Enriching a Building Typology with Data on Heating Systems and Renovation Measures

- A Case Study from Hamburg

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Abstract

This paper examines 1,500 energy certificates of residential buildings from the city of Hamburg to derive frequencies on typical heating systems currently operating in the building stock and their proposed replacements for an energetic renovation in context of public incentive programmes.

It was not possible to find a significant correlation between heating systems and IWU building types or heating systems and building's construction epochs in general. Yet, differences between heating systems in different construction types were found (for example multi-family buildings have a higher tendency to be connected to a district heating grid than single-family buildings). Furthermore, the frequencies of the considered heating systems within Hamburg's seven districts were derived from the dataset and may form a foundation for heat simulations on district- or city-scale.

Additionally, this paper delivers coefficients that display the correlation of final energy demand for different heating systems and allow the comparison of the system's efficiency within one energetic level, the baseline condition, "usual" or "advanced" refurbishment level. The final energy demand computations are based on the TABULA Calculation Tool developed by the IWU with adjustments on the heating system according to the findings of the dataset examinations.

In the end, an estimation of refurbishment costs, based on another publication of the IWU, complete the data for residential buildings and enable a holistic assessment of refurbishment measures in residential including the ecological and economical criterions.

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List of Abbreviations

CHP	Combined Heat and Power
DH	District heating
DHW	Domestic hot water
EFH	Single-family house (Einfamilienhaus)
GEWISS	Geographical heat information and simulation system
GMH	Apartment block
HH	High rise building
HP	Heat pump
IFB	Investitions- und Förderbank Hamburg
KfW	Kreditanstalt für Wiederaufbau
MFH	Multi-family house
RH	Row house
TS	Transfer station (for the district heating grid)
u-value	heat transfer coefficient, describing the heat transfer of a building part

1 Introduction

In respect of the climate change, a significant reduction of greenhouse gas emissions has to be achieved within the upcoming decades. Not only the German Government published their ambitions on climate protection and commissioned studies to examine the necessary measures to achieve them, but also federal states and cities like Hamburg recorded their own targets for the energy transition (BÜRGERSCHAFT DER FREIEN UND HANSESTADT HAMBURG, 2013).

Apart from electricity and mobility, heat forms the third important energy sector. The reduction of heat demand implies the decrease of energy losses caused by insufficient insulated building envelopes and the raise of energy efficiency of heating systems. However, it is difficult to assess the impact of different heating systems on the future development of the greenhouse gas emissions in a city like Hamburg because each system has its own advantages and disadvantages and the house owner motivations for or against using a specific system are dependent on various factors. For the city it is necessary to develop strategies for the transition of the heating sector and to decide which energy carriers and heating systems are most beneficial to achieve the climate protection goals. Based on that strategy, the city can offer financial incentives to motivate the house owners accordingly.

As an instrument for the preparation of such strategies, the GEWISS project[1] develops a digital heat cadastre for the city of Hamburg, which, among other things, is going to display the current heat sources and sinks as well as possible future scenarios.

On city scale, the heat demand of a large number of buildings has to be calculated and simulated and the conventional method for this matter is the usage of the German building typology, provided by the Institute for Housing and Environment (*Institut für Wohnen und Umwelt* – IWU). With the available information of the digital cadastre, an “IWU type” that contains an estimated useful heat demand, which is mainly dependent on the energetic quality of the building envelope, can be assigned to each building. However, to calculate the current greenhouse gas emissions, it is necessary to know the final energy demand, which includes the energy losses of the heating system on top of the useful heat demand. And although e.g. information about the location of natural gas grids is available and therefore, it can be assumed whether or not a building might heat with natural gas, it is still unknown what kind of boiler is used and thus, the actual size of the energy losses that occur during the transformation from gas to useful heat is unknown.

In this regard, this Master Thesis examines a set of energy certificates for Hamburg’s residential buildings to figure out whether there are possibilities to conclude the heating system based on the

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[1] Geographical heat information and simulation system, https://projektinfos.energiewendebauen.de/projekt/geografisches-waermeinformations-und-simulationssystem/

construction type or year of the building, or the district it is located in. The additional data on heating systems is completed with a simplification of the IWU-method to estimate the final energy demand of different heating systems and data on estimated refurbishment costs.

2 Approach

The Hamburg specific information on heating systems distilled from 1,500 energy certificates that contain data on the building's existing state and a proposed refurbishment option that allows the financial funding by Hamburg's state investment bank.

The heating systems in building stock and refurbishment proposal are examined to identify the most frequent heaters used for space heating and supply of domestic hot water, as well as the heaters age and insulation of distribution pipes. As one aim of this Master Thesis is to provide data that can be used to assign heating systems to buildings based on the information available in the digital cadastre, a number of possible connections to general building characteristics, such as the construction type (differentiated into single- or multi-family buildings), the construction year, and the districts of Hamburg, are tested and evaluated.

In the next step the calculation of the IWU building typology is enriched by the findings of the dataset analysis on heating systems. Additionally, the building envelope is slightly adapted for the "usual" and "advanced" refurbishment levels the energetic quality, especially the latter benefits from the information included in the dataset.

In the end, the information on refurbishment in residential buildings is completed by estimating the related costs, which include the expenses to insulate the building shell and install a new heating system. The estimation is mainly based on the regression analysis of actual refurbishments, performed by (HINZ, 2015) extended by approximate costs on electric instant water heaters.

3 Data Sources

3.1 IWU-Building Typology

In Hamburg the official digital cadastre, named ALKIS (*Amtliches Liegenschaftskataster Informationssystem*), contains various data on the building stock and is used as the basis for the calculations in the GEWISS project. In this context, the ALKIS needs to be enriched with data on heat demand from the national typology for residential buildings, which was developed by the Institute for Housing and Environment (*Institut für Wohnen und Umwelt* – IWU, LOGA ET AL., 2015). The IWU analysed one existing building for each epoch and building type for 42 nation-wide types in total and based on that formed a baseline condition, an "usual" and an "advanced" refurbishment level for each building type .

For the European research project TABULA and its follow-up project EPISCOPE the IWU and their European partners developed an Calculation Tool that computes the energy demand for residential buildings using a simplified version of the calculations of EN ISO 13790 and EN 15316 (LOGA ET AL., 2015, p. 75).

The IWU building typology and the TABULA Calculation Tool are the foundation of the computations in this Master Thesis. It is enriched with data on mainly heating systems based on the findings of the examination of energy certificates. Moreover, instead of the Passive House Standard the "advanced" refurbishment level aims at the Efficiency House Standard 55 and the u-values are adapted accordingly.

The TABULA Calculation Tool includes the climate regions of Germany according to DIN V 18599-10:2011-12. For official German energy certificates the reference climate of Potsdam has to be used, but as the building typology is enriched specifically for Hamburg, its local climate is taken for all energetic calculations within this Master Thesis.

3.2 IFB-Dataset

To get information on heating systems a set of energy certificates is used that was provided by Hamburg's state investment bank (*Investitions- und Förderbank Hamburg* – IFB), which, among other things, finances advanced refurbishment measures in residential buildings. In order to approve financing, the IFB demands a detailed energy certificate (*Hamburger Energiepass*) compiled by an authorised energy advisor and quality assured by second, independent engineer. This certificate provides information on the current energetic status of the building and proposes refurbishment measures in a more thorough manner than a common energy certificate.

The information on the existing state contains assumptions, such as the material density of the building parts etc., which affect the computed energy demand. Still the energy certificate provides an educated guess on the energetic properties of the building; especially the overall plausibility of the calculation can be considered to be relatively certain due to the quality assurance. In general, the *Hamburger Energiepass* as such gives no indication as to what extent and in what form energetic measures have actually been applied after the certificate was prepared. Yet, the refurbishment proposal was compiled on basis of the actual building and its conditions with the aim to satisfy the requirements for an incentive programme of the IFB and thus, is used to design the "advanced" refurbishment level in this Master Thesis.

About 7 700 certificates that were created between 2000 and 2012 were already analysed in a former research project (HERMELINK ET AL., 2014). The dataset contains processed building information, i.e. mean u-value for all walls of a building, limited information about the heating system, etc. and thus, have restricted value for the research on heating systems in this Master Thesis.

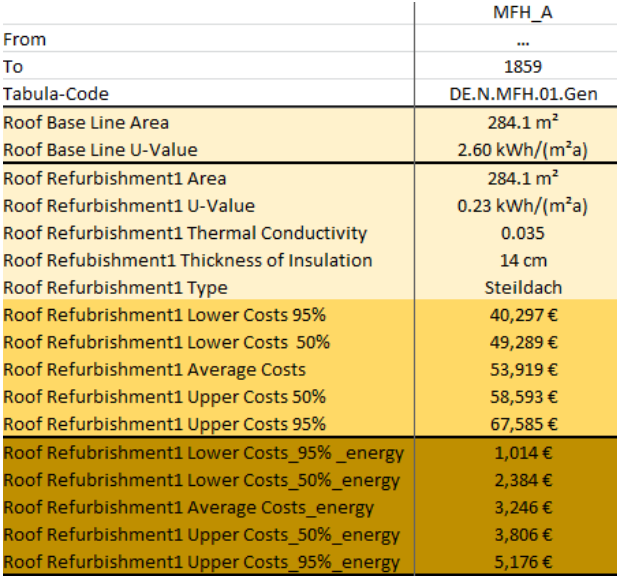
Recently, the IFB provided the newest certificates from the years 2010 to end of 2016[2]. The company Hottgenroth, whose software is used by most energy advisors to produce the *Hamburger Energiepässe*, compiled a dataset out of the raw files of these newer certificates. It contains 1,500 buildings in total with information on existing and refurbished state, u-values for every building part, settings of the heating system, etc.

This Master Thesis refers to the latest 1,500 buildings as *new* dataset, while the 7,700 buildings analysed by Ecofys are labelled as the *old* dataset and the focus lays on the former due to the more detailed information regarding the heating systems of the building.

3.3 Refurbishment Costs

Apart from the ecological efficiency of building refurbishment it is important that future strategies are financially feasible as well. The estimation of the refurbishment costs delivers an instrument to compare different refurbishment levels and various heating systems regarding their economical properties.

The cost estimation is mainly based on the publication of HINZ (2015) from the IWU. He analysed 1,177 refurbished buildings that used national incentive programmes of the reconstruction loan corporation (*Kreditanstalt für Wiederaufbau* – KfW) and made a regression analysis for the costs of individual measures. The regression functions of insulation measures are correlating with the thickness of the insulation, while heating systems are calculated on basis of the living space. The additional confidence intervals allow the evaluation of the range in which the actual costs may lie. Furthermore, Hinz differentiated between costs that had to be paid anyway, no matter whether the building part was insulated or not, and energy related additional costs. Based on his work a small tool was developed KÖHLER, 2017, see Figure 3.1.



	MFH_A
From	...
To	1859
Tabula-Code	DE.N.MFH.01.Gen
Roof Base Line Area	284.1 m^2
Roof Base Line U-Value	2.60 kWh/(m^2a)
Roof Refurbishment1 Area	284.1 m^2
Roof Refurbishment1 U-Value	0.23 kWh/(m^2a)
Roof Refurbishment1 Thermal Conductivity	0.035
Roof Refubishment1 Thickness of Insulation	14 cm
Roof Refurbishment1 Type	Steildach
Roof Refubrishment1 Lower Costs 95%	40,297 €
Roof Refubrishment1 Lower Costs 50%	49,289 €
Roof Refurbishment1 Average Costs	53,919 €
Roof Refurbishment1 Upper Costs 50%	58,593 €
Roof Refurbishment1 Upper Costs 95%	67,585 €
Roof Refubrishment1 Lower Costs_95% _energy	1,014 €
Roof Refubrishment1 Lower Costs_50%_energy	2,384 €
Roof Refurbishment1 Average Costs_energy	3,246 €
Roof Refurbishment1 Upper Costs_50%_energy	3,806 €
Roof Refurbishment1 Upper Costs_95%_energy	5,176 €

Figure 3.1 Screenshot from the cost estimation tool (KÖHLER, 2017)

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[2] There is some overlap between the ‘older’ and the ‘newer’ dataset - for the period 2010 - 2012

4 Preparing the Dataset

Originally, the newly compiled dataset provided by Hottgenroth included 4,316 entries, but it was quickly observed that several addresses could be found multiple times. One reason for this issue is that the IFB examines each certificate for its plausibility and in case of errors or doubtful information the responsible energy advisor has to hand in a corrected version and sometimes the measures have to be adjusted during the process of renovation due to unforeseen properties of the building and therefore, require an alignment of the energy certificate.
An interview with IFB showed that the entries with the newest dates are usually the ones, on which the funding process is calculated and thus, the redundant data was adjusted based on the dates of certificates (VON VALTIER, PERSONAL COMMUNICATION, 2017).[3]

Unfortunately, the dates are not included in the dataset and consequently, another method had to be developed to identify and delete the old certificates as well as the addresses that were saved accidently with the intended ones.

