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Factoring Building Refurbishment and Climatic Effect into Heat Demand Assessments and Forecasts: Case Study and Open Datasets for Germany

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Abstract: Reducing the heat demand of existing buildings is an essential prerequisite for achieving a greenhouse gas-neutral energy supply. Numerous studies and open-source tools deal with heat demand mapping. It is not uncommon that estimated heat demands deviate from real heat consumption, so existing approaches should be improved by including in-depth building information. Some tools have recognised this problem and offer built-in functions for factoring various parameters into their assessments. Nevertheless, the necessary information is usually missing and should be obtained first. In this paper, we analyse the impact of thermal refurbishment and climate on building heat demand; hence, generate public datasets with corresponding key figures for each building type in different efficiency states and years. Accounting for already performed refurbishments in methodologies for assessing the actual state heat demand for cities will result in a reduction of at least 8% up to more than 21%, depending on whether conventional or passive house components were installed. As a result of climatic differences within Germany, a building's heat demand can be up to 39% higher or up to 21% lower than the heat demand of an identical building in the reference climate of Germany. By further developing the approaches of the tools Hotmaps and Heat Cadastre Hamburg, we could improve the estimated heat demand of Hamburg to a value approximating the real consumption.

Keywords: energy efficiency; heat demand; modernisation; climate factor; open data

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Citation: Salaymeh, A.; Peters, I.; Holler, S. Factoring Building Refurbishment and Climatic Effect into Heat Demand Assessments and Forecasts: Case Study and Open Datasets for Germany. *Energies* **2024**, *17*, 690. https://doi.org/10.3390/en17030690

Academic Editors: Constantinos A. Balaras and Tomasz Cholewa

Received: 5 December 2023
Revised: 27 January 2024
Accepted: 29 January 2024
Published: 31 January 2024

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1. Introduction

The major driver of final energy consumption in Germany is heat demand in the form of space heating (28.0%), hot water (5.5%) and process heat (22.6%) [1]. Private households account for about 27.8% of the final energy consumption [1,2]. For the past ten years, the share of renewable energies in the total heat consumption of Germany has remained at a low level between 14.0% and 16.5% [1–4]. Conventional heating systems powered by fossil fuels and direct electric boilers are widespread in Germany with a share of about 75% in the heating sector [1,5,6]. With the amendment of the German Climate Protection Act in June 2021, the target for achieving the goal of greenhouse gas neutrality in Germany was tightened and the time horizon was adjusted from 2050 to 2045 [7]. Realising these goals will require a fundamental transformation of the infrastructure and existing technologies [8,9]. Numerous studies and scenarios illustrate the path to achieving the target of a greenhouse gas-neutral heat supply. A common thread among these scenarios is the imperative of curtailing heat demand in buildings to meet this target. Whether on a European or German scale, heat demand reduction scenarios typically range from 30–50%. Zeyen et al. [10] examine possibilities to mitigate heat demand peaks in buildings in a highly renewable European energy system. They conclude that building renovations with space heating demand savings of 44–51% result in the strongest effect on the reduction in total costs for system transformation with 14% cost savings. Likewise, Hansen et al. [11] investigate the heat saving potential for different countries in Europe. Their findings indicate that overinvestments in heat savings can be avoided by saving heat until a level of approximately 30–50%. Palzer and Henning [12] specify that 50% of savings in space heat demand are cost-optimal by providing a 100% renewable energy supply in Germany. There are three further target scenarios for achieving a climate-neutral building stock in Germany "Target scenario (a) Efficiency, (b) Renewable energies and (c) Climate-neutral building stock" that envisage reductions in space heating demands of 51%, 32% and 36%, respectively, by 2045 [13]. In Switzerland, the current targets for residential buildings imply a 46% reduction in final energy consumption by 2050 compared to the present levels [14,15].

In recent years, various approaches and open-source tools have been developed to map the heat demand of building stock. Heitkoetter et al. [4] describe an approach to use excess electricity feed-in for heating applications. They used detailed data on the spatial distribution of heat demand to identify regions, in which power-to-heat (PtH) technologies can contribute to the integration of renewable energy sources. Weiler et al. [2] additionally developed a method for dimensioning energy system components based on the heat demand which they determined by means of 3D Building Models using the software "SimStadt 2.0". Chambers et al. [14] address the provision of heating energy services through both reduction in demand with building energy retrofits and efficient heat supply using heat pumps and district heat networks. They attribute challenges to lack of information on refurbishment [15,16]. Yang et al. [17] present a GIS-archetype-based bottom-up building stock model for space heating. Due to a lack of refurbishment records, their model applies a "random allocation" of relatively high cumulative refurbishment rates (ground floors 63%, external walls 77%, roofs 81% and windows 88%) for all buildings constructed before 2000. Only few studies such as Dochev et al. [18] address the validation of their methods for heat demand estimation, since they are primarily carried out due to the lack of available real data on heat consumption [19,20]. In addition to the studies described above, Table 1 lists information on the heat demand mapping in selected tools.

Table 1. Characteristics of heat demand mapping in selected tools.

Tool	Usage Example	Availability	Databases	Max. Spatial Resolution
THERMOS [21,22]	[23]	Worldwide	Mostly OpenStreetMap (OSM); using own LiDAR (Light Detection and Ranging) data is possible.	Building level
Hotmaps [19,24,25]	[9,14,26]	Europe	Datasets on population, building stock characteristics, land use and surface-to-volume ratio for calculating the heated gross floor area.	Hectare level
Peta atlas [20,27]	[4,28]	Europe	Country-specific per-capita floor area derived from the Eurostat Census 2011.	Hectare level
Heat Cadastre Hamburg [18,29]	[29]	German fed. state	Authoritative Real Estate Cadastre Information System (ALKIS) of Hamburg.	Building level
Heat Cadastre Saarland [30]	[18,30]	German fed. state	3D Building Models in Level of Detail 1 (LoD1) and ALKIS of Saarland.	Building level
Energy Atlas Baden-Württemberg [31]	[4,32]	German fed. state	Information on building type, building age and floor area derived from the Census 2011.	Hectare level

The completeness and accuracy of the OSM data (used in the THERMOS software) were examined in some studies [33]. The majority of buildings in OSM do not contain information on building height or number of storeys, which affects the accuracy of heat demand assessment. THERMOS primarily uses OSM data to estimate heat demand in nearly all European cities, except for a few where LiDAR data on building heights are available and processed by THERMOS (see Figure 1).

Figure 1. Availability of LiDAR data in THERMOS (LiDAR in pink highlighted areas, screenshot of THERMOS on 24 February 2023).

The spatial resolution of the census data used in the Hotmaps tool, Peta atlas, and in the Energy Atlas Baden-Württemberg is lower than the one in the OSM data. However, additional parameters (e.g., useful floor area and number of dwellings per building type and per construction period) could be obtained. They are available at a maximum spatial resolution of one hectare (max. 0.01 km^2) for Germany [34], and at lower resolutions for entire Europe (max. 1 km^2 for population and city level for housing census) [35].

Three-dimensional Building Models and Authoritative Real Estate Cadastres offer the highest accuracy with regard to information required for heat demand assessments (e.g., building height and use, roof shape, areas). These data are often not provided as open data for research purposes and their utilisation can be associated with high costs and processing requirements. They were used, for example, in the development of the Heat Cadastres of Hamburg and Saarland. Based on the present research, 3D Building Models are currently available as open data in 9 out of the 16 federal states in Germany (see data sources in Supplementary Material).

