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Heat atlas accuracy compared to metered data

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ABSTRACT

This study investigates the accuracy of the modelled heat demand (kWh/m^2/year) in a heat atlas compared to metered data. The Danish heat atlas is compared to metered heat demand values from more than 1 million buildings. Statistical analysis is applied to the two datasets, to investigate how well the heat atlas predicts the actual heat consumption and how accurate it is for different sized groups of buildings and groups consisting of different building types. The study results in a higher certainty and better knowledge of the accuracy of the results. In this way, the utilization of the tool in actual planning for the Danish heating sector is improved. Furthermore, by identifying in which areas or building types the heat atlas is lacking accuracy it is possible to consider this in the results of calculations using the tool. The results indicate that the estimates of the heat atlas mainly can be considered valid for single-family buildings, but for other categories, there are larger uncertainties and thus the heat atlas should be used with more caution for those building categories.

Keywords:

District heating;
Heat mapping;
GIS;
Spatial analysis;
Heat atlas;

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1. Introduction

Recent studies show, that in many cases a higher coverage by district heating in the heating sector can be an important part of a smart energy system with a high renewable energy penetration [1–3]. A higher penetration of district heating enables a more diverse heating sector with better integration of renewables, e.g. with biomass [4] or combined heat and power plants [5], but especially in the so-called fourth generation district heating, where supply temperatures are lowered [6–8]. Furthermore, district heating can be used as a cross-sector storage of waste heat and surplus electricity from the electricity sector [2,9]. Studies also show, that a high district heating penetration is economic feasible compared to focusing on individual heating solutions, especially in dense urban areas [10,11]. To determine the feasibility of district heating in different areas, information regarding the spatial distribution of the heat demand is essential, since the economic feasibility of district heating is related to the heat demand density in the specific areas [12]. Furthermore, as shown in [13] the heat density of district heating is related to energy renovation of buildings. Many different analyses indicate that heat savings are also a crucial part of the smart energy system[14], and thus this should also be considered when planning for the future heat supply.

District heating is only suitable in areas with a high heat density or in places with access to a low-cost heat source such as surplus heat from industrial processes and electricity production. This means that the economic feasibility of district heating depends on spatially explicit conditions. Often heat maps or heat atlases are used to investigate the location of the heat demands in a spatially explicit way. Recent studies have generated heat atlases for several places, amongst others Japan [15], USA [16], Denmark [17,18], and the European Union [19–21]. The methods to develop these heat atlases differ but can all can be divided into two general categories; bottom-up and

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top-down. The division depends on the data used in the development of the heat atlases. When aggregated national or regional heat demand data is distributed across the geographical entity by the use of population data or similar, the heat atlas can be considered to use a top-down approach. On the contrary, bottom-up heat atlases work with detailed data on heat demand on a local level, e.g., single buildings. One of the strengths of the bottom-up approach is that this detailed data can be summarized for any geographic entity as desired, an approach that is much easier than disaggregating national data. The background for this paper is the need for knowledge on how well the indicators perform when compared to the actual consumption in the buildings.

2. Heat atlases

Both types of heat atlases have advantages and disadvantages. The top-down approach often entitles an easier access to data about the heat demand, as this type of data is often available in national or regional statistics as part of the monitoring of energy consumption. Sometimes the data is available in a similar format for larger groups of countries e.g. the European countries through Eurostat [22]. The challenge in the development of these type of heat atlases lies in the spatial distribution of the heat demand. It is often assumed, that a large part of the heat demand is related to the human settlements, that is: heat demand exists where people are located. Furthermore, a large portion of the heat demand is linked to the industry and service sectors. The largest disadvantage for top-down heat atlases arises from the assumptions necessary to distribute the heat demand to multiple locations. Although, the heat demand is strongly linked to the location of human settlements as well as the industry and service sectors, the exact amount of heat related to each category is hard to estimate on a regional or national level. This suggests that the distribution will be based on average perceptions of the convergence between each of the categories and the heat demand. As seen in [23], this means that the heat demand on average can be well represented and distributed. However, it is hard to represent local variations and thereby accurately estimate the heat demand on a smaller scale.

The bottom-up approach relies heavily on local data collection. It is essential for the method, that local data about heat demand is collected, and it often relies on heat demand data for individual buildings. This gives a very detailed insight into the geographic distribution of the heat demand, which as mentioned before, can then be summarized as needed for further analysis. The challenge with the bottom-up method come from the data collection, as it is rare to find metered consumer data on heat demands for all consumers within a large area. This results in two cases; one where data is available for all buildings but only for a smaller area of interest, and the other where data is available for a larger area but not for all buildings. In the first case, assumptions have to be made as to how well the data represents all heat demands also outside the small area of interest. In the second case, assumptions are needed regarding the representation of buildings and locations without data available. A recent example of a bottom-up approach is seen in this case study for Belgium [24].