4.1 Sorting by zip-File Name and Date

The Hottgenroth software produces zip-files which were sent to the IFB, who usually saved these files in the following format using the underscore symbol as separator:

Street_HouseNumber_Date_NumericalCode.zip

With the help of VBA macros the names of the original zip-files were compiled into an Excel spreadsheet and out of that, the address and date were read. In the following step the addresses from the zip-files were linked with the addresses of the dataset provided by Hottgenroth and the comparison showed that a few zip-files addresses are not in the dataset because the zip-file is broken and therefore, could not be read by Hottgenroth. Furthermore, some file names do not include a date, while in others the address was spelled differently or included other house numbers than the address that was written in the file itself.
All in all, the entries in Hottgenroth’s dataset have the same order as the zip-files in their folder, which allows a rather simple, partially manual, matching of addresses despite of different spelling. File names that did not meet the common structure were corrected manually.

Finally, a macro identified the youngest date of an address and deleted the rows with the older dates.

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[3] Another problem was that the new IFB dataset includes some buildings that were not located in Hamburg. Taking a look at the original zip-files, which are produced by Hottgenroth software, it was revealed that single files included more than one building. This can be ascribed to the software’s workflow: Multiple buildings can be opened simultaneously and they can be saved all together in one zip-file. To save them individually, one has to activate an additional checkbox that can be easily forgotten. Apparently for a few buildings the whole workspace was saved and sent to the IFB.

4.2 Adding Hamburg Districts

For the analysis of spatial patterns it is necessary to know the districts in which the buildings are located.

DOCHEV ET AL. (2017b) used the cleaned dataset prepared in Section 4.1 in combination with a python program and matched the building addresses with georeferenced address points of the Hamburg digital cadastre. Combining these results with information on districts of the city of Hamburg (LGV, 2017) allowed to add the district to each address of the new dataset.

4.3 Assigning IWU Types

IWU building types were assigned to the entries of the new dataset to enable the examination of possible connections between heating system and building type or construction year.

In their working paper (DOCHEV ET AL., 2017a) developed a method to assign IWU building type based on data available in the ALKIS such as year of construction, number of storeys, and “construction type”[4]. Furthermore, DOCHEV ET AL. (2017c) built a GIS-model of Hamburg, using their assignment method in combination with interpolation to assign IWU types to residential buildings without information construction year based on the age of neighbouring buildings. This method is prone to errors and therefore, is more of a best guess.

Since the energy certificate dataset was linked to the official addresses of the ALKIS using geocoding methods (DOCHEV ET AL., 2017b) it enables a connection between the GIS-model of Hamburg and the dataset and therefore an assignment of IWU-types.

Yet, a few entries of the dataset still lacked an IWU type or are assigned to building types from 1995 or younger, which is not plausible because the incentive programmes of the IFB are restricted for objects with a building application dated from 31st of December 1994 or older (IFB, 2017a, p. 9; IFB, 2017b, p. 5). For these entries the data included in the energy certificate was used to assign an IWU building type. However, since the main purpose of the energy certificate is to describe energetic properties, additional information like the construction year (or the living space[5] for that matter) given in the certificate could be just estimated or contain a typing error. Thus, the assigned IWU types constitute an educated guess based on non-perfect information rather than an obvious and clear building characteristic.

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[4] *Bauweise*, i.e. single-family house, multi-family house, etc.

[5] The German energy certification uses a reference area different from the living space (usable area – “*Nutzfläche EnEV*“. Therefore the living space given in the energy certificates is additional information given for reference and can also be prone to errors.

5 Heating Systems in General

5.1 Gas and Oil Fuelled Systems

In context of this Master Thesis, the term “heating system” will usually comprise the boiler which provides the space heating (can also be a transfer station in the case of district heating), the distribution system as well as the system used to supply domestic hot water (DHW).

One can differentiate between two heating systems: the first one is a *building-central*[6] system that uses the same boiler to produce space heating and DHW, while the second, *building-decentral* system uses electrical appliances for DHW supply.

The oldest boiler type, which is not state of the art anymore, is the so called constant temperature boiler (*Standardkessel* in German). As the name indicates, it has a fixed operating temperature with more than 70 °C and uses cold water to mix it down to the required heating temperature (JAGNOW & WOLFF, 2009, p. 2; ÖKO-ZENTRUM NRW, 2011a, p. 30).
A couple of variations of this boiler are available, using slightly different burning mechanisms or being specialised either on firing natural gas or heating oil[7]. Literature does not give many details on the energy losses for each system and the Hottgenroth software lists all these boiler types under the header *constant temperature boiler*. And as, the TABULA-Calculation Tool also does not include further differentiation, all these boilers are summarised as constant temperature boilers in this Master Thesis.

Low-temperature boilers are able to adapt their operating temperature on basis of the outdoor temperature. Usually the heating water has temperatures between 75 °C and 40 °C (ÖKO-ZENTRUM NRW, 2011a, 30).

Condensing boilers are forming the current state of the art and make use of the energy included in the exhaust gases. Thus, they can reach energy efficiencies higher than 100 % because the efficiency rating is based on the lower heating value which excludes the energy of the exhaust air. Firing natural gas in condensing boiler is more advantageous because heating oil contains more sulphur, which makes it necessary to neutralise the condensate before it can be fed into the canalisation (ÖKO-ZENTRUM NRW, 2011a, 30).

Usually the three named boiler types are differentiated into three installation periods: “until 1986”, “1987-1994”, and “after 1995”. In addition, condensing boiler from 1995 can have an improved efficiency.

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[6] In this case the stress lies on “building” as on city-scale district heating grids can be considered a central system, while all other heating systems can be regarded as decentral systems

[7] *Gebläsekessel, Spezialkessel, and Wasserdurchlauferhitzer*

Table 5.1 shows that the newer the technology and the installation year of the boiler, the smaller is the expenditure factor of the system, which is basically the sum of usable energy and process losses divided by the usable energy (DIN V 18599-1:2016-10, pp. 16, 88).

Table 5.1 Excerpt of expenditure factors for boilers (LOGA, 2016)

Boiler for Single-Family-Houses		**Expenditure Factor**	
		Heating	**DHW**
Constant Temperature Boiler	until 1986	1.46	1.76
	1987 - 1994	1.42	1.72
	from 1995	1.37	1.63
Low Temperature Boiler	until 1986	1.35	1.38
	1987 - 1994	1.29	1.35
	from 1995	1.23	1.27
Condensing Boiler	until 1986	1.21	1.31
	1987 to 1994	1.18	1.29
	from 1995	1.16	1.23
	from 1995 & improved efficiency	1.08	1.21

5.2 Biomass Fuelled Boilers

In building stock decentral stoves can be found that are fired with wood. Often they do not have a high share in the provision of the overall heat demand and tend to be used more for comfort and ambience than for the purpose of heating itself. In energy certificates often a share up to 10 % is set for the wooden material as due to the regulations of the KfW incentive programmes a share of up to 10 % for wood fired boilers or solar thermal devices in the production of space heating does not have to be verified with more detailed system calculations (KFW, 2016, 24, 26).

Apart from the wood fired stove the TABULA Calculation Tool provides data on pellet boilers. In comparison to the firing of logs or woodchips, pellets have the advantage of a constant material quality and the highest degree of utilisation. On the downsides pellets have the highest material costs and slightly higher greenhouse gas emissions than the other wooden fuels (ÖKO-ZENTRUM NRW, 2011a, 36).

Wood pellets boiler in single-family houses have an expenditure factor of 1.37 compared to 1.60 for wood firing stoves (LOGA, 2016).

5.3 District Heating Grids

Hamburg’s main district heating grid is operated by Vattenfall GmbH and supplies 470,000 flats with hot water mainly produced by combined-heat-and-power-plants (VATTENFALL WÄRME HAMBURG GMBH, 2016, p. 3).

House owners have the advantage that they only need a transfer station (TS) and distribution pipes in their building, the production of the heat takes place somewhere else. The transfer station itself has only little energy losses (expenditure factor = 1.02, (LOGA, 2016)).

In general, it is often more beneficial to use CHP in large scale plants as the economies of scale improve the profitability and simultaneously the process efficiency increases. A district heating grid obtains the possibility to integrate waste heat from industrial facilities, conventional power plants, or heating plants that fire biomass to decrease the greenhouse gas emissions of the overall heating grid.

On the downside, the expansion of district heating grids is costly and the decreasing heat demand of refurbished buildings and their lower operating temperatures are contrary to the heating grid's mechanics, which have negative effects on the overall profitability of the system (OSCHATZ ET AL., 2016). Therefore, it is necessary carefully plan the possible development of the heat demand and its effects on the district heating grids.

5.4 Heat Pumps

Most heat pumps (HP) in residential building sector are operating with electrical energy but appliances using natural gas are available as well. The main advantage of heat pumps is the usage of energy stored in soil, ground water, and external air. The efficiency is assessed with the Coefficient of Performance (COP) which amount to 3.5 or higher for heat pumps that use soil as heat source, meaning that each kilowatt hour of electrical energy produces 3.5 kilowatt hours of heat. Table 5.2 shows the related expenditure factors for heat pumps.

The efficiency of the system is dependent on the temperature difference between heat source and targeted heating temperature. As the temperature of the external air is fluctuating considerably over the year, they reach the smallest COP. In addition, the supply temperature of heat pumps has usually a maximum of 45 °C, preferably lower (ÖKO-ZENTRUM NRW, 2011a, p. 41) and therefore can be used best in refurbished buildings, because they have a lower heat demand than uninsulated buildings.

Table 5.2 Excerpt of expenditure factors for heat pumps (LOGA, 2016)

Heat Pump			**Expenditure Factor Heating**
Heat Source	**Heating Rod**	**Year of Installation**	
Soil, ground water or water stream	with h. rod	until 1994	0.36
		from 1995	0.32
	without h. rod	until 1994	0.32
		from 1995	0.29
External air	with h. rod	until 1994	0.45
		from 1995	0.38
	without h. rod	until 1994	0.42
		from 1995	0.35

5.5 Electrical Appliances

In building stock electrical night storage heaters can be found. For a couple of years, the Energy Saving Ordinance 2009 (*Energieeinsparverordnung* – EnEV) Paragraph 10a, required house owners to exchange their devices until 2020 or earlier in case the heater has a certain age. This regulation, however, was withdrawn in 2013 and thus, currently no legal requirements have to be met regarding electrical night storage heating.

Nevertheless, night storage heaters are often replaced in case of a holistic refurbishment, as they tend to be costly and inconvenient, because their regulation options are limited on the heat that was stored overnight. While electricity can be transformed to heat with little losses (expenditure factor of 1.00 (LOGA, 2016)), the electricity generation is connected to high greenhouse gas emissions.

DHW is often supplied by electric instantaneous water heaters, which have an expenditure factor of 1.00 (LOGA, 2016). Although electricity has high greenhouse gas emissions, it cannot be assumed that buildings that have building-decentral DHW production will change to a building-central DHW system, because the change can become costly as new pipes would have to be laid and additional planning would be required. Therefore, it is more likely that a considerable amount of buildings continue to produce their DHW in a decentral manner.

5.6 Primary Energy Demand and Greenhouse Gas Emissions

In the context of the climate protection targets the final energy demand and the connected greenhouse gas emissions are most relevant. Table 5.3 shows that electricity has the highest emissions, while wood and pellets have the smallest.

Table 5.3 Excerpt of primary energy factors and greenhouse gas emission values (IWU, 2016)

Fuel	**Total Primary Energy Factor [$\mathrm{kWh_{Prim}/kWh_{Fin}}$]**	**Primary Energy Factor, non-renewables [$\mathrm{kWh_{Prim}/kWh_{Fin}}$]**	**Greenhouse Gas Emissions [g/kWh]**
Natural Gas	1.1	1.1	241
Heating Oil	1.1	1.1	313
District Heating Norm	1.3	1.3	
District Heating Hamburg Vattenfall[8]		*0.57*	*146*
Firewood	1.2	0.2	11
Wood Pellets	1.2	0.2	18
Electricity	2.8	1.8	631

5.7 Summary

In scope of this Master Thesis, it is difficult to assess the heating systems and conclude whether one system is better than another as each system has its advantages and disadvantages. And for an overall assessment it would be necessary to include the operation and installation costs of the systems as well as the probable development of electricity production.

The short overview over the most common heating systems shows that younger systems have a higher efficiency and that the systems had a major development to more efficient systems, especially the natural gas or heating oil burning boilers.