Compared to the previous studies, this article provides a comprehensive analysis on the effect of factoring changes in thermal refurbishment and climatic conditions into heat demand assessments and forecasts. In addition, it provides improved key figures for heat demand mapping for each reference year between 2005 and 2050. Furthermore, it aims to develop procedures to integrate the aforementioned parameters into some existing tools and approaches (Table 1). This raises the following questions:

- What progress can be forecasted in thermal refurbishment and reducing building heat demand in Germany? Would this progress be adequate to achieve greenhouse gas neutrality in the building stock?
- How do heat demand reductions differ in relation to efficiency standards of thermal refurbishments?

Terms such as modernisation, insulation (also known as subsequent insulation), refurbishment and retrofitting are commonly used in the literature to describe the thermal refurbishment carried out after the building has been constructed in order to improve its energy efficiency. To reflect this meaning, we use the term "modernisation", which occurs in German and English experts' literature [8,36–38].

2. Materials and Methods

Figure 2 illustrates our workflow for analysing the effect of modernisation and climate on heat demand, and for integrating the results into the tools THERMOS and Hotmaps, along with the approaches for heat mapping in Heat Cadastres. The workflow is mainly driven by information on building heat demand, climate, modernisation and other characteristic building features such as the share of building components in the total building area and the share of buildings by year of construction in the building stock.

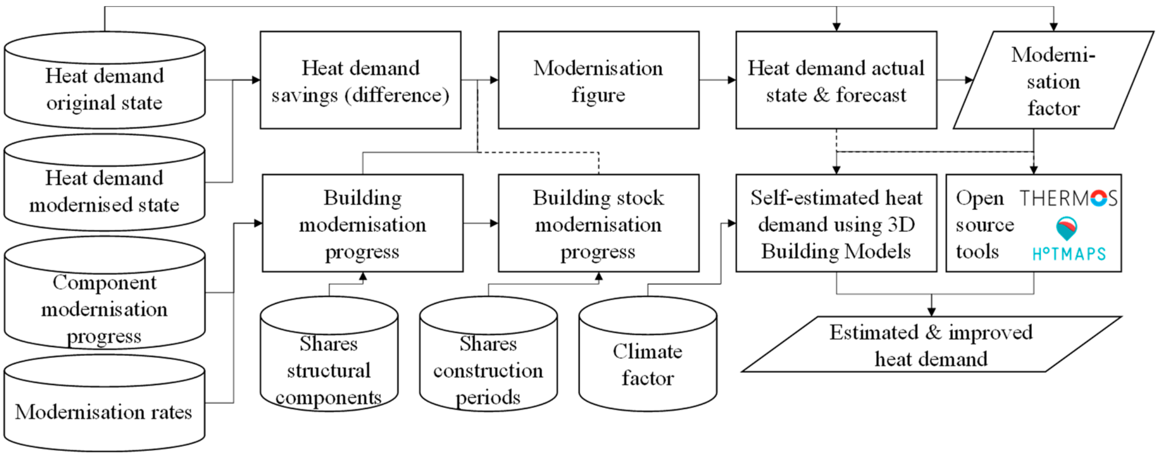

Figure 2. Workflow for analysing the effect of modernisation and climate on heat demand towards improving the accuracy of heat demand mapping (dashed lines: optional input).

In the *Intelligent Energy Europe projects "TABULA"* and *"EPISCOPE"* [39], typical building heat demands were provided based on calculation models that apply typological criteria and frequencies to offer features of typical buildings in different energy efficiency states. In these projects, a total of 40 building types (called basic types) were identified as representative for the German residential building stock and they determine the scope of this paper. As shown in Figure 3, the heat demand is first determined in the original state of the buildings (i.e., without thermal refurbishment) (Exception: Buildings built up to 1994 do not preserve their original windows (see Appendix D.2 in [40])). Then, after applying two modernisation or measure packages (MP) with two different energy efficiency (insulation) levels [36,40]:

- MPCon with the "conventional" energy efficiency level corresponds to the practical implementation if the minimum standards of the Energy Saving Ordinance (EnEV) are met. For existing buildings, the minimum requirements on thermal insulation were adopted in the current "German Buildings Energy Act (Gebäudeenergiegesetz, GEG)" [41]. The GEG requirements correspond to a moderate reduction of the space heating demand [42].
- MPAdv with the "advanced" energy efficiency level corresponds to the thermal protection standard of passive houses.

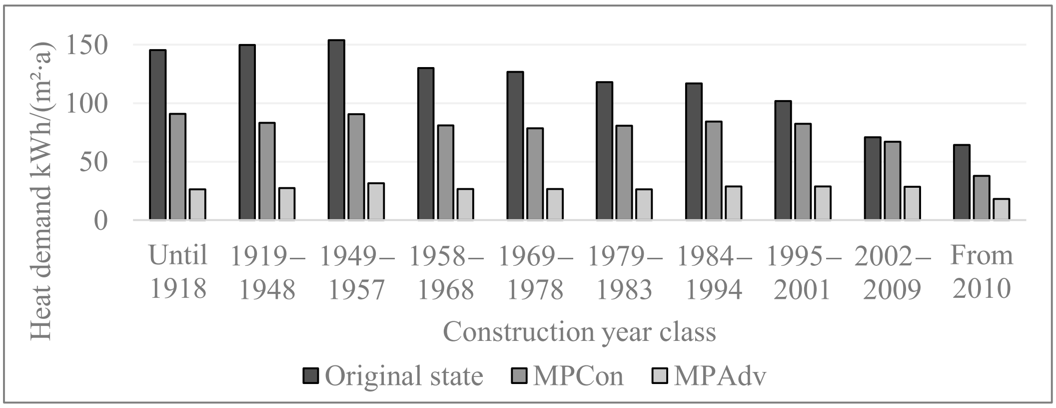

Figure 3. Area-specific heat demand values for space heating indicated as useful heat in different energy efficiency levels [40] (average values of all building types; see Supplementary Material for detailed data sets).

To pinpoint the necessary efficiency standards for achieving the target values of heat demand reduction outlined in Section 1, we analyse three additional efficiency standards encompassed within the German Federal Funding for Efficient Buildings (BEG):

- The Efficiency House (EH) standards EH 70, EH 55 and EH 40 have, respectively, 30%, 45% and 60% less energy demand than buildings constructed or refurbished according to the mandatory GEG standard. These savings relate to primary energy demand. However, in line with [13,43] they can roughly be extrapolated to final and useful energy demand.

It is important to point out that the substantial reductions shown in Figure 3, of up to −44% through MPCon and of up to −82% through MPAdv, compared to the original heat demand, are the result of the complete energy-efficient refurbishment of all building components by the described modernisation packages.

2.1. Impact and Key Figures of Modernisation

In [37] as well as in [36,38], Germany-wide data survey was conducted in 2009 and 2016 on the energy characteristics and modernisation rates in the residential building stock. A total of 16,982 building datasets from 683 municipalities distributed throughout Germany were surveyed and evaluated. Table 2 provides an overview of the proportion of the subsequently insulated areas of the structural components; namely: external walls, roof/top ceilings, basement/cellar ceilings, and windows. These proportions take into account the percentage to which the respective component was thermally insulated. For example, the percentage of old buildings (until 1978) with subsequent external wall insulation is 37.6%, and the percentage of the external wall area provided with thermal insulation layer is just 73.9%. Multiplying both values results in the proportion of subsequently insulated external wall areas in the total old building stock being 27.8% [37]. All values are listed for three construction periods: first for "old buildings" built up to 1978, then for the construction periods 1979–1994 and 1995–2009. The temporal delimitation for the first construction period can be explained by the commencement of the first German ordinance on thermal protection (WschVO) at the end of 1977. The shift by one year results from its practical implementation in the course of 1978. The two later periods (1979–1994 and 1995–2009) were chosen in [36,37,44,45] according to a further development of this ordinance (more than one within each period). For new buildings from 2010 onwards, we suppose, following [46] and based on an average Reference Service Life of 35 years of building envelope components [47], that no relevant improvements in thermal insulation have taken place. As Table 2 shows, more than half of the roof and window areas of the "old" German housing stock (erected until 1978) had already been thermally upgraded by 2016.