On one hand, the distribution grid companies within the heating sector, such as natural gas or district heating distributors have good knowledge of the demands within their own supply areas, as they know how much heat their costumers purchase. On the other hand, it is more complicated for the areas outside the existing supply areas as these have their own individual heat supply. When choosing the best heat supply option for all buildings, it is important that the economic calculations are based on accurate estimates of the heat demands. Often the knowledge of the heat consumption in buildings is kept within the distribution companies. In Denmark, the collection of electricity and heat consumption data was initiated across distribution companies with a law implemented in 2010 [25]. This means that data on actual yearly heat consumption has been collected for all the following years for more than one million buildings each year. This data has been used as the foundation for the latest version of The Danish Heat Atlas.

The study aims to investigate the accuracy of The Danish Heat Atlas by comparing the results with real-world data. In this way, it is possible to identify areas where improvement in the prediction capability of the heat atlas is needed. It is also a verification process of the heat atlas, defining to what extent it can accurately be used to estimate the heat demands in groups of buildings.

2.1. The Danish Heat Atlas

The development of The Danish Heat Atlas has been an ongoing process over a period of years, and the methodology has been developed to include new data types as they have become available. The overall methodology has been the same in all the years and is described in the following together with recent developments.

The heat atlas is developed based on the Building and Dwelling Register (BBR) of Denmark [26]. The BBR contains information on all buildings in Denmark including the year of construction and size of the buildings. Further, all buildings are divided into categories depending on their main purpose. The categories are seen in Table 1. Buildings in categories 910, 920 and 930 are left out of the further analysis since they are assumed to be unheated.

In the early editions of the heat atlas, the heat demand was based on indicators for heat demand for the normal consumption of different building types and ages developed by the Danish Building Research Institute [27, 28]. The building types follow the division in the BBR, and the age classification was correlated with updates of the Danish building regulations. The indicators were a per square meter heat demand per year which was multiplied with the inhabited floor area of the buildings.

In the newer editions of the heat atlas, the indicators from Danish Buildings Research Institute are replaced with indicators calculated based on metered data from Danish buildings (FIE data). The metered data is collected

Table 1: Building usage categories, adjusted from [27]

Code	Usage
110	Farmhouse at agricultural holding
120	Detached single-family house
130	Terrace-, linked or double house (horizontal separation between units)
140	A building of flats (A house for multiple families including two family housing (Vertical separation between units)
150	Hostel
160	Residential home (for elderly, for children or for young persons)
190	Other building for residence all year round
210	Commercial production regarding agriculture, forestry, market garden, nursery, raw material extraction, a.o.
220	Commercial production regarding industry, trades a.o. (Factory, workshop, a.o.)
230	Power station, gasworks, waterworks, district heating station, incineration plant, a.o.
290	Other building for production and storage in connection to farming, industry, a.o.
310	Transportation and parking facility (cargo hall, airport building, train station, a.o.
320	Wholesale trade and storage
330	Retailers, a.o.
390	Other building for trade and transport, a.o.
410	Cinema, theater, commercial exhibition, a.o.
420	Library, museum, church, a.o.
430	Education and research (School, gymnasium, research laboratory)
440	Hospital, maternity home, a.o.
490	Other institutions, including barracks, prison, a.o.
510	Holliday cottage
520	Unit for holiday purposes not a Holiday cottage (Holiday camp, youth hostel, a.o.)
530	Unit linked to sport (club house, sports center, swimming bath, a.o.)
540	Allotment hut
590	Other building for leisure time purposes
910	Garage with room for one or two cars
920	Carport
930	Outhouse

from heat providers such as district heating or natural gas providers. The data is collected in a central database for all of Denmark and is climate corrected before access is given to the researchers. Since the database only contains heat consumption information for buildings with metered heating systems, not all buildings are included in the database. Currently, it contains information for a bit more than one million unique buildings, which is around half of the heated building in Denmark, many of which have several years of metered data. In the current edition of the heat atlas, a total of 4.6 million yearly measurements are included in the statistical work. It has been decided to use data from the same buildings from various years, as this gives a more robust statistical analysis by including a higher number of observations.