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[8] SANDER, 2012a; SANDER, 2012b

6 Building Stock

6.1 General Dataset Characteristics

Figure 6.1 shows that the new dataset contains primarily buildings from the construction years 1919 to 1968 which corresponds with the Census data from 2011 (SÄBL, 2014), even the overall column heights between 1919 and 1969 resembles Dochev's results for assigning a building typology for all residential buildings recorded in Hamburg ALKIS (DOCHEV, 2017, p. 26). However, towards the other sources, the building epoch 1860-1918 (B) is slightly overrepresented while the years 1984 to 1994 (H) are underrepresented in the dataset, which seems to be plausible, taking into account that the dataset consists of energy certificates for building owners, who are at least interested in a holistic refurbishment concept and it can be expected that the motivation for energetic refurbishment increases with the building's age.

Comparing the construction types depicted in Figure 6.1 with Dochev's expected distribution, multi-family houses (MFH) appear to be overrepresented in the new dataset. The high share of multi-family houses might be caused by the "type" of ownership, owner of MFH might be more likely to have the financial means, the expertise and contacts for large scale refurbishments compared to single-family building owners.

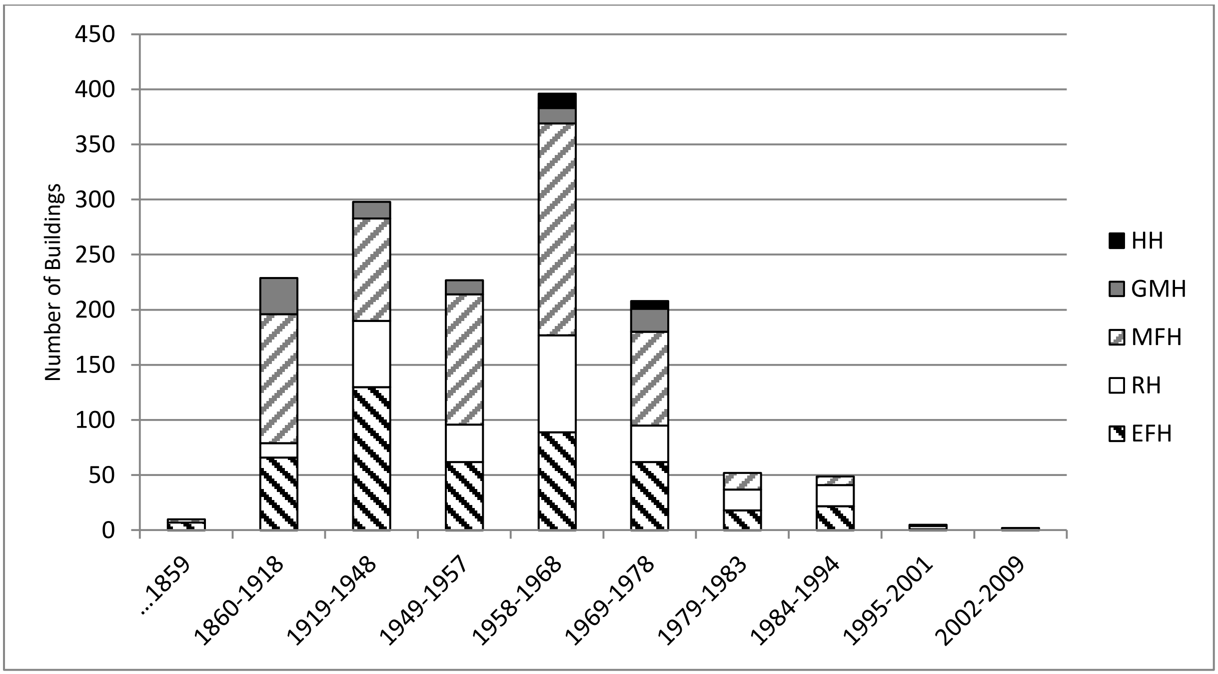

Figure 6.1 Distribution of IWU types[9] within the new dataset displayed over the epochs

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[9] EFH = single-family house, RH = row house, MFH = multi-family house, GMH = apartment block, HH = high rise building

The spatial distribution of the dataset is examined on basis of the seven districts in which Hamburg can be divided, shown in Figure 6.2.

Figure 6.3 shows the distribution of the energy certifcates within the districts resembles the outcome of the yearly surveys performed by the local statistical office (Figure 6.4, own graphic adapted from Statistisches Amt für Hamburg und Schleswig-Holstein (2017)). This similarity indicates that this aspect of the new dataset is representative for Hamburg.

Figure 6.2 Map displaying Hamburg's districts (adapted from LGV (2017))

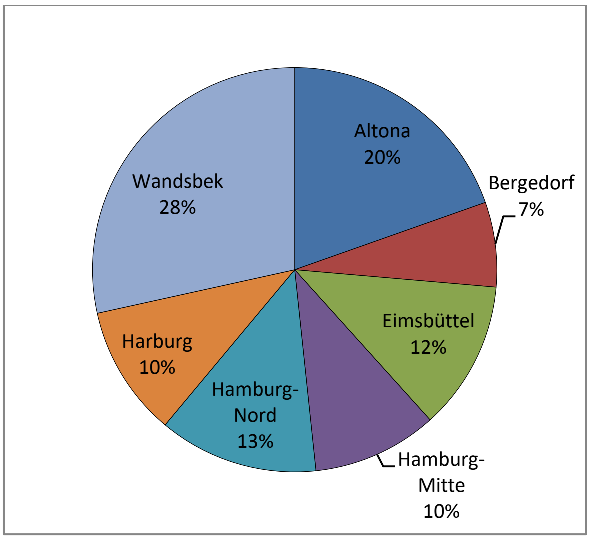

Figure 6.3 Buildings of the new dataset depicted per district

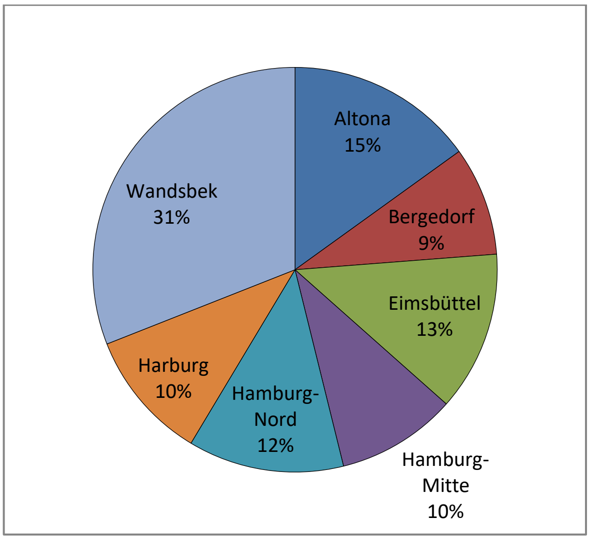

Figure 6.4 Distribution of Hamburg's residential buildings, adapted from Statistisches Amt für Hamburg und Schleswig-Holstein (2017)

In general, the new dataset includes a small share of buildings (8 %) that are under cultural heritage, of which most buildings are multi-family house types (75 %, MFH, GMH, & HH).0

6.2 Evaluation of the Dataset's Useful Heat Demand

The useful heat (in German *Nutzwärme* or *Heizwärmebedarf*) is primarily a function of the building envelope and characterized by ventilation and transmission losses, with the latter being based on transmissivity coefficients ("u-values") and thermal bridging. Ideally, the useful heat demand of existing buildings would deviate only little from the assigned IWU type, but in his Master Thesis, Dochev showed on basis of the old dataset that the useful heat demand can differ more than ± 100 kWh/(m²a) (2017, p. 32).

Figure 6.5 displays the results for the single-family and row houses of the new dataset. Despite the rather small sample of older and younger construction epochs, the overall tendencies show that the difference between 85th and 15th percentile ranges from 100 to 200 kWh/(m²a) and that in most cases the median is more than 40 kWh/(m²a) higher or lower than the useful energy demand according to IWU. The new dataset shows slight tendencies to have a smaller range between minimum and maximum for some building types, compared to Dochev's results (Figure 6.6).

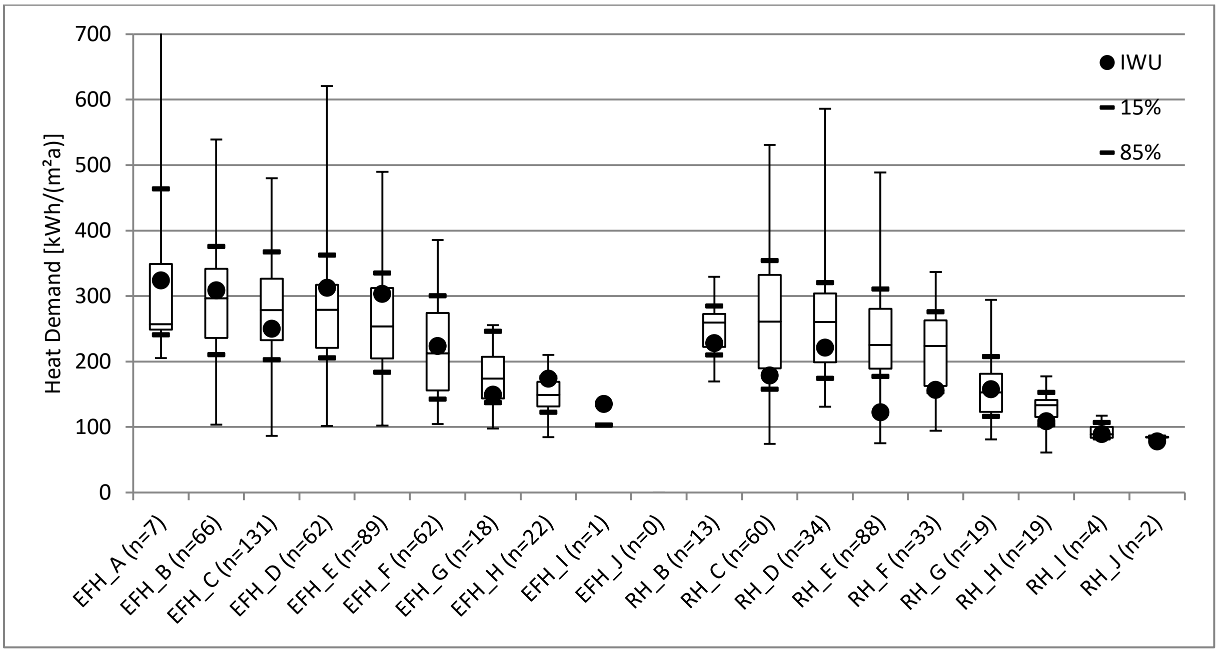

Figure 6.5 Deviation of the useful heat demand, displaying single-family buildings of the new dataset

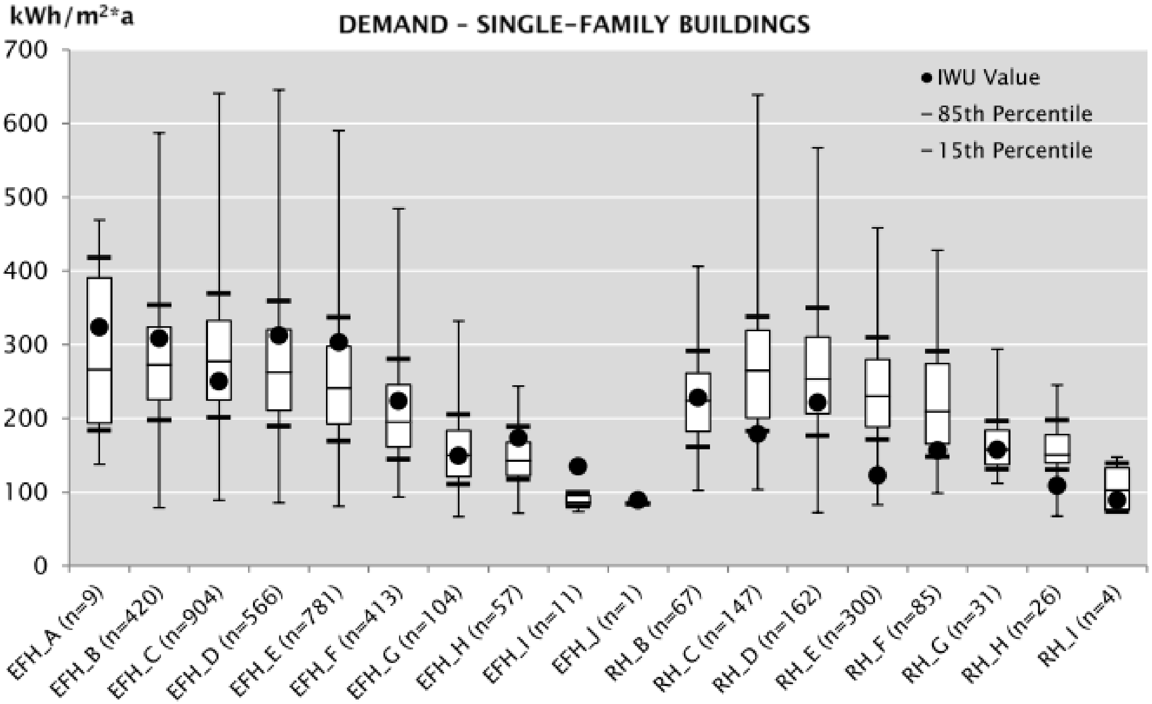

Figure 6.6 Distribution of the heat demand, displayed for single-family buildings of the old dataset (Dochev, 2017, p. 32)

The deviation of the heat demand for multi-family buildings has a range of 50 to 100 kWh/(m²a) between the 15th and 85th percentile as can be seen in Figure 6.7. The difference between minimum and maximum is varies for each building type.

