conversion scenarios for the Copenhagen area, where natural gas areas with individual heat supply by boilers are to be converted to district heating. The map shows the delineation of supply districts. In each district the building mass is described by heat demand, potential savings and the costs to develop district heating.

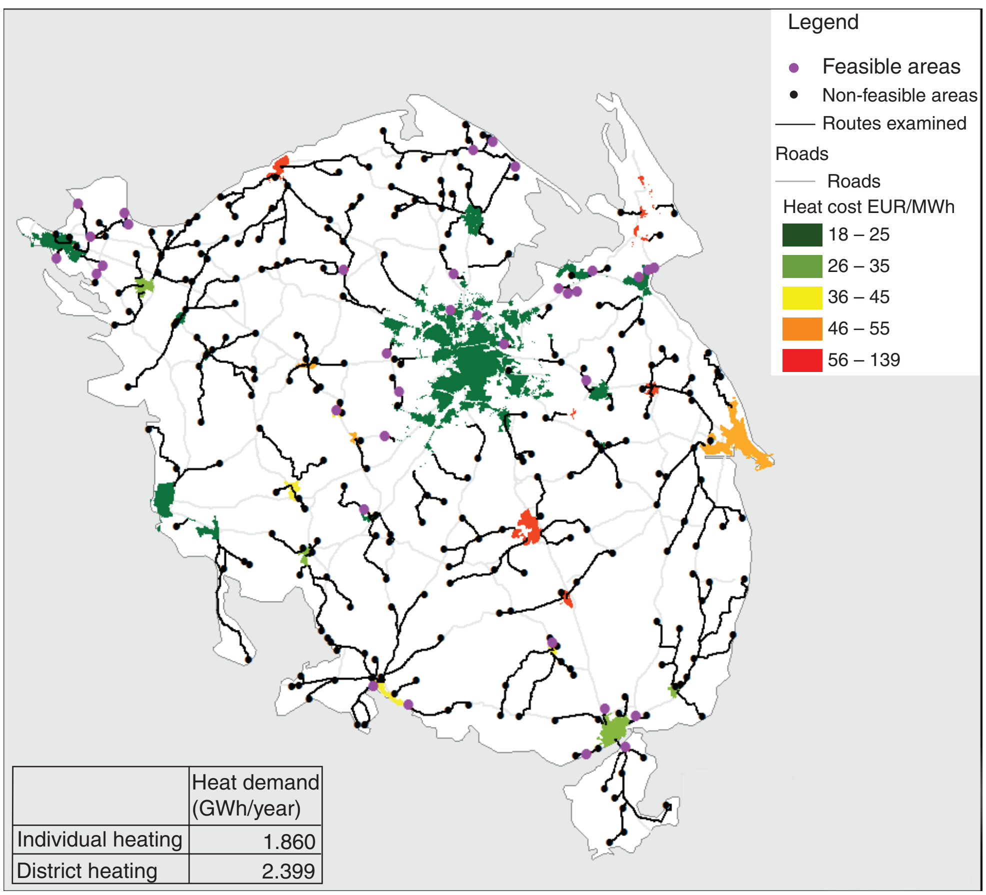

Figure 5: Use of the iterative district heating network model to identify, which new district heating areas could be feasible (purple dots) under heat cost constraints and comparing with individual heat pumps, shown for the island of Funen.

marks the scenarios for the Copenhagen area, where the potential for converting individual natural gas is particularly high. Triggered by the Heat Plan Denmark project many municipalities now desire local heat atlases to facilitate strategic municipal energy planning, which aims at demand, supply and local resources. Østergaard *et al.* [8] and Sperling and Möller [29] are recent examples of using heat atlases for identification of heat demand savings and costs as well as district heat expansion as part of local energy systems based on 100% renewable energy sources.

6.2. Exploration of new DH areas

Although there is barely a town left without district heating in Denmark, and even many villages have their own local heat supply, there might be opportunities to establish new district heating based on low-cost, low-temperature and more efficient technologies [47]. District heat distribution technology has developed significantly with lower specific heat losses in pipes, and lower costs. This may have pushed the frontiers of feasible district heating from the traditional district heating areas into the countryside. A heat atlas, together with suitable design tools, can be used to assess the costs and benefits of such systems: Information on building density, the length of road networks, as well as the distance to existing district heating grids are readily available here to identify the economically feasible potential of developing new district heating.