The coverage of the metered data is not evenly spread in all building categories. In Figure 1, it is seen how many measurements for unique buildings exists out of the total number of this type of building in Denmark. As the figure indicate, there is a large amount of data for the residential sector but substantially less for all other sectors. This, of course, affects the accuracy of the estimates of the heat demand since it is not based on metered data for the full population of buildings. It also affects the comparison, since it is only possible to compare the estimated data with metered data for the buildings where it is available. For the residential sector is seems a fair assumption that the buildings left out of the analysis will have a heat demands similar to the ones included. However, in many of the other categories, the amount of excluded buildings supersedes the amount of included buildings. Without metered data, it is not possible to include them in the analysis.

When metered data exists, it might seem wasteful to generate a heat atlas containing estimated data based on statistical analyses. There are, however, several reasons for this approach. Firstly, the metered data is considered sensitive data and is to be kept confidential. This means that a heat atlas based directly on the metered data also is to be kept confidential. With a heat atlas based on statistical data, it is possible to use it more freely and publish the data. The current edition is available online in a version with the data aggregated on administrative zones in Denmark [29]. Secondly, the metered data only covers a share of the buildings, as seen in Figure 1. The output of the statistical analysis is, therefore, a necessity

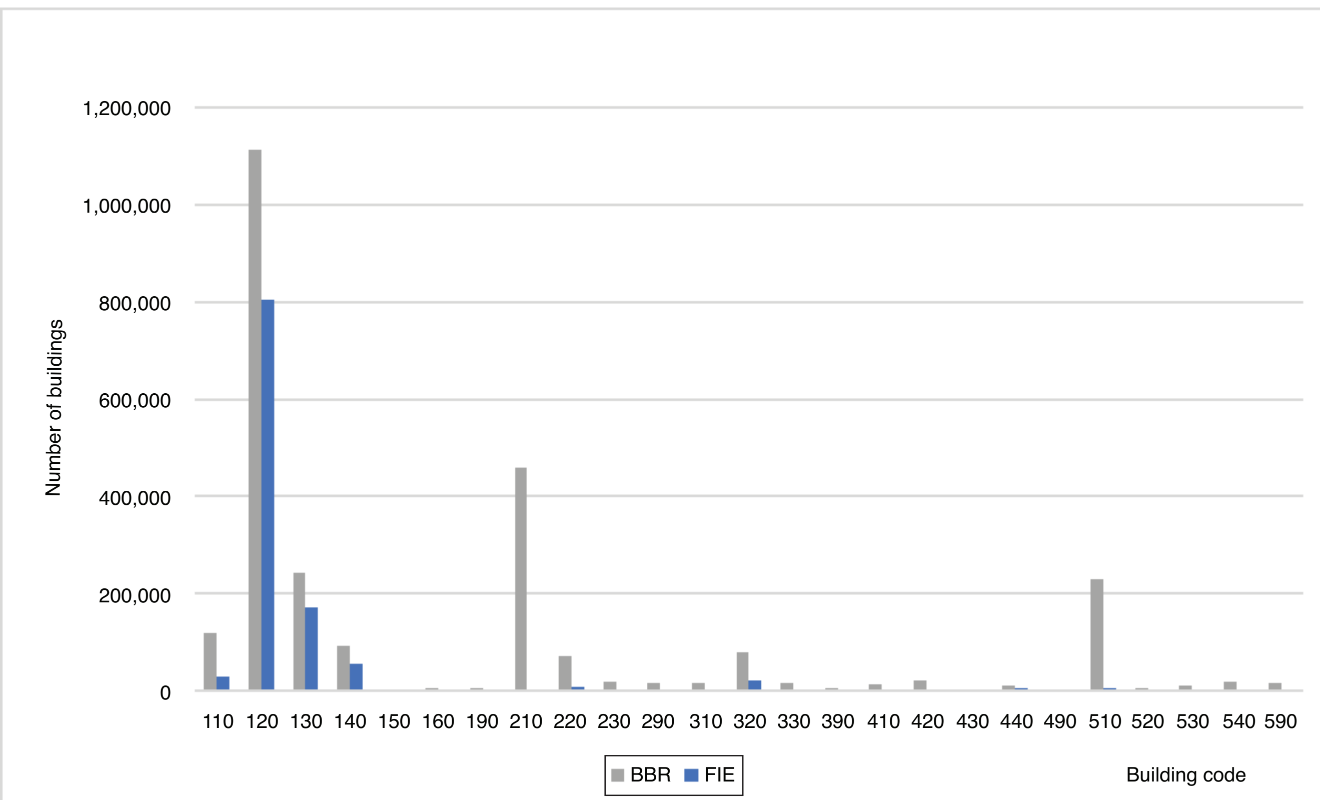

Figure 1: Number of buildings with metered data (FIE) compared to actual number of buildings in Denmark (BBR)