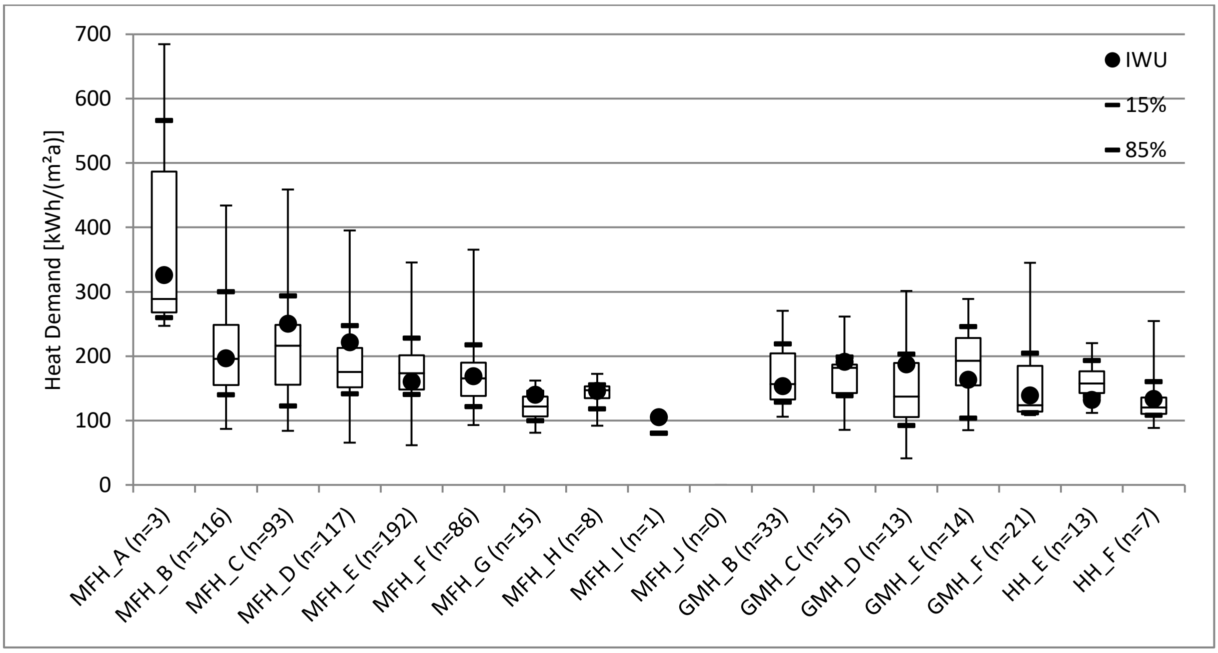

Figure 6.7 Deviation of the certificate's heat demand, displaying multi-family buildings

Although the sample size of both datasets clearly differs, in general, the new dataset appears to have mainly similar tendencies as found for the old dataset by Dochev. This indicates that the overall quality of the IWU type assignment and useful heat demand is comparable for both datasets.

6.3 Preparation of the Heating Systems

Although the following explanation refers to the baseline condition of the buildings, the same procedure is applied to analyse the proposed refurbishment of the energy certificates.

A self-written macro analyses the heating system elements of each building individually. A complication for the analysis is that for each building up to ten different boilers with their energy carrier can be listed – mainly when individual dwellings use separate boilers. Usually the *usable area* supplied by a boiler is listed and in some cases a number of identical heaters seem to be summed up as one area (this applies mostly for electrical appliances). After pre-processing with the macro and manual check, most heating systems could be matched meaningfully with areas.

The analysis summarizes a number of different heaters as *constant temperature boilers*[10], and in addition all kinds of CHP-plants and district heating systems are summed up as *district heating* (DH). The latter summarisation is a bit inconvenient as it would have been advantageous to examine patterns and frequencies while differentiating systems that actually use one (small) CHP unit to supply one building, a small district heating grid that supplies heat to a few buildings, and Hamburg's main district heating grid operated by Vattenfall GmbH. This information would have been beneficial in the context of policy making and urban planning.

Figure 6.8 displays an excerpt of the analysis with each row showing all boilers used in one building. It shows that e.g. about half of the total space heating of the first entry is supplied by a condensing boiler, about a third by a constant temperature boiler, and supported by a low-temperature boiler. The fifth row is empty as the entry contains two different boilers but only one area is given and therefore, the calculation of a share is not possible.

Eventually, the last column summarizes all boilers that have a percentage higher than 0 % and it obtains the option to exclude heaters underlying a chosen threshold from further analysis. However, the test showed that the exclusion of boilers with a share smaller than 9 %[11]does not have an effect on the overall boiler frequencies and even a threshold of 25 % does not significantly change the share of the most frequent boilers, although it shortens the list of boiler combinations. Therefore, the threshold feature was not used in further analysis.

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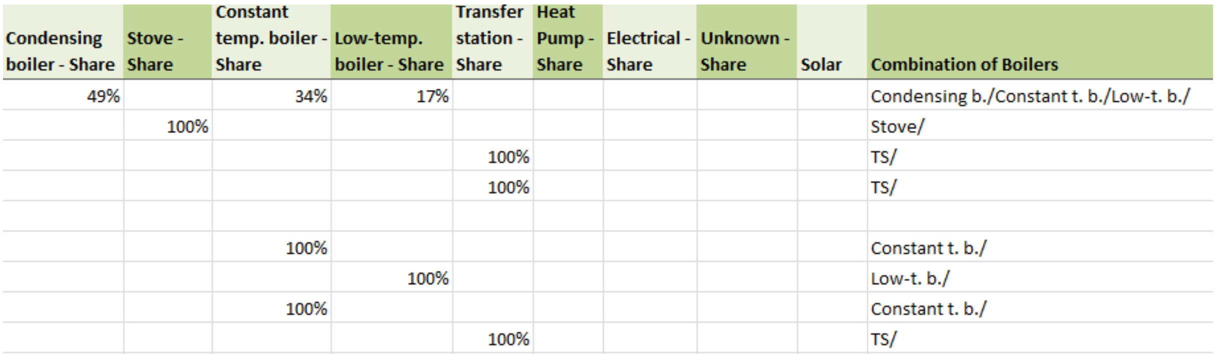
[10] *Gebläsekessel, Spezialkessel, Wasserdurchlauferhitzer* and *Standardkessel* are all listed under *Standardkessel* = constant temperature boiler in the Hottgenroth energy advisor software

[11] Due to 10 % rule in the regularities of the KfW incentive programmes (KFW, 2016, 24, 26) that do not need a detailed system calculation, if wood fired boilers or solar thermal devices in the production of space heating



Condensing boiler - Share	Stove - Share	Constant temp. boiler - Share	Low-temp. boiler - Share	Transfer station - Share	Heat Pump - Share	Electrical - Share	Unknown - Share	Solar	Combination of Boilers
49%		34%	17%						Condensing b./Constant t. b./Low-t. b./
	100%								Stove/
				100%					TS/
				100%					TS/
		100%							Constant t. b./
			100%						Low-t. b./
		100%							Constant t. b./
				100%					TS/

Figure 6.8 Excerpt of the analysis of the heating boilers

The vast number of possible combinations of boilers for heating and boilers for DHW in the new dataset shows that the old dataset was simplified to a large extent. The 7,700 buildings of the old dataset often do not have any information about the boiler type at all, while the refurbishment measures are generally not included. Thus, the analysis of the heating system uses focusses on the new dataset.

6.4 Frequency Distribution of Heating Systems

6.4.1 Space Heating Supply

Figure 6.9 shows that the boilers for all buildings of the new dataset are distributed quite equally. With 28 % constant temperature boilers have the greatest share while the rest ranges between 15-20 %. Electrical devices, such as night storage heating, amount to a small share of 3 %.

A large difference can be observed between the single- and multi-family buildings. For example the majority of buildings connected to district heating are multi-family building types, which is to be expected, since the their total heat demand is higher which is advantageous for district heating.

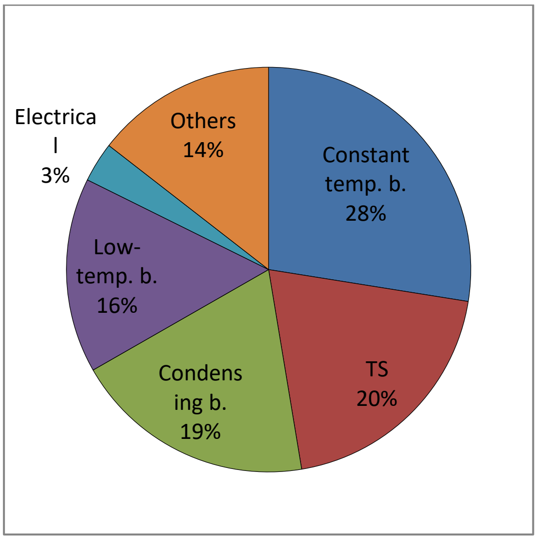


Figure 6.9 Shares of most common boilers used for space heating in the new dataset

Although the assignment epochs contains uncertainties as explained in Section 4.3, the following figures display the typical share of a boiler within an epoch, to examine whether patterns can be found. Figure 6.10 shows the results for single-family buildings. For each boiler type the share in each epoch is displayed and one can see for example that the low-temperature boiler shows a curve over the epochs. Moreover, in the newest epochs the share of condensing boilers tends to be increasing.

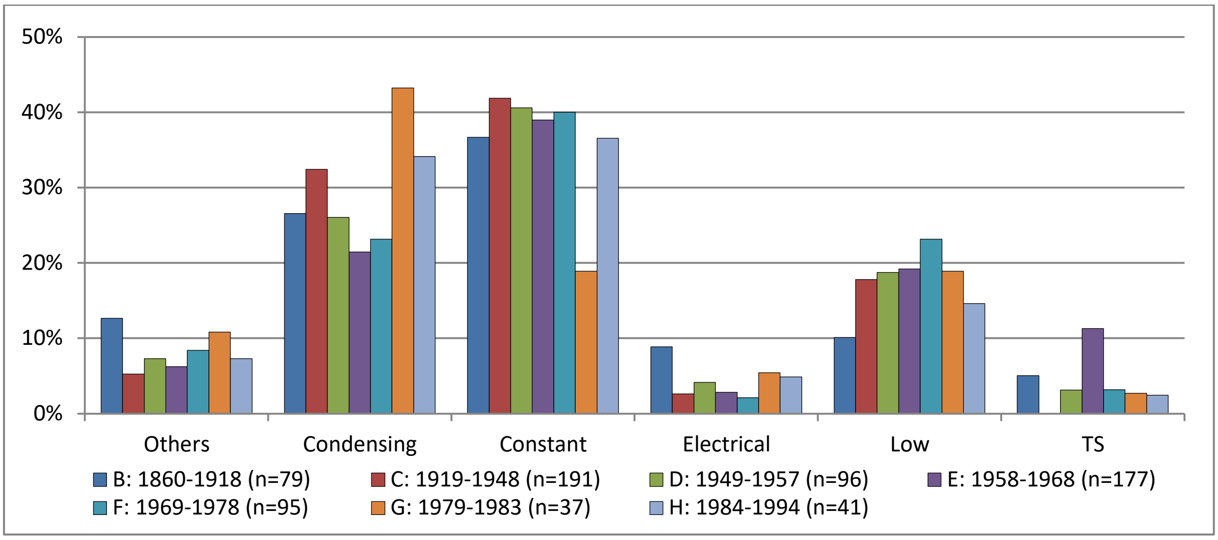


Figure 6.10 Boiler distribution considering the construction year of single-family buildings