In order to identify towns and villages that can be connected to existing district heating schemes by means of network extensions, a model has been designed [32], which calculates the costs of district heating development versus the costs of individual heating for every building. An iterative approach calculates to total heating costs per building, composed of heat supply costs as well as investments in transmission and distribution pipes as well as house installations. The model hence allows for defining the geographical and economic boundary between individual and collective heating. Oil-gas- and electricity prices are the main variables that determine this boundary, which in time is influenced by the development of investment costs and efficiencies. A system like this may be used every now and then to reassess the spatial planning of heat supply.

It should be stressed, however, that the methodological boundaries between a planning tool like this and pipe dimensioning and design should be respected. Hence, as part of the Fleksenergi-project [48] a heat atlas was designed to specifically identify and evaluate smaller potential district heating islands in rural areas, which were to be connected to existing district heating networks in order to reduce the dependency of rural housing on oil. This was done manually by identifying clusters of buildings with sufficient total heat demand, heat demand density, the number of houses as well as geometric data such as the length of roads within the cluster as a proxy for distribution pipe length and the distance from each building to road centre lines as a measure of required connection pipes. The output was a collection of relevant decision parameters for each identified cluster, to be used for screening of possible candidates for the establishment of new district heating networks. After this screening a district heating grid was designed using the Termis software [49] and the calculated heat demand by location conveniently derived from the heat atlas.

6.3. Interconnection of DH systems

As part of the above-mentioned Fleksenergi-project the interconnection of several smaller district heating networks and current natural gas supply areas was investigated. By interconnecting different district heating units based on waste-to-energy schemes, biomass boilers, geothermal heat and natural gas-fired CHP, heat can be distributed among participating district heating networks based on a spatially-interconnected, but temporally disconnected mode. This means that surplus capacities from waste incineration together with geothermal heat could provide low-cost base-load heat to the whole system, while seasonal and diurnal peaks in heat demand could be covered by marginally more costly production from biomass boilers and natural gas-based CHP. The economy of the latter is further depending on the power price, which means that higher flexibility in the heat source may be required at some times. Also, it was pointed out that these systems could be beneficial for the integration of fluctuating wind power, by allowing heat pumps to use surplus wind energy in a system with 100% renewable power supply on an annual basis.

Using the Fleksenergi heat atlas for the municipalities of Thisted and Morsø in the North Western part of the country, possible transmission interconnectors of 5–20 km length have been sketched, see figure 6. The heat atlas has produced the required data for the future heat market, including new buildings as well as significant savings in the existing building mass. Furthermore, the potentials of connecting new district