for all buildings without metered data. Thirdly, following the analysis in this paper, it is possible to use the estimated heat demands with knowledge about the accuracy depending on the number of buildings in the analysis. This is important, since the annual heat demand in a building is not a static value. It changes between years, both with the seasons and the behavior of the inhabitants. Statistical data has the advantage that it is based on the behavior in many buildings and for various years and therefore on average will predict the heat demand better. It is just as sensitive to, e.g., new inhabitants in the buildings but with the statistical analysis done in this paper that sensitivity is well known.

The aim of The Danish Heat Atlas is not to be accurate on a single building level, as too many unknowns exist to achieve this goal, amongst others: user behavior, specific energy performance of the building and economic constrains to energy renovation or consumption. Rather, the heat atlas aims at accurate estimations of the average heat demand in the different building categories. A high accuracy in this context is, therefore, an estimated heat demand close to the metered heat consumption for groups of buildings as opposed to individual buildings.

The two indicators used in the heat atlas are age and type of the buildings and indirectly the size since the heat demand is calculated as a per square meter demand. These indicators are chosen since they contain important information about the individual buildings. The type indicates the typical usage of the buildings and is divided into several categories for residential, service and industry buildings. However, the division is sometimes very rough as in category 410, which amongst others contains theaters, museum, and churches. The building age indicates under which building tradition and regulation the buildings were constructed. However, it does not reflect the renovation standard of the buildings and improvements of the energy performance after the construction, which can vary substantially between buildings of the same age category. The estimated heat demand represents the average for all buildings in the same building category and of similar age. The use of the floor area of the buildings assumes a linear correlation between the energy consumption and the size of the building. This is principally not the case, since the ratio between the surface of outer walls and floor area will have an influence. In principle the surface of the outer walls is proportional to the square root of the floor area. The area of outer walls is not known in the BBR register. One of the main influences on the heat demand in a building is the user behavior. The number and demography of the inhabitants of the buildings are not known as this is confidential information. This factor is therefore not included in the heat atlas, and the resulting consumptions for the buildings, therefore, reflect an average of the user behavior in the building types and ages.

As stated above, it is not possible to predict the heat demand perfectly on a single building level; however, it is possible to predict it well for groups of buildings and with increasing accuracy with higher number of buildings. This study will investigate the accuracy depending on the number of buildings and thereby increase the usability of the heat atlas.

3. Method

The method section describes, firstly, the method used to merge the heat atlas with the observations of metered heat consumption. Secondly, it describes the method used in the statistical comparison of the two datasets.

The merge of the heat atlas with the observations of metered heat consumption is performed in RStudio version 1.0.143 enabling an easy script-based approach. The following random sample statistics are also performed using Rstudio, while the statistics in a geographic context is done using ArcGIS version 10.3. Rstudio is an integrated development environment for R [30], a language for statistical computing and graphics [31].

The heat atlas is compared to metered data for individual buildings. The metered data was collected for the years 2010–2015. Table 2 shows the number of observations for each of the years. Since some buildings only have metered heat consumption for one year and

Table 2: Number of observations of metered heat demand per year, and number of observations joined with the heat atlas.

	2010	2011	2012	2013	2014	2015
Number of observations	1,069,597	1,120,254	1,107,974	1,129,937	1,087,632	1,079,367
Number of observations joined	1,054,879	1,102,895	1,088,457	1,111,111	1,074,698	1,068,927

others have for several years, an average of all observations for each individual building is calculated. This could also have been estimated by using other methods, such as a weighted average using the degree day method. Using the average further reduces the statistical uncertainty arising from climatically induced differences in the data for the different years and matches the goal of the heat atlas to predict the average heat demand in buildings.

After joining the FIE data to the heat atlas, each building is represented by a row in a table containing information about the type, age, size, and location together with estimated heat demand from the heat atlas and observed heat demand for individual years and an average of all observations. All buildings without metered data are removed from the dataset since the performance cannot be evaluated for these buildings. This leaves 1,231,791 buildings in the dataset for the statistical comparison.