Table 2. Share of modernised building components in the housing stock by 2016 (component modernisation progress $m_{c,y}$) [37].

Construction Period	Roof	Wall	Basement	Window
Until 1978	0.549	0.278	0.142	0.559
1979–1994	0.190	0.099	0.047	0.195 *
1995–2009	0.036	0.022	0.015	0.045 *

* Calculated based on Table 3.

Table 3. Ratios of the modernisation progress of building components relative to "Until 1978".

Construction Period	Roof	Wall	Basement	Window
Until 1978	1.00	1.00	1.00	1.00
1979–1994	2.86	2.84	2.90	2.87
1995–2009	15.12	12.76	9.10	12.34

The proportion of subsequently insulated structural component areas is expressed with regard to a given reference year as modernisation progress of the building stock. According to the definition given in [37], the modernisation progress reflects the modernisation activity (hence, the sum of the annual modernisation rates) in the past. Based on [37] as well as with regard to the statistical error margins, the values in Table 2 can be considered as representative for all regions in Germany.

For buildings constructed from 1979, the reviewed studies do not provide any information on the modernisation progress of windows. However, based on the data of the other components, by forming ratios between the individual values ("Until 1978" to "1979–1994" and "Until 1978" to "1995–2009"), we may assume that windows refurbishment has increased at a ratio similar to that of other components (see Table 3). For example, the modernisation progress for the roofs "Until 1978" is 54.9% and 19.0% for "1979 – 1994"; and thus about three-times higher in buildings "Until 1978". Based on this, we determine an average value from the other building components and periods for the modernisation progress of windows in 1979–1994 and 1995–2009. Accordingly, windows show a slightly higher modernisation progress than roofs, and a several times higher modernisation progress compared to external walls and basement/cellar ceilings.

The projection of the modernisation progress for the individual building components is characterised by its high level of detail. Since this information is not available for all regions, it is useful to aggregate the modernisation progress at lower levels (e.g., per building and construction period or for the entire building stock). Furthermore, this aggregation is particularly useful for a holistic view of the development of energy efficiency in building stock. Diefenbach et al. [38] evaluate the share of the structural building components in the total building area (building envelope) (see Table 4). They consider that refurbishing the different structural components can influence the heat demand of the building to varying extents (e.g., one m^2 of wall insulation reduces the heat demand more than one m^2 of basement ceiling insulation) [37,38].

Table 4. Share of the structural components s_c in the total building area (building envelope) [38].

Structural Component	Share in Envelope
Basement	0.12
Wall	0.50
Roof	0.25
Window	0.13

Using the values on the component modernisation progress $m_{c,y}$ of each component $c \in \{wall, roof, window, basement\}$ and the share of the components in the total building area (envelope) s_c from Tables 2 and 4, we can calculate the building modernisation progress $MP_{cp,y}$ for each construction period cp in year y based on Equation (1):

$$MP_{cp,y} = \sum_{c} m_{c,y} \cdot s_c \quad (1)$$

It is also possible to determine the modernisation progress over all construction periods if its share in the total building stock is known. This information is available in the Population and Housing Censuses [35] for all European countries and cities. Concerning Germany, it was evaluated in [40] based on the German census survey [34] (see Table 5).

Table 5. Share of buildings by construction period in the housing stock s_{cp} [40].

Construction Period	Share in Housing Stock
Until 1978	0.64
1979–1994	0.19
1995–2009	0.17

By using the information on the building modernisation progress of a given construction period $MP_{cp,y}$ from Equation (1) and the information on the share of the construction periods $cp \in \{Until\ 1978,\ 1979-1994,\ 1995-2009\}$ in the total housing stock s_{cp} from Table 5, we can determine a building stock modernisation progress $MP_{allcp,y}$ at the district, city or country level based on Equation (2).

$$MP_{allcp,y} = \sum_{cp} MP_{cp,y} \cdot s_{cp} \tag{2}$$

It is also possible to estimate the modernisation progress of existing buildings for certain years in the future based on the historical development of modernisation rates, the building stock modernisation progress $MP_{allcp,y}$ and the building modernisation progress $MP_{cp,y}$ determined before. In [37,38], information on the average annual modernisation rates in the periods 2005–2009 and 2010–2016 can be found. We hypothesise that the modernisation rates will increase in the future at the same ratio of the aforementioned periods, whereby the average modernisation rate increases by approx. 28% every six years (ca. 4.7%/a) compared to the previous period. We indicate a period of six years here as the evaluated studies have determined mean values over this period. This assumption seems feasible, at least based on the historical development recorded in [36–38]. It is also important to note that 5% of old buildings built up to 1978 in Germany are fully or partially listed (protected as historical monuments) [40], so we limit the modernisation progress of this construction period to 95%.

The preceding key figures on modernisation progress provide, in combination with heat demand values (Figure 3 and Supplementary Material), the basis for analysing the development of heat demand and improving its assessment methodologies. Since the states (original, refurbished with MPCon or MPAdv) represent two extremes (not refurbished, fully refurbished), their respective area-specific heat demand values cannot be applied without adjustment for a realistic heat demand assessment in the actual state. An adjustment to a certain year y can be carried out starting from the calculation of the following key figures:

- Modernisation figure $q_{m,y}$ in kWh/(m^2·a) quantifies the reduction in heat demand expected in year y as a result of the modernisation progress until that year.
- Modernisation factor $MF_{p,y}$ expresses the factor by which the heat demand is expected to decrease in year y as a result of the modernisation progress until that year.
- Adjusted heat demand $q_{adj,y}$ in kWh/(m^2·a) describes the specific heat demand in year y.

In Equation (3), the difference between the heat demand in original state q_{orig} and the heat demand q_{MP} after applying MPCon or MPAdv represents the achievable heat demand savings in kWh/(m^2·a) in the case of a full refurbishment of all building components. To account for the actually performed refurbishments, this difference has to be multiplied by the building stock modernisation progress of all construction periods $MP_{allcp,y}$ or, more specifically, by the building modernisation progress of a given construction period $MP_{cp,y}$. By subtracting the modernisation figure $q_{m,y}$ from the heat demand in original state q_{orig}, an adjusted heat demand $q_{adj,y}$ can be determined for the given year y (Equation (4)). Based on the adjusted heat demand and the heat demand in original state, a modernisation factor $MF_{p,y}$ can be derived for a certain year y by using Equation (5). In this study, we estimate the named key figures for each year between 2005 and 2050; nevertheless, this period can be extended based on the described approaches.

$$\begin{gathered} q_{m,y} = \left(q_{orig} - q_{MP}\right) \cdot MP_{p,y} \\ y \in \{2005, 2006, \ldots, 2050\} \\ p \in \{allcp, cp\} \\ cp \in \{Until 1978, 1979-1994, 1995-2009\} \end{gathered} \tag{3}$$

$$q_{adj,y} = q_{orig} - q_{m,y} \tag{4}$$

$$MF_{p,y} = \frac{q_{adj,y} - q_{orig}}{q_{orig}} \tag{5}$$

When applying Equation (3) based on the building stock modernisation progress $MP_{allcp,y}$ the specific heat demand values are the average values of all construction periods.