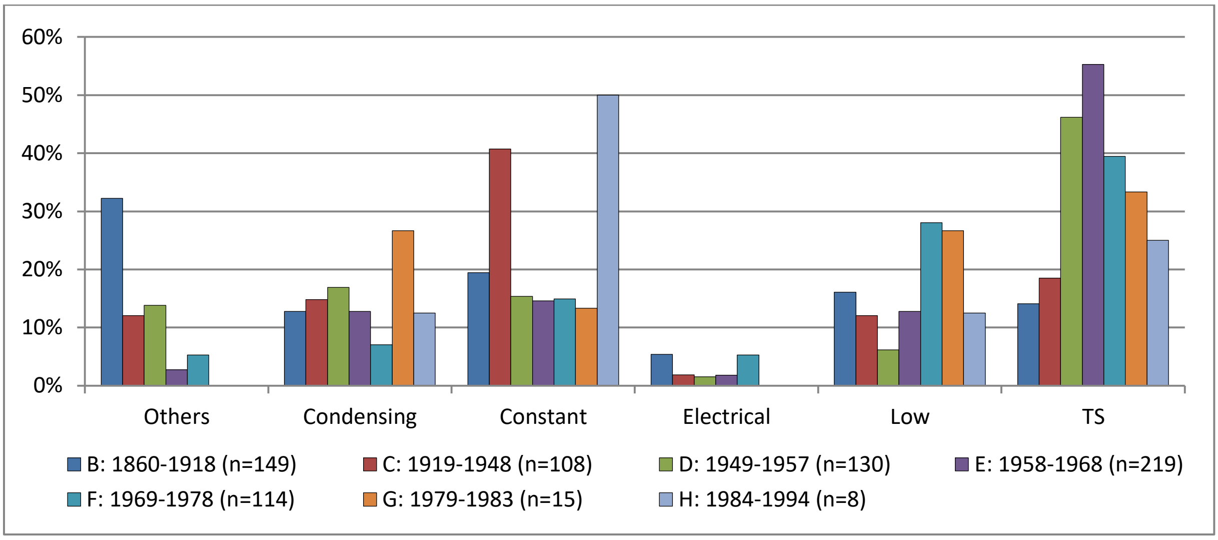
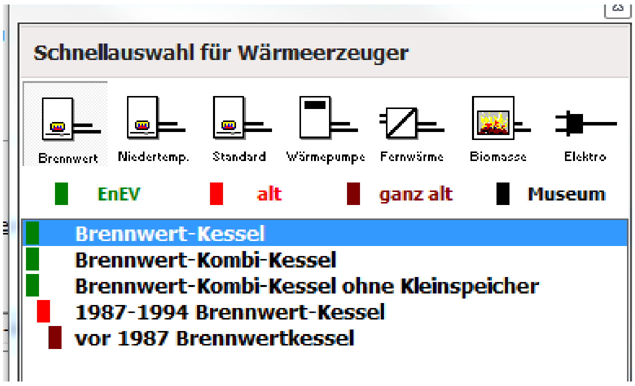


Figure 6.11 Boiler distribution considering the construction year of multi-family buildings

In Figure 6.11 one can see that buildings of the epoch E (1958-1968) show the highest tendency to have transfer stations (TS) of district heating grids and the share of district heating is decreasing afterwards. The amount of "other" boilers – including various combinations of boilers as well as wood fired ovens, a few heat pumps, solar thermal support of the DHW supply, etc. – usually have a share of less than 10 %, only multi-family house of the epoch B make an exception with ca. 30 %.

However, there does not appear to be a significant connection between construction epoch of the building and boiler type. It is doubtful whether an assumption of this aspect (in e.g. a digital heat cadastre) would improve the assignment of heating systems and the resulting energy demand.

For about half of the boilers no year of installation is mentioned in the energy certificate, which indicates that the boiler was installed after 1995, as the Hottgenroth software only includes the installation period in the labels for older boilers, as to be seen in Figure 6.12 on the next page. About another third was installed between 1988 and 1995. A crosscheck with a publication of the German Federal Association of Chimney Sweepers shows that roughly 80 % of the gas and oil firing boilers were installed between 1991 and 2015 (BUNDESVERBAND DES SCHORNSTEINFEGERHANDWERKS, 2017), which supports the results of the dataset.



Schnellauswahl für Wärmeerzeuger

🟩 EnEV 🟥 alt 🟥 ganz alt ■ Museum

🟩 Brennwert-Kessel
🟩 Brennwert-Kombi-Kessel
🟩 Brennwert-Kombi-Kessel ohne Kleinspeicher
🟥 1987-1994 Brennwert-Kessel
🟥 vor 1987 Brennwertkessel

Figure 6.12 Screenshot of the boiler selection interface from the Hottgenroth software "Energieberater 18599"

Figure 6.13 displays the year of boiler installation and shows the dominance of the boilers installed after 1995 in all epochs. The share of installations after 1995 has an slightly increasing tendency with younger becoming epochs, interrupted by the youngest epoch from 1984-1994 (H), which has roughly 50 % new boilers and 50 % boilers from the year of building erection.

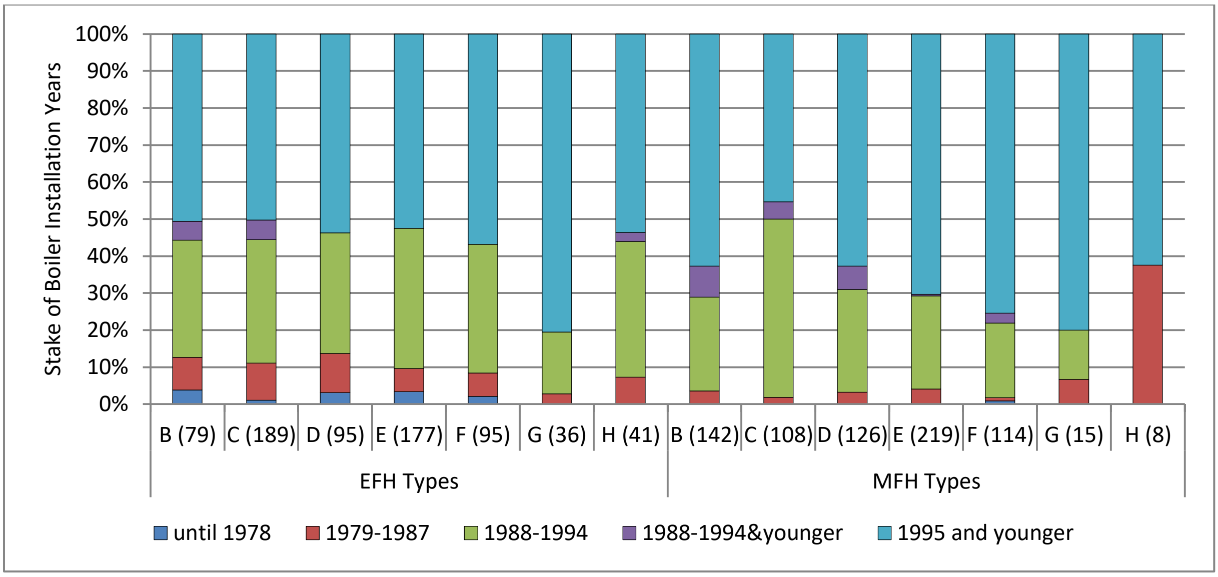


Figure 6.13 Distribution of the year of boiler installation over the building type epochs

6.4.2 DHW Supply

In total about 30 % of the buildings in Hamburg supply domestic hot water (DHW) with some kind of electrical device (electric instantaneous water heater, electric hot water storage, etc.) excluding heat pumps. In both datasets, the old and the new one, the share of electrical DHW production is quite similar but percentages of the remaining boiler types differ.

Figure 6.14 shows that the share of buildings providing their DHW with electrical devices, low-and constant temperature boilers seem to decrease in the recent epochs, while the share of condensing boilers is increasing.

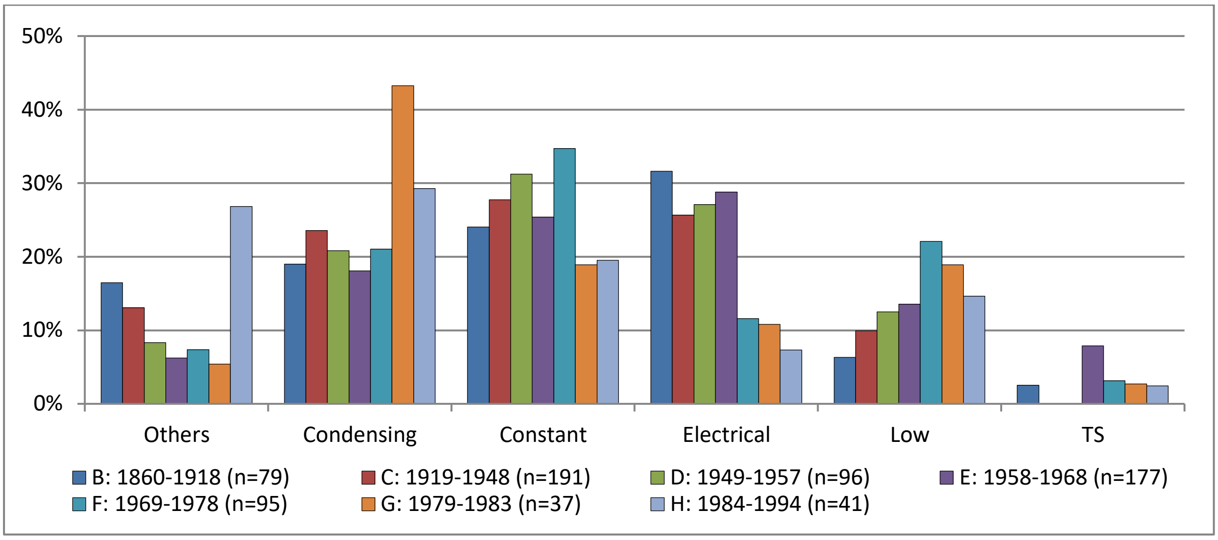


Figure 6.14 Distribution of devices for DHW production considering the construction year of single-family buildings

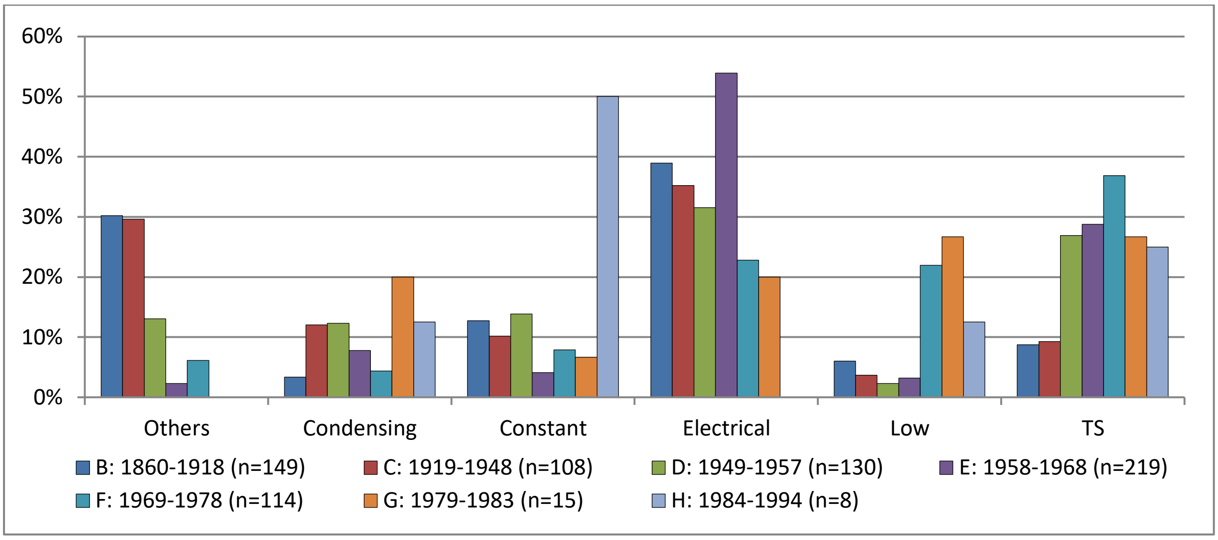


Figure 6.15 Distribution of devices for DHW production considering the construction year of in multi-family buildings

Figure 6.15 depicts the DHW production in multi-family buildings. Over the epochs, a decreasing share of electrical DHW supply can be observed in combination with an increasing share of low-temperature boilers and district heating.

It might be possible to adopt a decreasing usage of electrical instant hot water devices for younger building epochs in the assignment of heating systems to buildings, which might have effects on the overall results as the usage of electricity causes high greenhouse gas emissions and therefore, influences the assessment of the environmental friendliness of the building stock.

6.4.3 Energy Carrier

The majority of residential buildings in Hamburg use natural gas[12] to supply the space heating. Both, the new and the old dataset, show similar tendencies, although biomass has a larger share in the old dataset (compare Figure 6.16 and Figure 6.17). The category "Others" summarizes mainly buildings that use more than one energy carrier; for example the combination of natural gas and electricity that amounts to a share of 2 % of the overall new dataset.