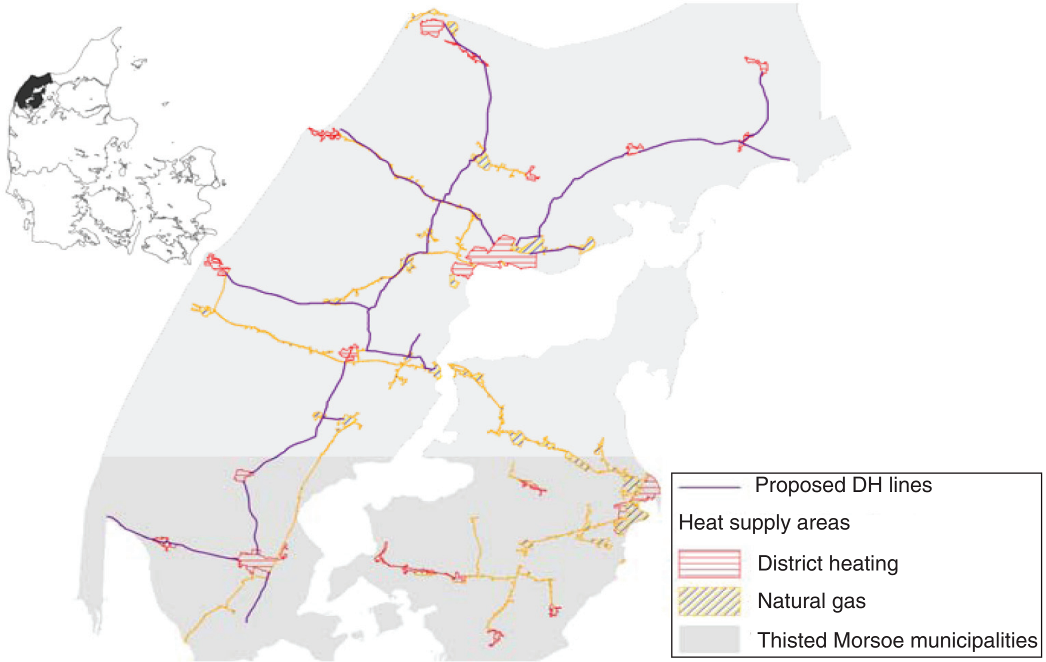

Figure 6: Interconnection of existing district heating areas and conversion of areas with individual natural gas supply in North West Denmark.

heating customers along the proposed pipelines have been identified, and the total potentials by expansion costs have been quantified. Unfortunately the project was not carried out because of denied permission to build a new waste-to-energy plant in Thisted, the central town in the area.

6.4. Mapping energy vulnerability

Energy vulnerability is here defined as the negative impact on household economy any increase of energy costs may have. It may be described as the proportion of the energy costs by the disposable income, as well as the economic means to ameliorate the current situation, e.g. by investing in heat savings. The heat atlas has been used in a national study [50] to identify those buildings and areas of the country, which may be vulnerable in terms of energy performance. It was here assumed that the economic ability to invest in energy savings is a certain proportion of the public property value, which is an assessment value used by the tax authority for property taxation. Assuming most buildings have a mortgage proportional to the property value, and investments in heat savings are to be financed by re-mortgaging, the economic capability of a house owner to invest in additional insulation can be assessed by calculating the share of the property value required as investments to reduce the heat demand. Herein lay the assumptions that households live in buildings that represent the household's economic capabilities, and that the publicly registered property values used for taxation are proportional to the market value of a property, which is somewhat more difficult to extract for all buildings. If accepting these stipulations, vulnerability can be mapped on a national scale by calculating the investments needed to save e.g. 50% of annual heat demand and divide this by the registered property value. The heat atlas includes heat saving scenarios based on the representative building properties resulted in annual energy savings and the required investment costs, and a database relate to the registered property value. Calculating the proportion of property value that would be required to bring each single detached dwelling (the method works best for a one-to-one relation of physical buildings and building ownership) to consume 50% less heat, a map reveals possible energy vulnerability issues, see Figure 7. For reasons of clarity the 1.2 million data points of individually-owned detached buildings were aggregated to a 1 km grid.

The map indicates where in Denmark a mortgage cannot finance significant energy savings and it shows