2.2. Climate Factor

The specific heat demand values in Figure 3 and in the Supplementary Material refer to a certain location "Reference Climate Germany". Since the German Energy Saving Ordinance 2013 (EnEV 2013), Potsdam represents the reference climate of Germany [48]. The Germany National Meteorological Service (Deutscher Wetterdienst DWD) provides the so-called climate factors for adapting heat demands to the climatic conditions of a specific location. They are available for 8234 locations in Germany with different postal codes and are used in accordance with GEG for issuing energy consumption certificates [49]. A climate factor $f_{climate}$ is calculated for running 12-month periods as quotients of the degree-days of the reference station Potsdam G_P and the annual degree-days of the study area G_{SA} (see Equation (6)).

$$f_{climate} = \frac{G_P}{G_{SA}} \tag{6}$$

In contrast to Heating Degree Days (HDDs), which are calculated when the average outdoor temperature falls below a "base temperature" (termed as "heating temperature limit" by VDI 4710 [50]) and refers to a certain location [51,52], climate factors encompass a wide range of meteorological variables (temperature, humidity, solar radiation, etc.) that describe general weather patterns and climatic conditions relative to the reference climate [48]. The adaption is obtained through dividing the heat demand by the climate factor of an investigated location (Section 2.3.3.).

2.3. Application in the Selected Tools

Since this section aims to illustrate procedures for improving heat demand assessments in existing approaches and open-source tools, we refrain from a detailed description of the corresponding methods. With reference to Section 1, Hotmaps and THERMOS offer the possibility to adjust the estimated heat demand via built-in functions. The heat demand assessment is conducted automatically in these tools and the climatic influence is already taken into account by means of the HDDs of the respective location; hence, only the integration of the modernisation progress is required. For the approach utilizing 3D Building Models and ALKIS in the Heat Cadastres Hamburg and Saarland, a completely autonomous data preparation and model development is required in order to estimate the heat demand of building stock. Here, both the climatic influence and the modernisation progress must be factored into these models.

2.3.1. Application in Hotmaps

In [24], a Calculation Module (CM) provides the possibility to change some basic drivers of the heat demand assessment. The drivers associated with the approaches developed in this work are:

- CM—Scale heat density maps: This calculation module allows to scale the heat demand density up or down for the total building stock of a city (value: Min. 0; Max. 10). Thus, a scaling value enables to reduce the calculated heat demand to zero or to increase it by a factor of ten.
- CM—Demand projection: This calculation module allows to scale the specific heat demand up or down for each building construction period (value: Min. 0%; Max. 200%). Thus, a scaling value enables to reduce the calculated heat demand to zero or double it at maximum.

However, the above-mentioned scaling values are not included in the Hotmaps tool, and our developed approaches contribute to filling this gap. Relevant for the above-mentioned Hotmaps Calculation Modules is the value of the modernisation factor $MF_{p,y}$ (Equation (5)), which is presented in Section 3 for each reference year as a main result of this study.

Since Hotmaps provides total heat demands for space heating and hot water (without process heat) of European cities, and the preceding MPs only affect the space heating, we include a factor f_{sh} to specify the share of space heating in the total heat demand. Accordingly, the value required for the improvement of the first CM (heat density maps, for $allcp$) can be determined using Equation (7):

$$CM_{input,allcp} = 1 - \left| MF_{allcp,y} \right| \cdot f_{sh} \quad (7)$$

The "Multiplication factor" $CM_{input,allcp}$ can be entered into the Hotmaps Calculation Module via a built-in input mask after selecting a city, a series of cities or even an entire country (Figure 4). The value is set to 1 by default and must be reduced to less than 1 using the modernisation factor in order to reduce the heat demand as a result of the thermal refurbishment. The heat demand estimation improvement then takes place automatically via a "RUN CM" button and the result is output.

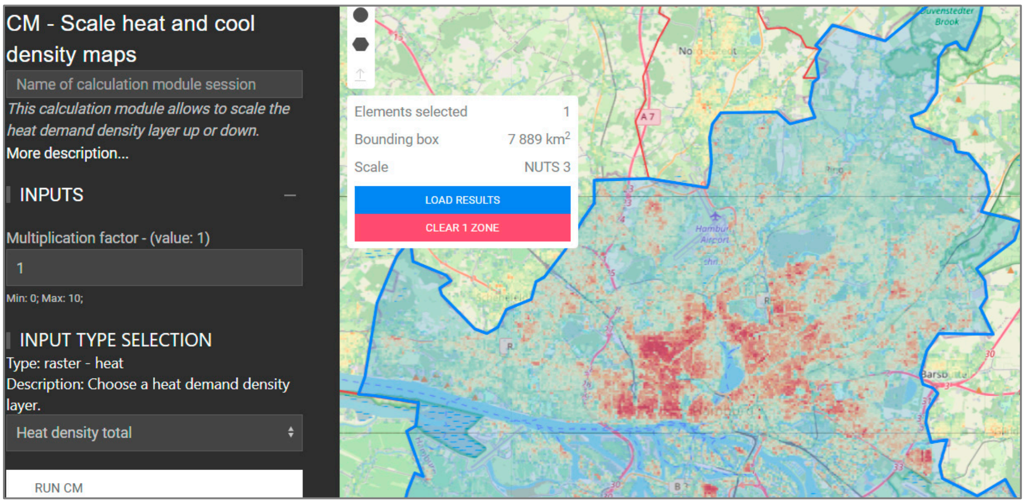

Figure 4. Built-in input mask for scaling the estimated heat demand in Hotmaps (CM—Heat density). The symbols (circle, hexagon and arrow) function as tools for drawing and importing shape areas.

The second CM (Demand projection) is useful if a higher level of detail is desired (subdivision per building construction period cp) or future scenarios are needed (heat demand forecast), as more parameters could be included in this CM (e.g., reduction in floor area, annual population growth, newly constructed buildings). In this case, $CM_{input,allcp}$ in Equation (7) must additionally be weighted by the share of the respective construction period in the total housing stock in order to obtain the desired value $CM_{input,cp}$ for CM (Demand projection) (see Equation (8)). This information is also available in Hotmaps under the layer "share of gross floor area" per construction period $f_{GFA,cp}$.

$$CM_{input,cp} = 1 - \left| MF_{cp,y} \right| \cdot f_{sh} \cdot f_{GFA,cp} \quad (8)$$

The multiplication factor $CM_{input,cp}$ is set to 100% for each construction period by default (see Figure 5). Here, a conversion from decimal to percentage is required.

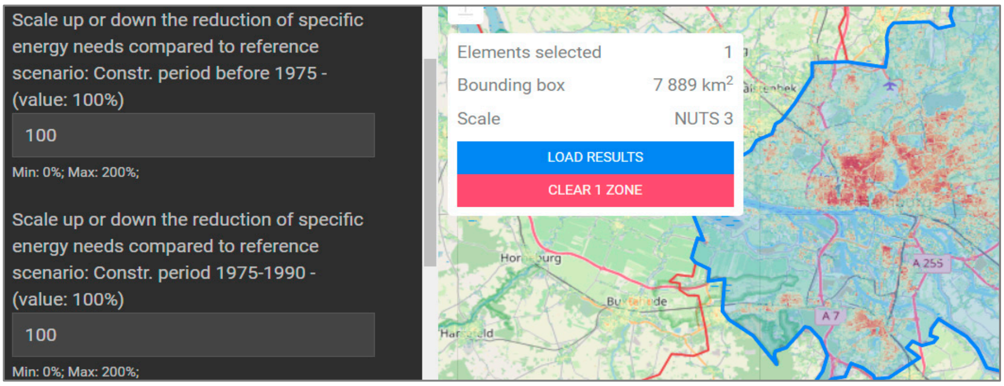

Figure 5. Built-in input mask for scaling specific heat demand in Hotmaps (CM Demand projection).