The statistical comparison takes two pathways. The first pathway examines the accuracy of the heat atlas in a geographical context. The merged data is exported to ArcGIS where it can be summarized within Danish administrative zones. These administrative zones are five regions, further divided into 98 municipalities and as the smallest entity urban zones. Urban zones in Denmark delimit all urban settlements with a few or more buildings that have a location name. This category is therefore very broad since the smallest settlements only consist of very few buildings and the largest of more than 100,000. The urban zones can therefore also be used to look at the performance of the heat atlas depending on the number of buildings. In this part of the comparison, the goal is to look at the overall performance of the heat atlas and the data is not split into categories according to building type. Instead, the mix of buildings within each zone is maintained to have a mix of building types in the calculations which represent the real-world mix of buildings. However, since all buildings without metered data are excluded in this analysis, and the distribution of observations is not equally distributed amongst buildings types, the comparison is not a complete representation of reality. In the comparison within urban zones, the buildings outside the urban zones are excluded. However, all buildings are included when comparing on the municipal or regional level.

The second pathway of the statistical comparison is focused on the performance within the individual building types and the overall heat atlas performance for a set of randomly selected buildings. This analysis is done in order to investigate the performance of the heat atlas without being confined to the limited samples available in the urban zones. For the individual building types, a subset of the data is generated containing all buildings with one building usage code. Random samples from this subset can then be extracted containing a certain number of buildings with the sampling repeated a certain number of times, the sample function in Rstudio was used for this purpose. The sample function extracts a random sample of a pre-set size from the subset. The estimated heat demand can then be compared to the actual heat demand of the buildings. In order to identify variations in the results between different samples multiple samples were extracted and summarized in boxplots. It was found that 5000 repetitions of the samples were sufficient to ensure stable outcomes, where the values no longer changed between runs of the model. This makes it possible to analyze the performance for e.g. detached single-family houses where a random sample of for example 10 or 100 is extracted from the subset 5000 times to see the variations in the. In this way, it is possible to analyze which building types have a high uncertainty and therefore should be handled cautiously when using heat demand estimates for smaller areas.

4. Analysis and results

All results in this section will be presented with the metered values as the reference value. The total number of buildings with one or more observed heat consumption values is 1,231,791. The total heat demand estimated by the heat atlas corresponds to 96.4% of the metered heat consumption when including all buildings. When only looking at the residential sector, which corresponds to building code 110–190, 1,161,926 buildings are included with the heat atlas estimating 95.7% of the metered heat demand. The geographical distribution of the accuracy is seen in Figure 1.

Following the general accuracy of the heat atlas estimating approximately 95.7% of the metered heat consumption, the geographical accuracy also tends to underestimate the heat demand. In the regions, the heat atlas estimates the heat demand within a five percent margin in all except one. In the municipalities, the majority are also estimated to a heat demand within a five percent margin of the metered value. Many of the rest are within a 10% margin of the metered value. One area with a particular high uncertainty is the areas of northeast Zealand, shown to the right in Figure 2. In the regional map, this area comes out at 89% of the metered heat consumption and similarly in the municipality map