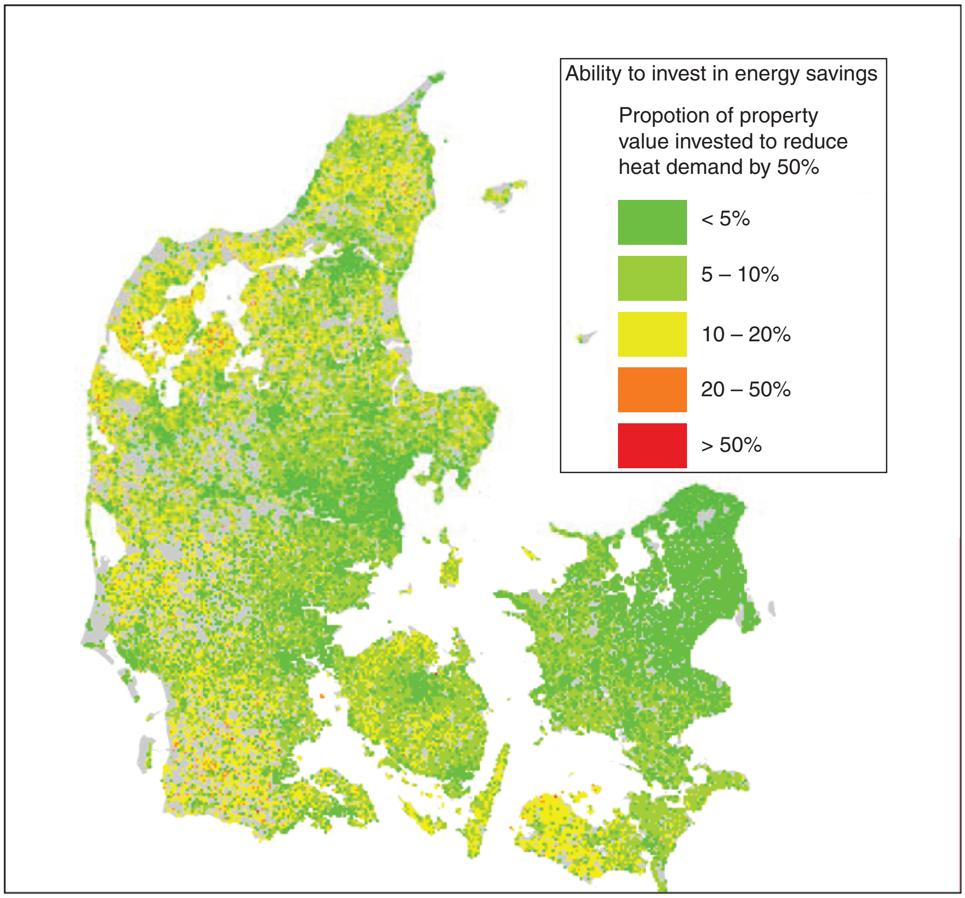

Figure 7: Data from the heat atlas combined with registered property values is used to calculate the proportion of property value, which is required to reduce heat demand by 50% in average.

a divided country: on one hand the more desirable urban areas, where high demand for buildings results in high property prices and where low cost district heating nevertheless makes heat savings unfeasible. On the other hand the rural areas with low value buildings, which are more expensive to heat with individual heating, and where improved energy performance of buildings is unaffordable. This way, it can be made plausible why not everybody in the country can enjoy an energy efficient home, being left with high energy costs. A major shortcoming here is the assumed average energy performance by use and age of buildings regardless location, as well as the average investment costs in heat savings, which do not consider that lower wages in rural Denmark. Further refinement of the database is required, using regionally diverse labour costs and a heat demand calculator, which represents the local or regional energy performance of buildings, which often is related to property value and the socio-economy of their inhabitants.

6.5. Assessing economic potentials for end-use efficiency

It follows from these applications that not all energy saving potentials in the existing building mass are economically feasible in the shorter or longer term, and that they may depend on the energy supply system available. Setting aside the socio-economic constraints discussed in 6.4, the economic potential for achieving substantial heat savings in the building mass is largely determined by age and use [40]. To identify the largest possible potentials for reducing heat demand in buildings for the least costs, the heat atlas has been used for a long-term energy vision for municipality of Aalborg [8] as well as a short-term energy strategy for the Renewable Energy City of Frederikshavn [29]. Potentials for heat savings are calculated for all

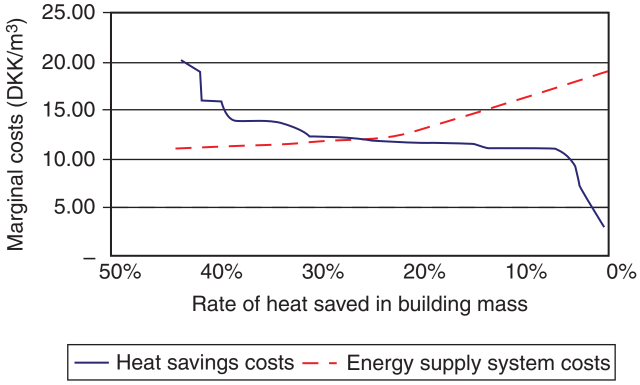

Figure 8: The marginal costs of supply against the marginal costs of reducing the heat demand in Aalborg municipality.

buildings along with the required investment costs, using a model that is maintained by the National Building Research Institute [40]. The heat atlas proved to be a good representation of building properties and their influence on energy demand, possible savings and the likely investment costs of getting buildings to a standard that achieves these savings. The heat atlas is used to map these savings relative to the heat supply in order to be able to identify the intersection of the costs of heat savings and the costs of supply, hence a means to facilitate demand-side planning on the utility scale. Hence the heat atlas findings were used in an energy systems analysis, and the system costs at various heat saving rates were compared to the heat saving costs. For Aalborg it appears that a feasible heat saving target is around 23%. Figure 8 shows the long-term marginal costs of investing in heat savings and the long term costs of replacing fossil fuels in the district heat supply for the municipality of Aalborg. It becomes evident that a high share of the potential heat savings can be harvested while saving investments and operation costs (mainly fuel) in the supply system.