2.3.2. Application in THERMOS

As previously described, THERMOS does not estimate the heat demand on hectare level such as Hotmaps, but at building level using OSM as a database in almost all European cities (Figure 1). To improve the heat demand estimation in THERMOS, a built-in function enables the inclusion of key figures on realised or planned thermal refurbishments (see Figure 6). Since the modernisation factor $MF_{p,y}$ considers the effect on the entire building, it is immaterial to which building component the measure is applied (column "Applies to"). However, there would be a difference with regard to the costs of the measures if these were also to be considered (column "Variable cost"). Also, the "Maximum area" column can be overlooked, as it determines the maximum insulatable area as a percentage of the overall area, which is already included in the modernisation factor we provide. In the end, only the column "Maximum Effect" is relevant.

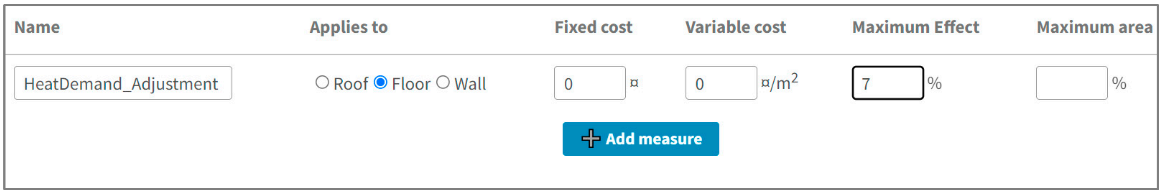

Figure 6. Input mask in THERMOS to consider refurbishments in the heat demand assessment (¤ symbolises an unspecified currency).

The input parameter "Maximum Effect" ME_{input} in THERMOS indicates the extent to which the heat demand should be reduced as a result of refurbishment. On the contrary, the "Multiplication factor" in Hotmaps denotes the ratio of the improved heat demand to the estimated heat demand. This means that the subtraction by 1 (Equations (7) and (8)) is already implied in THERMOS and the value for the input mask in Figure 6 is calculated based on Equation (9).

$$ME_{input} = \left| MF_{p,y} \right| \cdot f_{sh} \tag{9}$$

After entering the Maximum Effect ME_{input}, the refurbishment measures must be assigned to the buildings (to all $allcp$ or to a certain part cp of them) and the model must be set to "whole-system" and "Offer insulation measures" under "Objective" to obtain the desired results (more detail in [53]).

2.3.3. Application in Heat Cadastre Hamburg

The approaches for heat demand assessment based on 3D Building Models and ALKIS are described comprehensively in [29,30] using the Hamburg's and Saarland's Heat Cadastres as a case study. As already mentioned, neither the modernisation progress nor the climate factor were included in these approaches. As in Hotmaps, this can be implemented in two ways:

- By adjusting the specific heat demand values for self-performed assessments.
- By adjusting an already estimated heat demand.

The first approach with regard to the specific heat demand is useful if the methods of the Heat Cadastres are replicated. Here, in order to obtain an improved heat demand $Q_{imp,y}$ in kWh/a and year y, the corresponding adjusted specific heat demand values $q_{adj,y}$ (provided in Supplementary Material) must be adapted to the climatic conditions of the respective study area using the climate factor $f_{climate}$ (see Equation (10)). If the climate in the study area is warmer than the reference climate of Germany, the specific heat demand decreases; hence, it increases in colder areas where the climate factor is less than 1. In the next step, the domestic hot water demand q_{dhw} in kWh/(m^2·a) is to be added to the space heating demand and finally the sum is to be multiplied by the heated gross floor area (A in m^2).

$$Q_{imp,y} = \left(\frac{q_{adj,y}}{f_{climate}} + q_{dhw}\right)\cdot A \tag{10}$$

The second approach with regard to the estimated heat demand has the function of improving an already carried out heat demand assessment, based on Equation (11). For this purpose, the estimated heat demand Q (in kWh/a) is first multiplied by the share of space heating f_{sh} in the total heat demand. The result is then multiplied by the factor $\left(1 - \left|MF_{p,y}\right|\right)$ to reduce the space heating demand according to the performed refurbishment measures. In the last step, the space heating demand is adapted to the respective climate by means of the climate factor $f_{climate}$ and added to the domestic hot water demand (in kWh/a), which results from multiplying the estimated heat demand by the share of domestic hot water $(Q\cdot f_{dhw})$.

$$Q_{imp} = Q\cdot\left(f_{sh}\cdot\frac{1 - \left|MF_{p,y}\right|}{f_{climate}} + f_{dhw}\right) \tag{11}$$

3. Results and Application

In this section, we present the nationwide implications of the analysis and methodologies outlined in Section 2, providing an overarching perspective of Germany. Subsequently, we apply and validate these insights in the context of Hamburg, elucidating their specific relevance within the confines of this case study.

3.1. Findings for Germany

First, based on the Equations (1) and (2), Figure 7 shows the modernisation progress for each building construction period as well as for the total building stock. The modernisation progress is projected for a period of 45 years. Old buildings until 1978 show the highest rise in modernisation progress and reach a maximum of 95% in 2035, since the remaining 5% are listed (Section 2.1). Without considering the protection of listed buildings, the old building stock would have reached a 100% modernisation progress by 2036. In the target year 2045 of greenhouse-neutral energy supply in Germany, about half of the buildings of the construction period 1979–1994 and only one-eighth of 1995–2009 will have been modernised. The overall progress derives its course through the weighting of all construction classes (Section 2.1).

Based on the information on the modernisation progress and the specific heat demand in different efficiency levels (Original state, MPCon, MPAdv), we determine the impact of modernisation on heat demand based on Equations (3)–(5). In the Supplementary Material, we provide heat demand values in kWh/(m^2·a) adjusted to each year between 2005 and 2050 for the building types (single-family house (SFH), terraced house (TH), multi-family house (MFH), apartment block (AB)) and for each of the construction year classes indicated in Figure 3. Additionally, we illustrate in Figure 8, based on Equation (5), the projected modernisation factors for different years in the past and in the future. They describe the reduction in heat demand that can actually be achieved if buildings are modernised according to a certain modernisation progress (Figure 7) and via a certain modernisation package (MPCon and MPAdv). A list of the individual modernisation factors is available in the Supplementary Material.

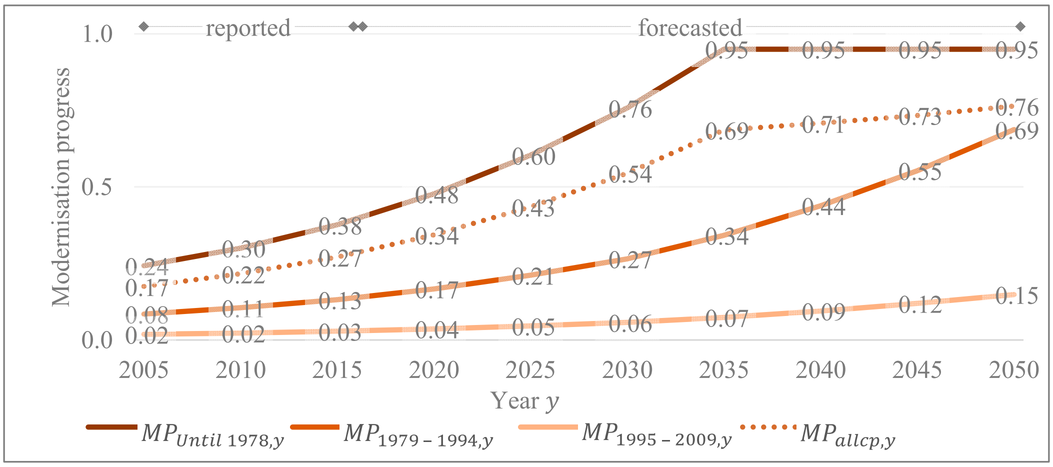

Figure 7. Reported and forecasted (after 2016) modernisation progress in the German housing stock (diamonds delineate period boundaries for reported and forecasted values).