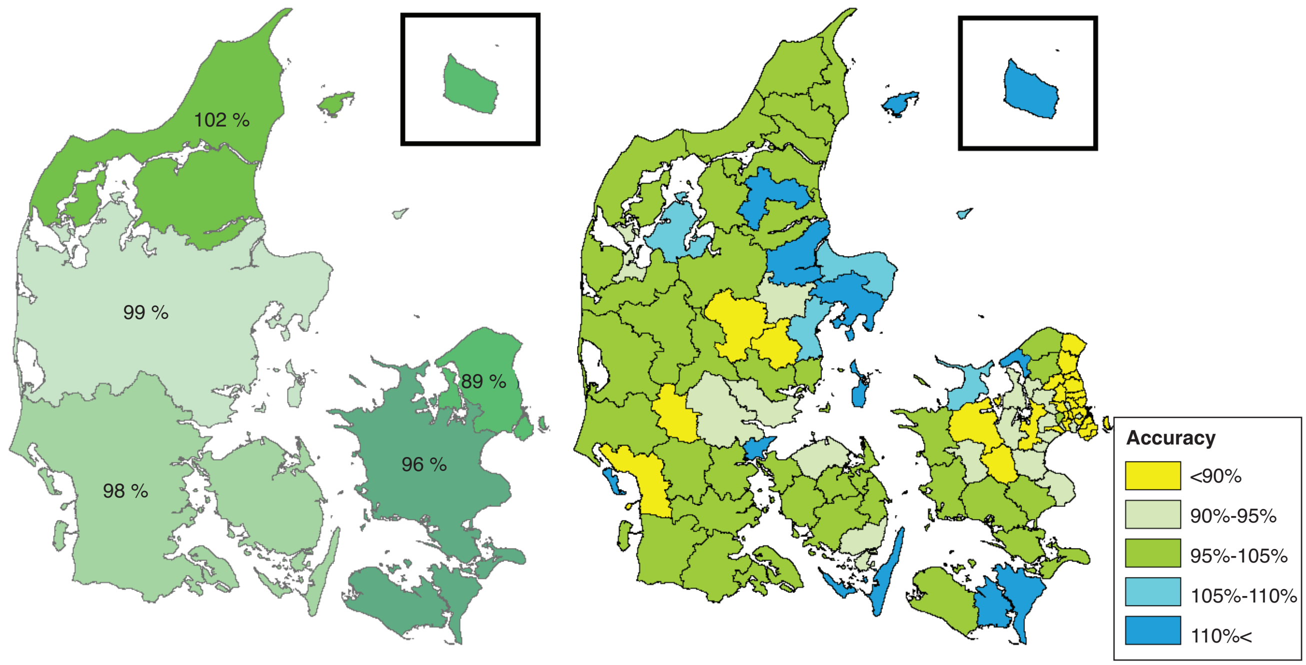

Figure 2: Accuracy displayed geographically in the Danish regions to the left and municipalities to the right. The value show the sum of the heat demand predicted by the heat atlas compared to the sum of the metered heat consumption within each region or municipality

this is the area with the most municipalities outside of the 10% margin of the metered value.

When looking at the accuracy on a smaller scale, larger deviations occur, as seen in Figure 3. The Figure displays the accuracy in percent for all urban zones with more than ten buildings with metered values. It is seen in the Figure, that the estimated heat consumption compared to the actual heat consumption in urban zones with 10–100 buildings in the majority of cases is between 50% and 200%, meaning between half and double of the metered heat consumption. Some outliers, however, have estimates reaching more than four times the metered value. Overall, a tendency seems to be a higher accuracy with a higher number of buildings. This is also well in line with the results from the statistical analysis of random samples of buildings.

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The random sample script extracts a given number of buildings and summarizes the estimated heat demand and the heat consumption to calculate the difference between the two. The number of buildings extracted is 1, 10, 100, 200, 300, 400, and 500 respectively. This is repeated 5000 times, to generate a boxplot of the results. Figure 4 left, displays the result for all building codes with 500 buildings in the random sample. The result displayed in Figure 4 left is well in line with Figure 3, with the range of the outliers declining with higher building numbers and with the majority of buildings approaching correct estimates. Figure 4 right display similar results but only for detached single-family houses, which is the building category with the highest representation in the data. It is also a well-defined category, in which the variation between the buildings is expected to be smaller than in many of the other categories. It is seen that detached single-family houses approach a high accuracy already with more than ten buildings and that the outliers have a low spread at 100 buildings.