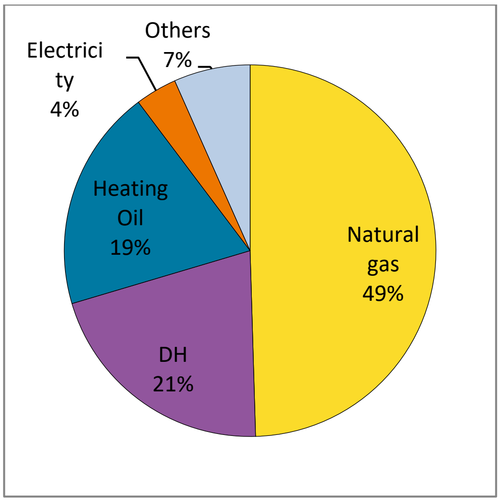


Figure 6.16 Distribution of energy carriers used for space heating in the new dataset

About 1.7 % of the buildings included in the new sample use wooden material in combination with another energy carrier, but usually wood provides less than 10 % of the heat demand. According to the dataset six buildings still heat partially with coal. In some cases the use of wood or coal is possibly not documented in the energy certificate since either the house owner did not inform the energy advisor correctly or the energy advisor decided that the area heated with wood or coal can be ignored.

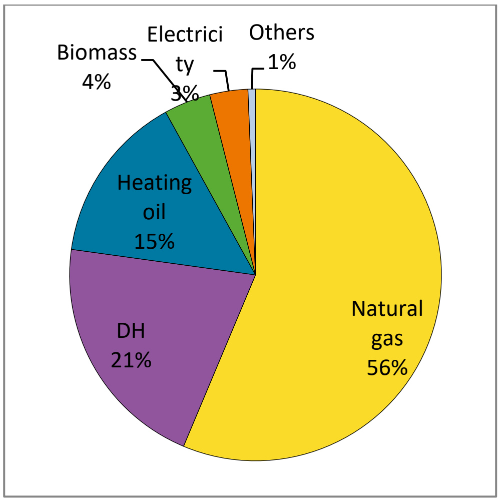


Figure 6.17 Distribution of energy carriers used for space heating in the old dataset

The partial usage of night storage heating can be found in roughly 6 % of all buildings. While half of these buildings provide their total heat demand with electricity, some buildings seem have roughly one flat that uses night storage heating.

Solar thermal devices that support the heating system are rarely found in the building stock. Among 1,490 buildings only ten houses use some solar heat, whereas domestic hot water is provided by a solar thermal system in 1.8 % of the new dataset.

Most results of the analysis of Hamburg's energy certificates point into the same direction like nationwide studies on the energy carriers for space heating. For Germany, in general, the share of natural gas for heating amounts to ca. 50 % as well, heating oil has a share of 26 % while district heating comes to ca. 14 % in 2016 (BDEW, 2017). The differences in the usage of heating oil and

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[12] Includes natural gas, liquid gas, and city gas (the latter was stated in two buildings although in general the city gas should have been replaced by natural gas)

district heating can be explained by the different population densities. In cities like Hamburg it is economically more feasible to construct a large natural gas or district heating grids than in more rural areas.

All in all, the new dataset appears to be in line with Hamburg specific and nationwide statistics and the old dataset, which gives the new dataset more credibility and increases its assumed representativeness. The possibility of this sample being biased is possible, but rather unlikely. Therefore one could consider the dataset as generally representative of the building stock as a whole.

However, other studies with detailed data on the boilers and its distribution over the building's age was not available and therefore, this part of the new dataset cannot be verified.

6.4.4 Identification of *System Combinations* for DHW and Space Heating

After the individual analysis of the energy carriers, space heating, and DHW systems, the typical "system combinations" are identified, i.e. the combination of a system that provides space heating and the device that supplies DHW. For this purpose natural gas and heating oil are not differentiated since the energy carrier influences the primary energy demand and CO_2 emissions but not the final energy demand. And since nearly all residential buildings of the new dataset use natural ventilation, no further specification for the ventilation systems is necessary. The system combination is not distinguished for each IWU type, as no satisfying pattern could be found in Section 6.3. Still a separation into single- and multi-family buildings is applied.

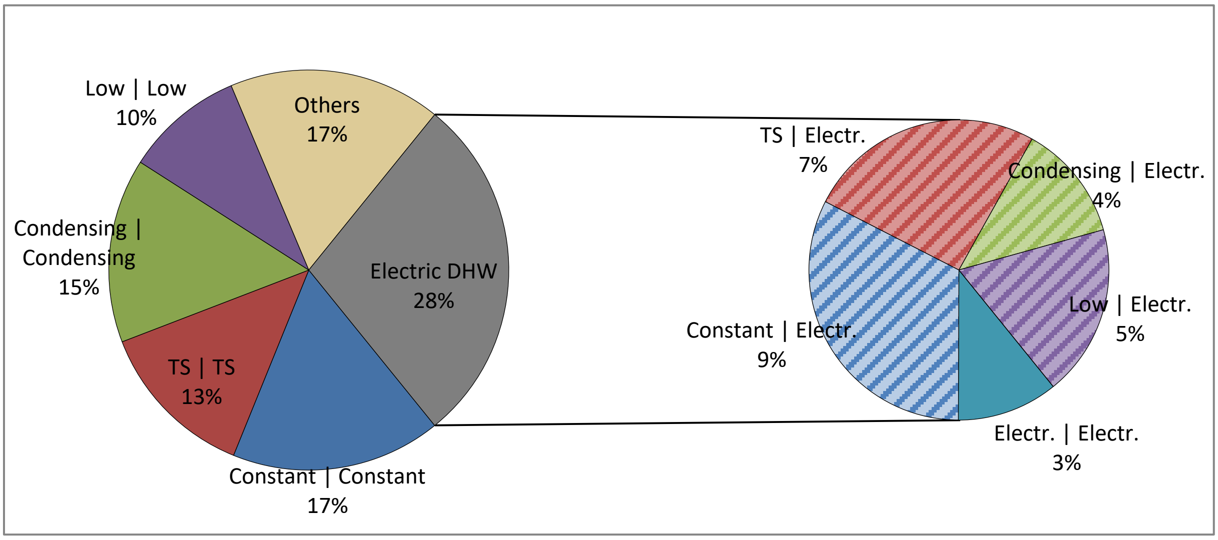

Figure 6.18 Distribution of the combinations of heating and DHW systems according to the sample

Figure 6.18 depicts the distribution of system combinations. The first mentioned boiler is providing the space heating, the latter serves for the DHW production. About 54 % of all buildings use a central heating system with the same boiler for space heating and DHW provision. 28 % use electrical appliances for DHW supply, only 3 % of all buildings use electricity for space heating. The category “Others” includes all buildings that use a mix of different boilers or lack information on at least one system part. “Others” amounts to a share of 17 %, however, most of the system combinations in this category can be found in only one building and are considered as exceptions.

As already observed in the previous section, multi-family buildings are more likely to be connected to a heating grid than EFH building types. In addition, the share of multi-family buildings that have an electrical DHW supply is higher than for single-family buildings (for details see Appendix Section 13.1.2 on page 51).

Table 6.1 Frequencies of boilers based on the used fuel

Gas or Oil Firing Systems:	**EFH**	**MFH**	**Total**
Constant | Constant	35%	18%	29%
Condensing | Condensing	28%	19%	25%
Low | Low	16%	17%	16%
Constant | Electrical	11%	23%	15%
Low | Electrical	6%	14%	9%
Condensing | Electrical	4%	9%	6%
DH Systems:			
TS | TS	68%	64%	64%
TS | Electrical	32%	36%	36%

Another result of the analysis of “system combinations” can be utilised to assume the heating system used in a building, on basis of the used energy carrier. Table 6.1 shows that about 35 % of all single-family houses can be supposed to heat with oil or gas heat with a “*Constant | Constant*”-system. With the same mechanism, one can expect that nearly two thirds of all buildings connected to a district heating grid use it to provide space heating and DHW, without significant differences between EFH and MFH at least on city level. In the Section 13.1.4 the same tables can be found for the seven districts.

6.4.5 System Combinations in Hamburg’s Districts

The analysis of the local differences on system combinations was done at the district level (seven districts in total) since the sample size was too small to have representative samples at neighbourhood level (104 neighbourhoods). Again it differentiates between single- and multi-family house types.

Single-family buildings are displayed in Figure 6.19, which shows that constant temperature boiler-based systems have the largest share in Hamburg-Nord, while the smallest share is located in Bergedorf. Hamburg-Mitte does not have as many EFH as other districts, but these EFHs are more likely to have night storage heating. The share of “Other” system combinations lies between 10 and 20 %, only in Bergedorf it amounts to 25 %.

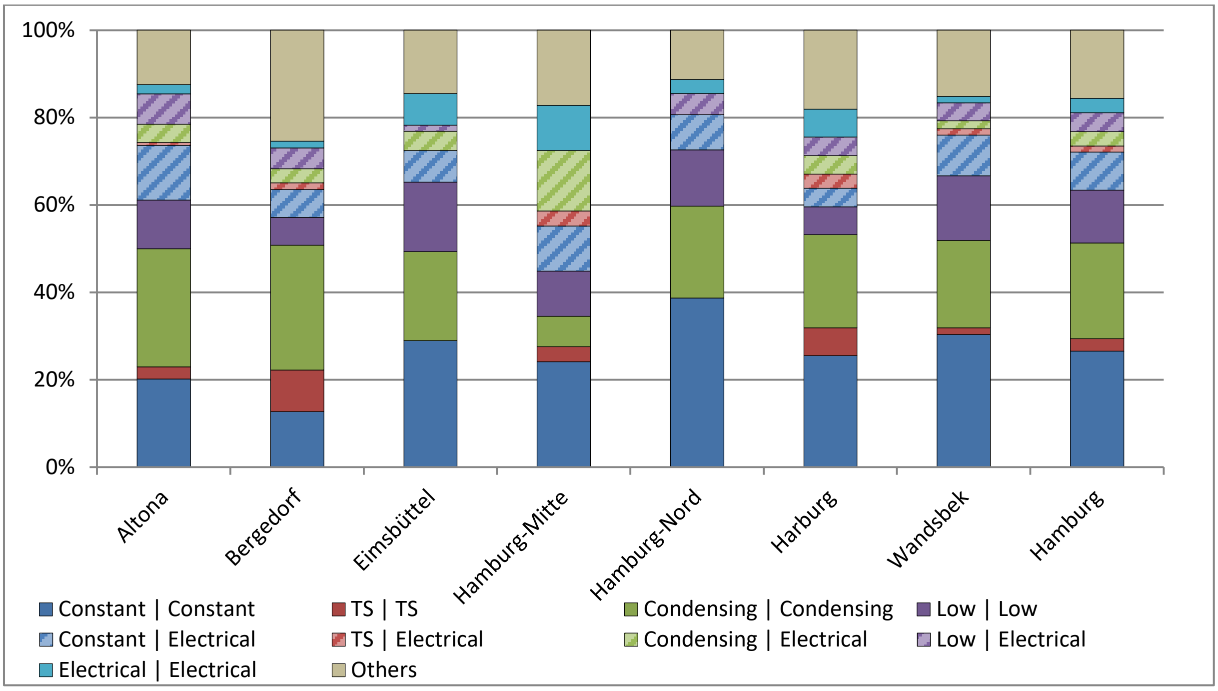

Figure 6.19 Distribution of heating systems in single-family buildings in Hamburg's districts

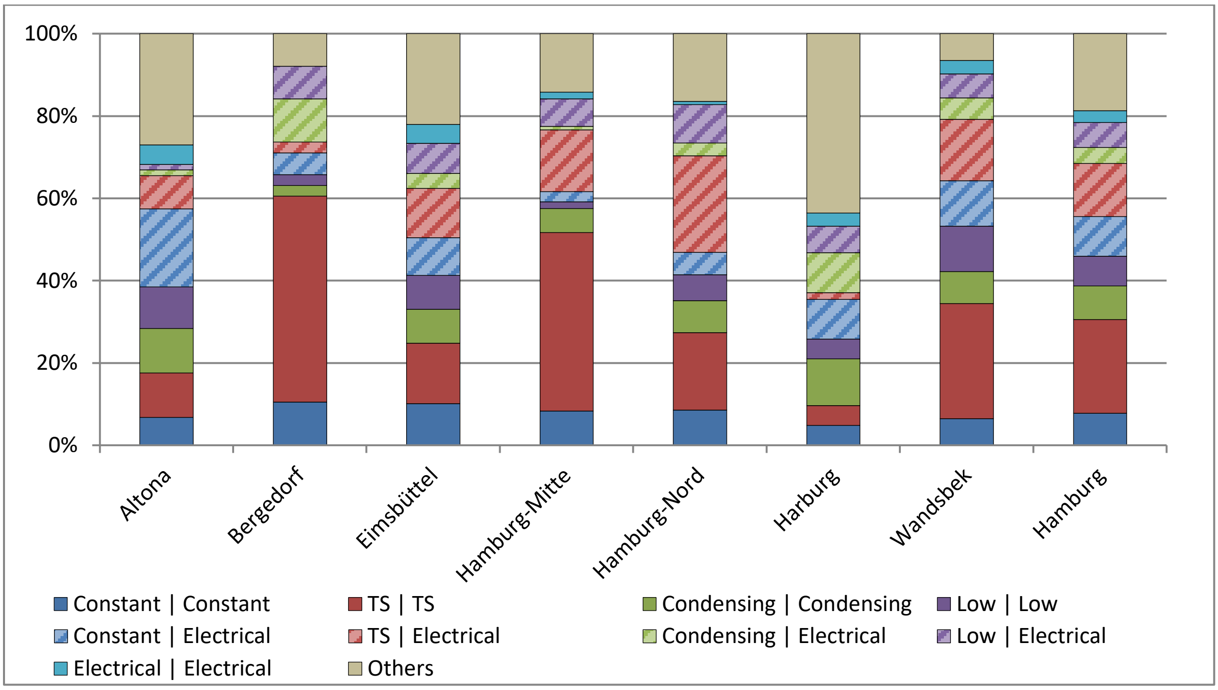

Figure 6.20 The distribution of heating systems in multi-family house types in Hamburg's districts

In all districts, multi-family buildings do not use as much constant temperature boilers as single-family houses – the share is usually below 10 % (Figure 6.20). The share of district heating is largest in Bergedorf and Hamburg-Mitte, while lowest in Harburg. In general, the share of “Other” system combination is greater for multi-family house types, yet, with a share of 44 %, Harburg has an unusual high amount.