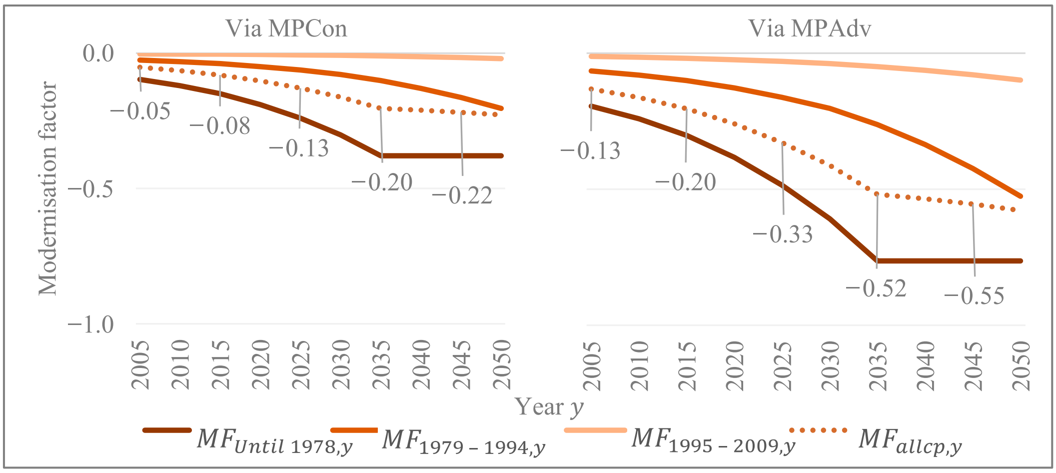

Figure 8. Modernisation factors of the German housing stock in different years (reduction in specific heat demand between original state and MPCon and MPAdv after factoring the modernisation progress; more details in Supplementary Material).

As already mentioned in Section 1, many studies expect an approx. 30–50% reduction in heat demand in order to achieve greenhouse gas neutrality in Germany and Europe. However, Figure 8 indicates unattainability of this goal by refurbishing in accordance with the Conventional/Mandatory (MPCon), while highlighting achievability via the Passive House Standard (MPAdv). The implementation of MPCon is expected to lead to a maximum heat demand reduction of 22% by 2045, while adhering to MPAdv is forecasted to result in a significant reduction of 55% within the same timeframe.

The heat demand of old buildings can be reduced by a maximum of 38% if the modernisation package MPCon is implemented. Without accounting for resource use and environmental impact, demolishing old buildings and constructing new energy-efficient ones would reduce the heat demand by an additional 5–10% [54,55], which leaves the adopted 30–50% reduction hardly achievable through MPCon. When MPAdv is implemented, a maximum reduction of 76% is achievable in old buildings. For the construction periods 1979–1994 and 1995–2009, a heat demand reduction of, respectively, 16% and 2% via MPCon, and 42% and 8% via MPAdv, is expected by 2045. As the old building stock reaches its maximum refurbishment level in 2036, the overall reduction in heat demand is modest (dotted line in Figure 8). The overall heat demand reduction (modernisation factor) progresses from −21% in 2036 to −22% in 2045 via MPCon and from 52–55% via MPAdv in the indicated years.

In order to identify the efficiency standards required to achieve the heat demand reduction targets in the German housing stock by 2045, the "Efficiency House" standards outlined in Section 2 are compared to MPCon and MPAdv in Figure 9. It illustrates that the implementation of the EH 55 and EH 40 standards can enable a heat demand reduction of over 30% as early as 2035, reaching a maximum of 33% via EH 55 and 36% via EH 40 by 2045. This implies that the minimum thermal insulation requirements specified in the current mandatory GEG regulation need to be adjusted to align with the standards in EH 50 and EH 45. Specifically, when buildings are refurbished, they need to achieve a 45% lower heat demand as prescribed by GEG in order to attain the heat demand reduction targets in residential buildings. In the case of refurbishments according to the Passive House Standard MPAdv, these targets can be attained within the next two years, and from 2035, they will be consistently exceeded, eventually reaching a 55% reduction by 2045.

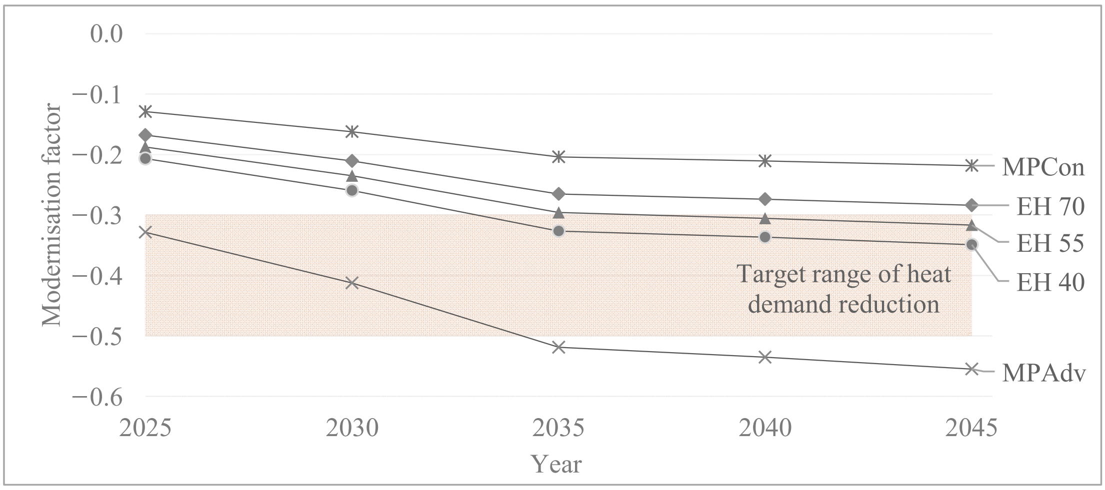

Figure 9. Identifying the efficiency standards required to achieve the heat demand reduction targets in the German housing stock by 2045.

As already described in Section 2.2, the indicated heat demands refer to the reference climate of Germany. Each site in Germany with a postal code is assigned a climate factor [49]. While warmer areas or years of a given postal code (indicated as site number in Figure 10) have higher climate factors than the reference climate, colder areas follow the contrary trend. Based on Figure 10, and with reference to the average values for the years (2009–2019), 68% of the areas in Germany have a warmer climate than the reference climate (climate factor 1). A detailed list of the values is available in the Supplementary Material. Climate factors are subject to strong temporal fluctuations and vary greatly from year to year for the same location.

Based on the average climate factors determined in Figure 10 for the years 2009–2019, the space heating demand can exceed the corresponding demand of the reference climate by a maximum of 39%, and can fall below it by a maximum of 21%. According to [56], a house in Düsseldorf with an annual heat consumption of 24 MWh would have a 32% higher consumption of 32 MWh if it were located in Munich. For a maximum climate factor of 1.3 and a minimum one of 0.7, the heat demand can differ maximally by a factor of 1.8 between two locations in Germany in view of climatic influences.