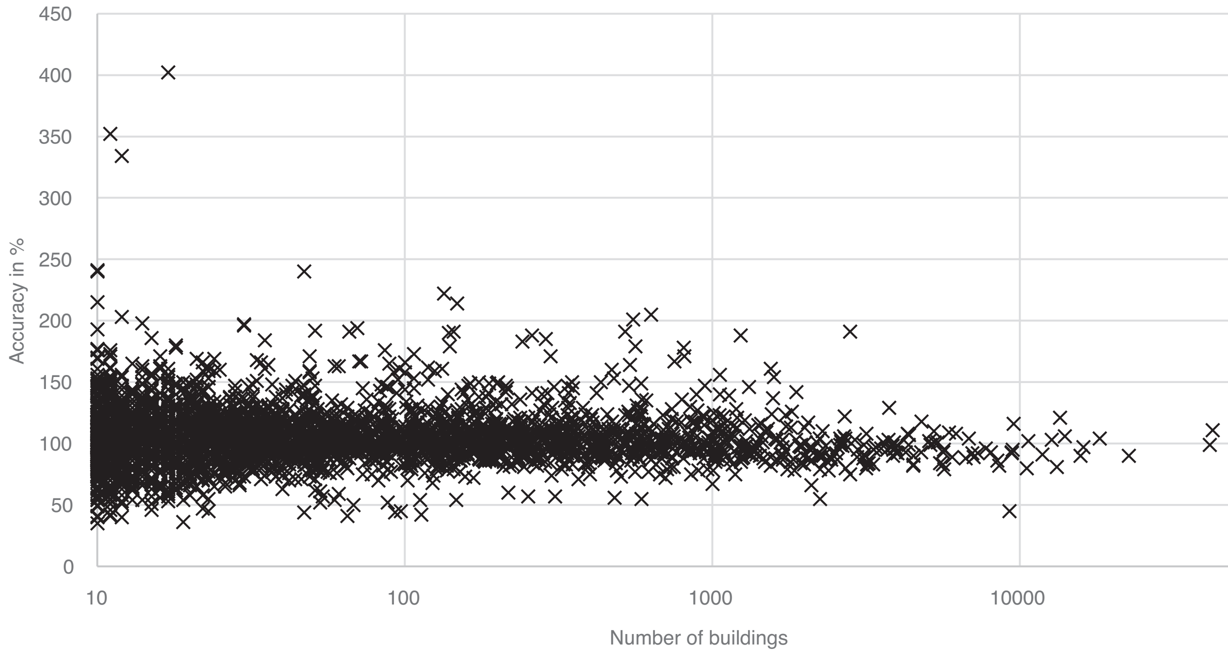

Figure 3: Accuracy in urban zones sorted according to the number of buildings with metered values

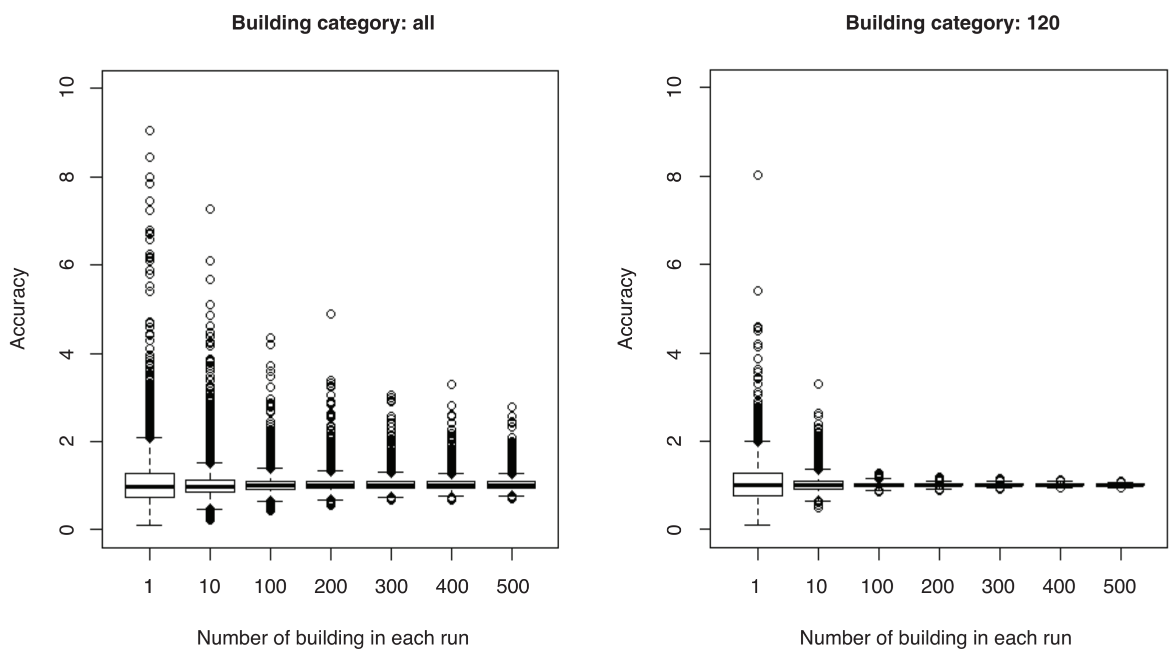

Figure 4: Accuracy depending on number of buildings, an accuracy of 1 means that the heat atlas estimation is the same as the metered heat demand. Left: All building codes. Right: Detached single-family houses

There are also building categories with substantially lower accuracy than the average displayed in Figure 4 left. All categories display an increased precision with increasing numbers of buildings. However, many categories have a poor accuracy where they do not approach the metered value. Figure 5 shows the accuracy