6.5 Calculation of Final Energy Demand – A Simplified Method

6.5.1 Summary of Considered Heating Systems

Aside of the eight most frequent system combinations found in the dataset, an additional system for single-family buildings is included: A low temperature boiler with a supplementary wood fired stove that provides 10 % of the demand for space heating (Table 6.2). The latter represents the most frequent system combination that contains a stove (with a total sample size of six buildings).

Table 6.2 Calculated system combinations for the baseline condition

Heating System | DHW System
1) Constant | Constant
2) Condensing | Condensing
3) TS | TS
4) Low | Low
5) Low & Stove | Low (EFH only)
6) Constant | Electrical
7) Low | Electrical
8) Condensing | Electrical
9) Electrical | Electrical

For all system combinations, the installation year of the boiler is set to be from 1995 or younger, corresponding with the results of the previous heating system analysis (Section 6.4.1). The insulation of distribution pipes is considered to be not the highest standard (see Appendix Section 13.1.1 for further details on the analysis of the new dataset regarding the peripheral heating system).

6.5.2 Final Energy Demand – Baseline Condition

The term final energy demand summarizes the useful heat and the losses that occur during the production and distribution processes. For its computation the TABULA Calculation Tool is used as foundation and basically all functions and values are not changed at all. Their components were only combined to describe the findings in the new energy certificate dataset.

In a first phase, it was examined whether it is possible to simplify the calculation step from useful heat to final energy demand, but the effects observed for energy efficient heating system towards inefficient system deviates depending on the useful heat demand. With a decreasing demand for useful heat, the weight of an energy efficient system decreases as well.

In the second phase, the final energy demand is calculated for all considered heating systems in combination with all building types. A relationship between the final energy demand of the heating systems could be found, which is independent from the building epochs but contains slight differences for single- and multi-family buildings, respectively. The heating systems are differentiated into two groups and each system of a group is compared with a reference system:

- The first group uses one type of boiler (or district heating) generate space heating and DHW and therefore is named *building-central-DHW* and its reference system is *constant | constant*

- The second group uses a boiler (or district heating) for space heating while DHW is produced by instant flow heaters, which is called *building-decentral-DHW*. The reference system is *constant | electrical*

Overall, three tables are needed to calculate the heating demand for all heating systems based on one reference system. The first table displays the final energy demand of the reference systems for each IWU-building type (see Table 6.3 with an excerpt containing one reference system, complete table can be found in Section 13.2).

Table 6.3 Excerpt of the final energy demand table for the reference system based on constant temperature boilers. All values in kWh/(m²a) related to useable area

	Constant | Constant			
IWU Building Type	**Final Energy: DHW**	**Final Energy: Heating**	**Aux.**	**Total Final Energy**
EFH_B	38.0	385.6	6.5	430.1
EFH_C	38.0	317.6	6.5	362.0
EFH_D	38.0	389.8	6.5	434.2
EFH_E	38.0	379.7	6.5	424.2
EFH_F	38.0	286.7	6.5	331.2

Table 6.4 Relationship between different building central heating systems and constant temperature boiler as reference heating system

Basis: Constant | Constant	**EFH & RH**		**MFH, GMH & HH**	
Heating Sys. | DHW Sys.	**Coefficient**	**Absolute Error Demand**[13]	**Coefficient**	**Absolute Error Demand**
Condensing | Condensing	0.835	-0.36 ± 1.50	0.903	-0.02 ± 0.83
TS | TS	0.742	-0.08 ± 1.59	0.825	0.16 ± 1.15
Low | Low	0.883	-0.46 ± 1.49	0.940	-0.08 ± 0.47
Low & Stove (Wood) | Low	0.905	-0.63 ± 1.92	-	-

The last two tables contain the coefficients to compute the final energy of the other heating systems – Table 6.4 contains the boiler-DHW-systems, and electric-DHW-systems can be found in the appendix.

Calculating the final energy demand with this simplified method leads to an error towards the detailed IWU calculation of less than 1 kWh/(m²·a). Only for the complete electrical system the error reaches up to 4 kWh/(m²·a). Boiler-DHW-systems tend to have negative errors, meaning that the result of the simplified method is slightly smaller than of the detailed TABULA method.

Example: For the *constant / constant* reference system of EFH_B has a total final energy demand of 430.1 kWh/(m²a) and the *TS / TS* –coefficient EFH types is 0.742. Multiplying both values results in a final energy demand of ca. 319 kWh/(m²a) for an EFH_B. The expected error lies between -1.67 and +1.51 kWh/(m²a).

---

[13] Error means the difference between the final energy demand calculated according to TABULA method compared to simplified method of this thesis [kWh/(m²·a)]

6.5.3 Estimation of the Consumption

The IWU typology delivers an approach to estimate the real consumption on basis of the calculated final energy demand, excluding the auxiliary energy (LOGA ET AL., 2015, pp. 77–80).

$$0 < q_{dem} < 100: \quad q_{con} = \left(-\frac{q_{dem}}{1000} + 1.1\right) \cdot (q_{dem} - q_{aux})$$

$$100 \leq q_{dem} < 200: \quad q_{con} = \left(-\frac{q_{dem}}{500} + 1.2\right) \cdot (q_{dem} - q_{aux})$$

$$200 \leq q_{dem} < 300: \quad q_{con} = \left(-\frac{7}{5000} \cdot q_{dem} + 1.12\right) \cdot (q_{dem} - q_{aux})$$

$$q_{dem} \geq 300: \quad q_{con} = \left(1 - \frac{q_{dem}}{1000}\right) \cdot (q_{dem} - q_{aux})$$

With:
q_{con} = “Realisic” final energy consumption
q_{dem} = Final energy demand calculated with the simplified method
q_{aux} = Auxiliary energy demand

Figure 6.21 Functions to estimate the final energy consumption of central heating system running on fuels or DH (adapted from LOGA ET AL., 2015, p. 80)

The functions are derived from a diagram published by the IWU that differentiates between central heating system running on fuel or district heating (Figure 6.21), manually fired stoves or direct electric heating (Figure 6.22), and central heating systems using electrical heat pumps (Figure 6.23). Each equation depends on the final energy and thus, can be applied not only on building stock results but on refurbishment levels as well. These functions are used for the final energy demand excluding the auxiliary energy (which is listed in an own column in Table 6.3).

$$0 < q_{dem} < 100: \quad q_{con} = \left(-\frac{q_{dem}}{500} + 1.1\right) \cdot (q_{dem} - q_{aux})$$

$$100 \leq q_{dem} \leq 200: \quad q_{con} = \left(-\frac{17}{10{,}000} \cdot q_{dem} + 1.07\right) \cdot (q_{dem} - q_{aux})$$

$$200 \leq q_{dem} \leq 300: \quad q_{con} = \left(-\frac{13}{10{,}000} \cdot q_{dem} + 0.99\right) \cdot (q_{dem} - q_{aux})$$

$$q_{dem} \geq 300: \quad q_{con} = \left(-\frac{q_{dem}}{1000} + 0.9\right) \cdot q_{dem}$$

Figure 6.22 Functions to estimate the final energy consumption of buildings using stoves or decentral electrical applications for heating (adapted from LOGA ET AL., 2015, p. 80)

$$0 < q_{dem} < 100: \quad q_{con} = \left(-\frac{3}{1000} \cdot q_{dem} + 1.1\right) \cdot (q_{dem} - q_{aux})$$

$$100 \leq q_{dem} < 200: \quad q_{con} = \left(-\frac{q_{dem}}{500} + 1.0\right) \cdot (q_{dem} - q_{aux})$$

$$200 \leq q_{dem} < 300: \quad q_{con} = \left(-\frac{q_{dem}}{1000} + 0.8\right) \cdot (q_{dem} - q_{aux})$$

$$q_{dem} \geq 300: \quad q_{con} = 0.5$$

Figure 6.23 Functions for central heating systems based on electrical heat pumps to estimate the final energy consumption (adapted from LOGA ET AL., 2015, p. 80)

Comparing the consumption on basis of the simplified method with the detailed IWU calculation shows that the deviation becomes slightly greater and amounts to ca. 2 kWh/(m²·a) for single-family house types and less than 1 kWh/(m²a) for multi-family house types. In all cases the error is negative, implying that the simplified method tends to overestimate the consumption.

As the method to estimate realistic consumption is more an educated guess than any kind of a precise prediction, the found error is considered to have a tolerable size.

Example: The previous EFH_B, using *TS* / *TS*, has a final energy of ca. 319 kWh/(m²a). The estimated consumption can be calculated with the last equation of Figure 6.21:

$$q_{con} = \left(1 - \frac{319}{1000}\right) \cdot (319 - 6.5) = 213\ kWh/(m^2a)$$

7 Usual Refurbishment Level

7.1 Legal Requirements and U-Values

In Germany, buildings that are going to be renovated need to obey the regularities of the Energy Saving Ordinance ("Energieeinsparverordnung", 2016 – EnEV). Therefore, the usual refurbishment level, which shall depict the minimum refurbishment, is oriented towards the EnEV. Although the first refurbishment level of IWU typology is also based on the EnEV, some u-values are changed in this paper as they appeared to be too ambitious.

As soon as a building part gets renovated, the house owner has to consider its energetic quality and eventually adopt measures to satisfy the u-values listed in the first table of the third annex of the EnEV (Table 7.1). Therefore, these u-values represent the minimum requirements for a refurbishment and are implemented in the calculation of the useful heat demand.

Table 7.1 Excerpt of the first table of the third annex in the EnEV 2016

Building Parts/Systems	**Maximum U-Value for Residential Buildings**
Exterior walls	U = 0.24 W/(m²K)
Windows, French doors	U_w = 1.3 W/(m²K)
Skylight	U_w = 1.4 W/(m²K)
Roofs, including dormers, walls against unheated attics, upper ceilings	U = 0.24 W/(m²K)
Sealed roof	U = 0,20 W/(m²K)
Wall against soil, floor slab, walls and ceilings against unheated rooms	U = 0.30 W/(m²K)

In addition, requirements regarding the overall transmission losses have to be satisfied, i.e. in case a building part is not refurbished the other building parts might need to get some extra insulation to obtain the requirements according to the second table of the first annex of the EnEV (Table 7.2).

Table 7.2 Excerpt of the second table of the first annex in the EnEV 2016

Building Type		**Maximum specific transmission losses**
Detached residential building	$A_N \le 350$ m²	H'_T = 0.40 W/(m²K)
	$A_N > 350$ m²	H'_T = 0.50 W/(m²K)
Semi-detached residential building		H'_T = 0.45 W/(m²K)
All other residential buildings		H'_T = 0.65 W/(m²K)

For some IWU building types that have an unfavourable surface-to-volume ratio it can be difficult to achieve the required transmission losses and therefore, in some cases, smaller u-values have to be entered into the calculation.

And finally, according to §9 of the EnEV 2016, the non-renewable primary energy demand of the building has to be smaller than for the reference building calculated according to first table of the first annex of the EnEV (Table 7.3) multiplied with a factor of 1.4.