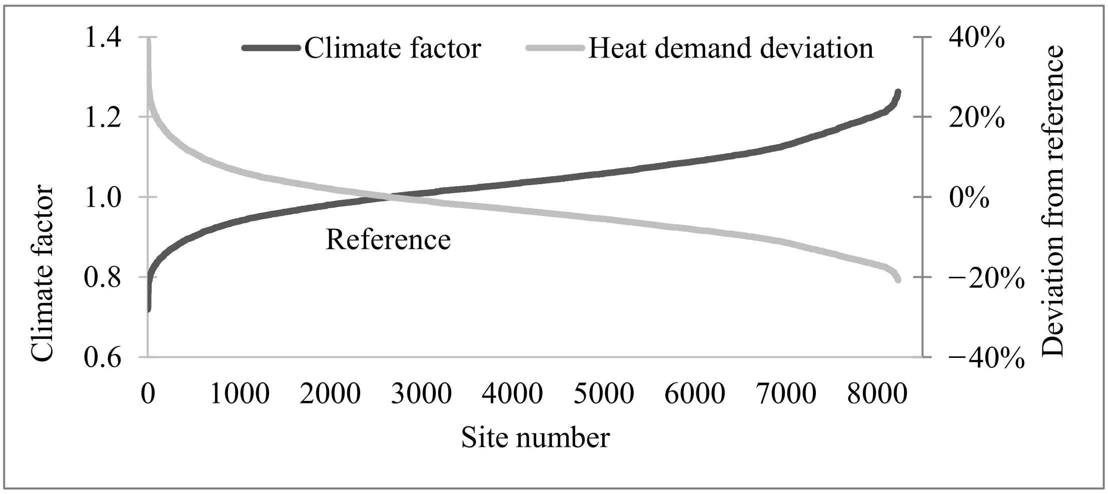

Figure 10. Effect of climatic differences on building heat demand. Specific heat demands (Figure 3) are standardised at the reference climate of Germany ($f_{climate}$ 1.0). Averaged climate factors 2009–2019 of 8234 different sites throughout Germany are provided for assessing climate-related deviations in heat demand.

3.2. Application and Validation for Hamburg

To validate our approaches, we use the above determined key figures to improve the heat demand assessments already carried out in Hotmaps and in the Heat Cadastre Hamburg. To bring about improvement, the modernisation factors of MPCon (Figure 8) are used since they correspond more closely to reality. Hamburg was chosen as a case study for the following reasons:

- Information on the real heat consumption of the city is available.
- Heat demand assessments carried out based on different databases and methods.
- The approaches are well documented, comprehensible and replicable.

The THERMOS software is an exception, as the heat demand in this software can be mapped at district level at most. We therefore limit this work to the approach described in Section 2.3.2. We successfully implemented a desired reduction in the heat demand according to the described approach for a small area. A new field "Insulated demand" with the improved heat demand was successfully produced in the software.

The Hotmaps tool estimates a heat demand for Hamburg of 18.56 TWh/a (related to in 2015), which exceeds the measured heat consumption by 7% [29]. In 2015, the modernisation progress in the total housing stock was 27%. According to Figure 8, a heat demand reduction of 8% is required to take the influence of modernisation into account. Following [29], space heating accounts for ca. 85% of Hamburg's building heat demand. This value approximately corresponds to the value reported for Germany in general [1]. Since modernisation measures only affect space heating, a modernisation factor of 93% can be calculated based on Equation (7), which can then be entered into the Hotmaps Calculation Module to improve the heat demand assessment (initial assessment using Hotmaps and result after improvement outlined by blue rectangles in Figure 11).

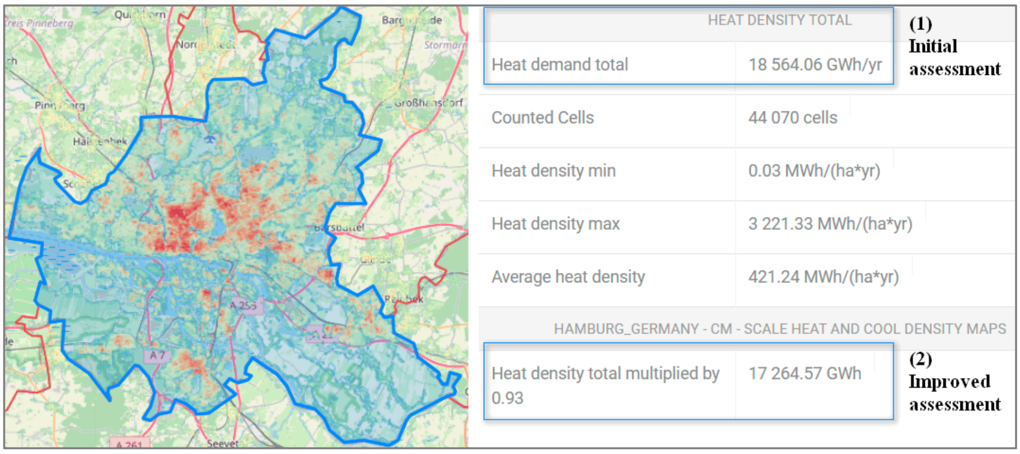

Figure 11. Improved heat demand assessment for Hamburg by factoring modernisation in the Hotmaps tool using the CM—Scale heat density maps.

Likewise, the estimated heat demand in the Heat Cadastre of Hamburg exceeds the actual heat consumption by 14%. Apart from the fact that modernisation was not taken into account, another reason for the high deviation was that the specific heat demand values were not adapted to the climatic conditions of Hamburg when applied. The averaged climate factor of Hamburg with the postal code 20095 is 1.11, as such the heat demand values should be reduced as in Equation (12) following Equation (11).

$$Q_{imp} = 19.80 \cdot \left(0.85 \cdot \frac{1 - |-0.08|}{1.11} + 0.15\right) = 16.92\ \text{TWh/a} \quad (12)$$

As demonstrated in Figure 12, the deviation from the measured consumption value is reduced from +7% to −0.2% in Hotmaps and from +14% to only −2.2% in the Heat Cadastre of Hamburg by improving the respective heat demand assessments. The real heat consumption of Hamburg was reported by the Hamburg Statistics Office based on measurements performed by the local energy utilities [29]. Finally, in view of the significant improvement through the use of modernisation factors based on MPCon, we can confirm the fact that buildings are not refurbished in accordance with the Passive House standard. The application of the modernisation factors according to MPAdv would have led to a strong underestimation of the heat demand.

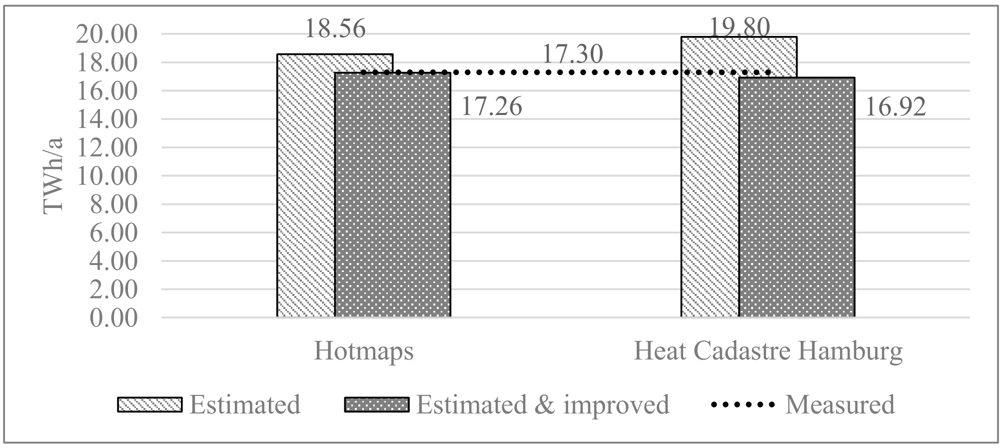

Figure 12. Validation of the approaches for improving two heat demand assessments for Hamburg (values refer to heat demand for space heating and hot water in 2015 [25,29]).