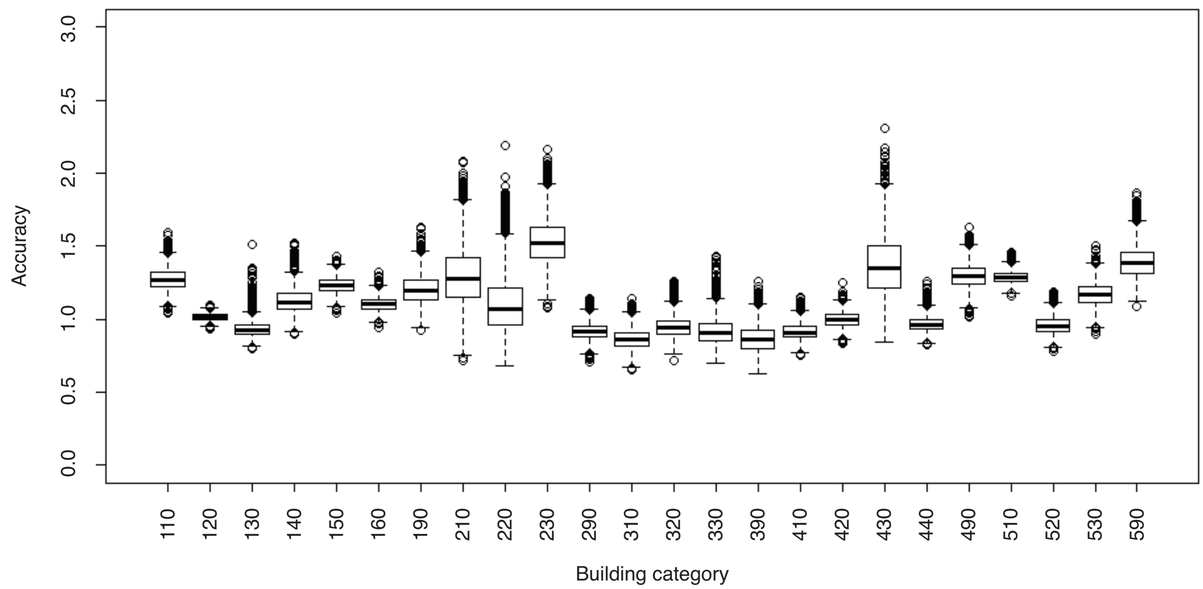

Figure 5: Accuracy for all building categories with 500 random buildings. An accuracy of 1 means that the heat atlas estimation is the same as the metered heat demand

of the individual categories with 500 buildings in the random sample. The worst of category is 230 (Power station, gasworks, waterworks, district heating station, incineration plant, a.o.) which approach an estimate of 150% of the metered value.

Overall, only category 120 (detached single-family houses) achieves a satisfying accuracy in regards to both approaching a correct estimation of the heat demands and simultaneously having a low spread, meaning that the outlier cases are still close to the metered heat consumption. Other cases are also, on average, estimating correct values, but with a higher spread in the predictions and outliers relatively far from correct estimations.

5. Discussion

In many categories, the number of buildings without metered heat consumption supersedes the number of buildings with metered heat consumption data. This adds to the uncertainty of the results in these categories.

The results depend on the parameters applied, which in this case are two relatively simple classifications. The BBR divides all buildings into 24 building types with 9 building age categories resulting in a 24 by 9 matrix, which has to represent all buildings. It might be possible to further improve the method by subdividing more, but there is a risk of ending with categories with too few buildings to determine the heat demand with a high accuracy, especially when considering that some building types are not represented well in the metered data. Thus, with the currently available data, the only category which can easily be subdivided further without the risk of too little data is the 120 (detached single-family houses), which already performs well in the heat atlas.

The results are mainly important for the prediction of annual heat demands and estimation of necessary production capacity for district heating projects. The pipes to the individual buildings are normally sized based on the required capacity and not the annual energy consumption. When considering district heating in a new area, the larger consumers are often the ones determining the feasibility of district heating. This means that an accurate prediction of their expected heat demand is important for the economic feasibility of the district heating system. The heat atlas can give an estimation of this demand; however, with a high uncertainty in the results and for feasibility studies, the information from the heat atlas should be complemented with local data on heat consumption. On the other hand, the heat atlas is likely to give and relatively accurate estimate of heat demands in the general building stock in a town, especially in cases with many detached single-family houses.

6. Conclusion

The aim of this study was to examine the accuracy of The Danish Heat Atlas compared to metered data. This was done by comparing the estimated demands of the heat atlas to metered consumption data from more than 1 million buildings.

The results show relatively large deviations between the metered heat consumption and the estimated heat demand from the heat atlas. One building category 120 (detached single-family houses) performs well in both approaching a correct estimation of the heat demands and having a low spread. For all other categories, the results are either approaching an overestimation or underestimation or having a larger spread in the results.

The results mean that the heat atlas should always be used with caution. In many real use cases, the estimated heat demand values for the majority of buildings are for detached single-family houses. For this group of buildings, the estimates can be considered valid. However, when other building types are included in the estimated heat demand sensitivity analysis of the consequences of changes in their heat demand should be performed. Alternatively, actual heat consumption data should be sought for.

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