7. Conclusions

This paper has addressed the issue of heat atlases for mapping heat demand and supply in energy systems, which ultimately will be based on 100% renewable energy. First, 100% renewable energy systems are discussed in a geographical context. It is made plausible that geospatial methods are required, which map energy demand and supply geographically. Next, the tradition of carrying out geographically oriented heat planning in Denmark is described. Reasons for taking up this matter are presented. The paper then elaborates on the required functionality and the elements needed to build geographically detailed heat atlases, which allow for spatially explicit analyses of future renewable energy systems. Emphasis is here on a rigorous analysis of the energy end-use savings, their potential, costs and location relative to the supply system.

Using GIS and database technology, the design of a heat atlas using publicly available data has been described. The smallest functional unit of the heat atlas is the single building, allowing for studies of demand and supply in terms of energy and economy at unprecedented costs, and the subsequent aggregation to larger units. The result is a spatial database, which can be used for queries and statistics, as well as the production of cost-supply curves to establish a mathematical relationship between cumulative resources and continuous marginal costs. The database is designed in such way, that geographical entities such as administrative boundaries, as well as other parameters may be used to disclose heat demand and supply by all kinds of properties, to be used for several planning tasks.

Therefore, finally a range of actual and possible applications described in current research is presented and placed in the context of the general idea of this paper. There are many tasks on national, regional and local levels, where heat atlases can improve planning by the highly detailed data provided by heat atlases. The core of them is that heat demand no longer is a subject to be dealt with én bloc, but in a spatially and economically continuous way.

The end-use sector being a major element of future energy strategies, any closer examination of the investments by means of a heat atlas will assist in quantifying energy savings in the built environment. This will comprise potentials as well as costs, by current heat supply, and for any given spatial unit. Assuming that the massive investments in the building sector in unevenly distributed in the country, a heat atlas can be used to summarize economically feasible investments by area unit, e.g. by municipality. After having identified which investments make sense on a large scale, in a long-term perspective, and as elements of a national plan, locally required investments can be identified. In using figures for labour intensity and revenue, the local potential to create jobs and beneficial socio-economic growth can be assessed, in combination with local figures for unemployment, workforce availability etc. Because this approach delivers actual figures linked to the spatially determined energy system, undesired outcomes such as investments in heat savings overlapping with increased heat supply can be avoided, which otherwise may happen if using data on an aggregated scale or without link to the mapped energy system.

Closely related to this is the discussion of the organisation of the energy system in terms of ownership and market regulation; see Lund & Hvelplund [6]. By having established a link between energy savings potentials and the possibilities to expand district heating as well as the mapping of socio-economic impact of these changes to the current population, building mass, employment etc., it is possible to describe impacts of these measures on local socio-economy and sustainability.

In order to identify potentials for utilising renewable energy sources in locally owned energy companies, a heat atlas and the data it delivers may assist local communities to make informed decisions, reducing risk and creating awareness. Both factors are crucial for establishing local energy solutions: acceptance and local prosperity is increased with reduced risk caused from uncertainties. Awareness is required to make people engage themselves in the solutions that can be formulated if they are aware of the technological, organisational and political choices they have.

The present heat atlas, the long range of applications and the rather simple design principles also show, is absolutely feasible for Danish strategic energy planning on the local, regional and national levels. The general idea, that planning boundaries can and have to be redrawn for a sustainable development of the heating sector, is reflected in the design of the heat atlas. The heat atlas describes heat demand, efficiency and supply opportunities and the associated costs as continuous phenomena; hence the degree to which heat savings, the expansion of district heating or the investment in individual solutions is carried out may depend on costs and benefits.

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