4. Discussion

It is clear that omitting key information on implemented refurbishment measures in heat demand assessments will lead to overestimations. If the heat demand still deviates from the real consumption value, despite the inclusion of the refurbishment, the influence of other parameters should be examined. The approaches presented in this paper are a good aid in the field of heat mapping. Nevertheless, they should be used with caution when mapping at the building level, as these approaches reduce the heat demand in percentage over all buildings of a certain construction period. The authors are also aware that applying the aforementioned approaches to further cities can strengthen the significance of the results notwithstanding the fact that the heat demands of cities are not usually estimated using multiple approaches, as is the case in Hamburg. The projected modernisation progress up to the year 2050 is based on the assumption that the future increase in modernisation rates is identical to the historical one, whereby the average modernisation rate increases by approx. 28% every six years (ca. 4.7%/a) compared to the previous period. This assumption represents a realistic scenario for the authors, which can, nevertheless, be influenced by political decisions. For instance, the European Parliament adopted amendments to the Energy Performance of Buildings Directive (EPBD) on 14 March 2023 [57]. They declared that residential buildings must attain a minimum energy performance of Class E by 2030 and Class D by 2033, corresponding to the EU's Energy Performance Certificates (EPCs) rating classes. They range from A to G, whereby buildings of the classes E, F or G are classified as "worst-performing buildings". The rating scale in Germany according to GEG has two further classes (A+ representing the highest and H representing the lowest energy performance). Since EPBD refers, in its amendments, to the two worst-performing buildings (Classes E and D), the question arises whether Germany will reclassify the GEG rating Class H to G and G to F. As a result, over 6 million houses (approx. 30% of residential buildings) are expected to be subject to the regulation. This would lead to an average reduction of the heat demand in these buildings of 30–35%, following the GEG rating scale. This reduction corresponds to the outcomes depicted in Figure 8 when MPCon is applied to the buildings of the construction period "Until 1978", where the Classes F and G would most likely be situated. As per Figure 8, and with respect to the limitation of modernisation progress to 95% in Figure 7 due to protection of historical monuments, much greater heat demand reductions would not be possible for old buildings built up to 1978, even with a complete refurbishment via MPCon. Consequently, even in light of EPBD amendments, achieving the targeted 30% to 50% heat demand reduction in the entire residential building stock ($MP_{allcp,y}$ in Figure 8) as indicated in various greenhouse gas-neutral energy supply scenarios would be challenging, if not unattainable. Figure 9 illustrates that attaining this objective is feasible with MPAdv, EH 40 or EH 55 retrofits. However, this prompts an inquiry into the expenses associated with high-efficiency retrofits, aligning with the primary aim of the German GEG, which seeks to ensure that the costs of energy-efficiency retrofit measures pay back over their 25-year lifetime through energy savings [42]. The influence of the rebound effect on heat demand post-implementation of thermal refurbishments is noteworthy, despite not being explicitly examined in our study. Finally, ongoing discussions revolve around additional challenges related to the technical implementation of high-efficiency standards, stemming from constraints imposed by building regulations, urban planning, fire safety, and issues of limited acceptance [13].

5. Conclusions and Outlook

This work projects the modernisation progress and building heat demand over a period of 45 years, in accordance with five different energy efficiency standards. In light of the building energy efficiency targets presented in various scenarios, which strive for a 30–50% heat demand reduction as an enormous stride toward a greenhouse gas-neutral heat supply, we conclude:

I. If refurbishments are carried out in accordance with the current German Buildings Energy Act GEG, a maximum reduction in heat demand of only ca. 22% can be achieved by the target year 2045. Likewise, the efficiency targets stated are not achievable by implementing the Efficiency House standard EH 70, which has a 30% lower heat demand than specified in GEG.

II. The minimum requirements, as set forth by the GEG, must be at least adjusted to match the EH 55 standard, featuring a 45% lower heat demand. This adaptation enables the attainment of the targets as early as 2035.

III. Adopting standards higher than EH 55, such as EH 40 and the Passive House Standard, certainly enables the attainment of the target. However, this introduces cost-effectiveness concerns and the widely debated implementation challenges in existing buildings, which emanate from factors like building regulations, urban planning, fire safety, and limited public acceptance.

IV. The proposed amendments to the Energy Performance of Buildings Directive (EPBD) require buildings to attain a minimum energy performance of Class D by 2033. This will affect over 6 million houses, which amount to about 30% of the German residential buildings. Although this will accelerate refurbishment progress in Germany, it will fall short of achieving the targets due to its exclusive focus on two "worst-performing buildings" classes and the moderate efficiency improvements, especially given the presence of additional classes A+ and H within the GEG rating scale.

It also transpires that a building's heat demand within Germany can reach up to 39% higher or up to 21% lower than the heat demand of an identical reference building in the reference climate of Germany due to climatic influences. Furthermore, as part of the validation process, we improve the heat demand of Hamburg that was estimated in Hotmaps and in the Heat Cadastre of the city, where the deviation from the measured consumption value is reduced from +7% to −0.2% in Hotmaps and from +14% to only −2.2% in the Heat Cadastre.

The approaches developed in this study are transferable to other locations in Europe; however, the key figures determined for Germany are not; and can only be applied to German cities and at most at the district level. The feasibility of extending our approaches to other countries is viable with the presence of similar databases. It remains to be answered whether the modernisation progress can be mapped at the building level, which is of great importance with regard to the planning of heating networks, as more precise information with a high level of detail is required for pipe and plant dimensioning.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/en17030690/s1. It includes five data sheets with information on the development of thermal refurbishment as well as the heat demand in the German housing stock for each year between 2005 and 2050. It also contains an additional sheet that provides data for adapting heat demands to the climatic conditions of different locations.

Author Contributions: A.S.: Investigation, Data Curation, Methodology, Formal analysis, Visualisation, Validation, Writing—original draft; I.P.: Supervision, Review and Editing; S.H.: Supervision, Review and Editing. All authors have read and agreed to the published version of the manuscript.

Funding: This research paper was prepared and refined as part of the project "Biomass Integration for System Optimisation in the Energy Region Hümmling (BISON)", funded by the German Federal Ministry of Food and Agriculture (BMEL) under grant No. 22031718; and the project "Development of Open Source Geodata for Municipal Heat Planning (KomWPlan)", funded by the Energy Research Centre of Lower Saxony (EFZN) with state funds of the Clausthal University of Technology under grant ID EFZN-PA-2022_03.

Data Availability Statement: Data are contained within the article and Supplementary Materials.

Conflicts of Interest: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Abbreviations

AB	Apartment Block
CM	Calculation Module
DWD	Deutscher Wetterdienst
EH	Efficiency House
EnEV	Energy Saving Ordinance
EPBD	Energy Performance of Buildings Directive
EPC	Energy Performance Certificate
GEG	German Buildings Energy Act
HDDs	Heating Degree Days
LiDAR	Light Detection and Ranging
MFH	Multi-family House
MP	Modernisation package
MPAdv	Advanced Modernisation Package
MPCon	Conventional Modernisation Package
OSM	OpenStreetMap
SFH	Single-family House
TH	Terraced House
WschVO	Ordinance on thermal protection

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