Table 7.3 Excerpt of the first table of the first annex in the EnEV 2016

Row	Building Parts/Systems	Reference Building
1.1	Exterior walls, ceiling against outdoor air	U = 0.28 W/(m²K)
1.2	Wall against soil, floor slab, walls and ceilings against unheated rooms	U = 0.35 W/(m²K)
1.3	Roof, upper ceiling, walls of nave aisle	U = 0.20 W/(m²K)
1.4	Windows, French doors	U_w = 1.3 W/(m²K) g = 0.60
1.5	Skylight	U_w = 1.4 W/(m²K) g = 0.60
1.7	Exterior door	U = 1.8 W/(m²K)
2	Thermal bridges surcharge	ΔU_{TB} = 0.05 W/(m²K)
5	Heating system	Condensing boiler with improved efficiency, - up to 500 m² usable area: within thermal envelope - more than 500 m² usable area: outside of the thermal envelope
6	Domestic hot water	Production with the heating system described in row no 5 with solar thermal device and buffer storage
8	Ventilation	Central exhaust air ventilation

7.2 Heating Systems

A set of different heating systems is considered (Table 7.4) and again, the heating systems are provided as boiler-DHW as well as electric-DHW-systems.

The EnEV does have requirements regarding the air tightness of refurbished buildings but not specifically for the ventilations system. Usually natural ventilation is sufficient to achieve the energetic requirements of the EnEV and it is assumed that a house owner who just wants to meet the minimum requirements would not voluntarily install a ventilation system, especially as it is connected to additional costs.

Table 7.4 List of heating systems that are considered in for usual refurbishment

Heating System | DHW System
1) Condensing Boiler | Condensing Boiler
2) Condensing Boiler | Condensing Boiler + Solar
3) HP (Soil) | HP (Soil)
4) HP (Air) | HP (Air)
5) Pellets | Pellets
6) TS | TS
7) Condensing Boiler | Electrical
8) HP (Soil) | Electrical
9) HP (Air) | Electrical
10) Pellets | Electrical
11) TS | Electrical

7.3 Final Energy Demand – Refurbishment Level 1

The final energy demand does not need a separation into boiler-DHW and electrical-DHW in the usual refurbishment level. The condensing boiler system is used as reference system and its final energy demand calculated for all building types can be found in the Appendix Section 13.2.

Viewing Table 7.5 with the coefficients to transform the reference system into the other observed heating systems, on can see that often the coefficients for EFH and MFH of one system lie close together. The absolute error of the final energy demand is close to 0 kWh/(m²a) and has a standard deviation of usually less than 1.5 kWh/(m²K)).

Table 7.5 Heating system coefficients to calculate the final heat demand based on one reference system

Basis: Condensing | Condensing Heating Sys. | DHW Sys.	**EFH & RH**		**MFH, GMH & HH**	
	Coefficient	**Absolute Error Demand**	**Coefficient**	**Absolute Error Demand**
Condensing | Condensing & Solar	0.883	-0.21 ± 1.76	0.898	-0.08 ± 0.87
HP (Soil) | HP (Soil)	0.319	0.09 ± 0.77	0.306	0.02 ± 0.28
HP (Air) | HP (Air)	0.373	0.09 ± 0.74	0.362	0.02 ± 0.27
Pellets | Pellets	1.354	0.15 ± 1.29	1.045	0.03 ± 0.38
TS | TS	0.947	0.00 ± 0.04	0.966	0.00 ± 0.03
Condensing | Electrical	0.895	-0.18 ± 1.57	0.914	-0.06 ± 0.73
HP (Soil) | Electrical	0.361	0.16 ± 1.39	0.398	0.09 ± 1.06
HP (Air) | Electrical	0.405	0.14 ± 1.21	0.442	0.08 ± 0.95
Pellets | Electrical	1.180	-0.16 ± 1.33	0.925	-0.06 ± 0.64
TS | Electrical	0.854	-0.16 ± 1.36	0.887	-0.06 ± 0.64

8 Advanced Refurbishment Level

8.1 Incentive Programmes

The national building typology of the IWU uses the Passive-House-Standard as an orientation for the design of the advanced refurbishment level. However, statistics of the KfW incentive programmes show that the majority of buildings apply for the programme “individual measures” (*Einzelmaßnahmen*), while the number efficiency buildings decreases with an increasing efficiency standard. In 2015 only 545 out of nearly 96,000 funded buildings with one to two dwelling units (including “individual measures”) refurbished to the Efficiency Building Standard 55, while the share for multi-family houses is even smaller (Diefenbach et al., 2016, p. 16). The KfW and IFB Efficiency Standard 40, which are roughly equivalent to Passive Houses, is not even included in the evaluation of the KfW incentive programmes, which indicates that only a small amount of buildings aimed for this ambitious Efficiency Standard.

Therefore, in this Master Thesis, the advanced refurbishment level is oriented towards the KfW Efficiency House Standard 55, which also corresponds with the strategy on future energy efficiency in buildings from the German government (BMWi, 2015, 47-48,51).

The KfW or IFB Energy Efficiency House 55 has a primary energy demand that is equal or less than 55 % of the EnEV-reference building and specific transmission losses are 30 % below the values of the second table of the first EnEV annex (IFB, 2017b, p. 37; KfW, 2016, p. 9).

The IFB offers – besides the Efficiency House Standards 55, 40, and plus energy – two additional programmes in which instead of the primary energy demand the achieved final energy demand is crucial. In these two programmes all building parts that undergo a refurbishment have to meet a maximum u-value (Table 8.1 offers an overview over the developments in recent years). Nowadays, the requirements for the main building parts are identical to the KfW programme for individual measures. In case of constructive challenges or cultural heritage building owners and planners can ask for exceptions.

Table 8.1 The required u-values of the IFB-incentive programmes[14]

	Required U-values between 2010 - 2017
Steep Roof / Ceiling	0.20 - 0.14
Flat Roof	0.15 - 0.14
Dormer Walls and Roofs	0.20
Skylight Window	1.20 - 1.00
Window	1.10 - 0.95
Exterior Walls	0.20
Basement Ceiling, floors, walls against soil or unheated basement	0.25

8.2 Refurbishment U-Values in the Dataset

The new dataset does not include information on the targeted IFB funding programme, nor does it provide data on the reference building, with which it would be possible to identify buildings that achieve an Efficiency Building Standard. Still, the available u-values of the new dataset are analysed to get the amount of building parts that get insulated in general and moreover, to observe whether these building parts satisfy the required u-values of the IFB or not.

The new dataset distinguishes four building part categories: Roofs and upper ceilings, walls and doors, floors and basement ceilings, as well as windows and skylights. Unfortunately, the IFB requirements vary depending on the construction type (EFH or MFH) and the year in which the energy certificate was calculated. While it is possible to make assumptions based on the u-value and area, whether a building part is more likely to be a wall or a door, it is more problematic for roofs and windows.
Macros that contain rules to make assumptions about the building parts nature and therefore, the required u-values, based on the energy certificate's year of creation, u-values, and surface areas, are used to analyse the u-values of the new dataset[15].

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[14] Based on the incentive programme leaflets published by the IFB in during these years. Newest: IFB, 2017a; IFB, 2017b

[15] First result of the analysis is that a considerable amount of building parts have u-values of 0 W/(m²K). With a share of 28 %, roofs have the highest amount "empty" u-values. As the reason for that is not clear at this point, these building parts are excluded in further analysis.

8.2.1 U-Value Change between Existing and Refurbished State

Table 8.2 shows that the majority of the building parts satisfy the required IFB u-values after refurbishment. 63 % of the roofs achieve the required u-value, even though a separation of tilted or flat roof for multi-family houses, which have different requirements to meet, was not possible. 24% of the roofs do not get any insulation.

Table 8.2 Analysis of the new dataset on the proposed u-values for refurbishment and their connection to requirements of incentive programmes

	Roof & Upper Ceiling	**Wall**	**Floor & Basement Ceiling**	**Window**
Satisfied IFB requirements	63%	38%	50%	64%
Missed IFB requirements	14%	18%	10%	9%
No insulation	24%	28%	40%	24%

With 40 % a high amount of floors/basement ceilings do not get insulated, while another 10 % do not satisfy the IFB-requirements. Usually the insulation is put underneath the basement ceiling, as the insulation of floor slab is often impossible. Yet, a complete insulation of the basement ceiling is can be tricky as well, as the space might already be occupied by wires and distribution pipes or the ceiling height of the basement may be too low. In these cases, the energy advisor enters two basement ceilings into the software: an insulated one and the uninsulated one. The results of this analysis seem to confirm the described practice.

The share of walls that meet the IFB-requirements amounts to only 38 %, perhaps another 11 % satisfy the requirements for walls against soil or unheated basement, at least the u-values lie within the necessary range. The influence through buildings under cultural heritage is considered to be minor as only ca. 8 % of the walls belong to that category.Walls of buildings under cultural heritage have a higher tendency to miss the required u-values and the share of building parts that do not get insulated at all rises to 45 %.
The reason for the high amount of apparently uninsulated walls cannot be found.

8.2.2 Weighted Mean U-Values

For the refurbishment measure of every building and each building part category, the weighted mean u-value based on the respective surface area is calculated.

For the roofs and upper ceilings roughly 50 % of the mean u-values are smaller or equal to 0.14 W/(m²K), another third ranges between 0.14 and 0.20 W/(m²K). As the previous chapter showed that about 24 % of the roofs do not get any insulation, the mean u-values indicate that a rather large number of buildings already have insulated roofs or upper ceilings in the existing state (Figure 8.1, next page).

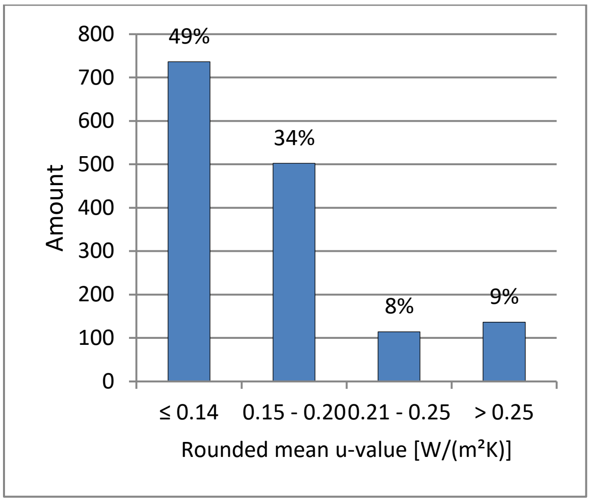

Figure 8.1 Rounded mean u-values for roof/upper ceiling proposed

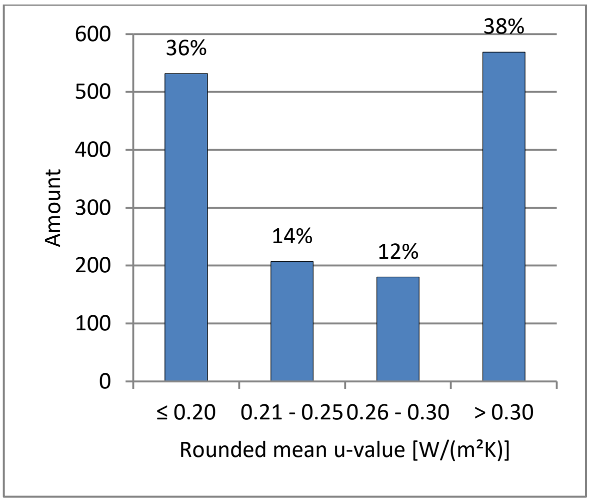

Figure 8.2 Rounded mean u-values for walls

The expected mean u-value for refurbished walls lies between 0.20 and 0.25 W/(m²K), comparable to the mean u-value of 0.22 W/(m²K) for exterior walls of KfW granted buildings (DIEFENBACH ET AL., 2016, p. 27). However, only 14 % are within that range, whereas 38 % of the walls have a u-value even larger than 0.30 W/(m²K) (Figure 8.2).

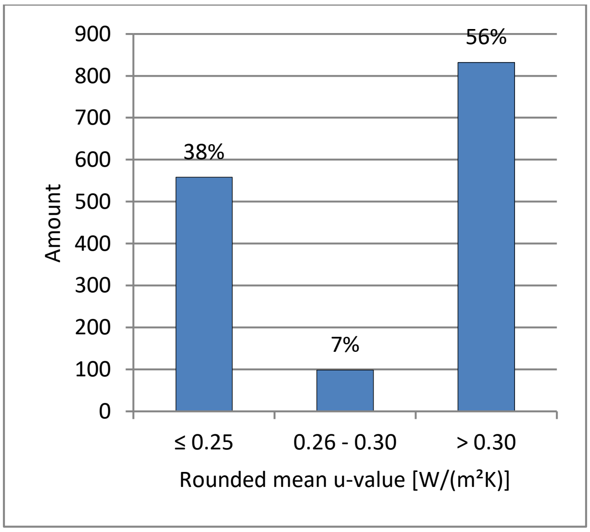

Figure 8.3 Rounded mean u-values of the floor/basement ceiling

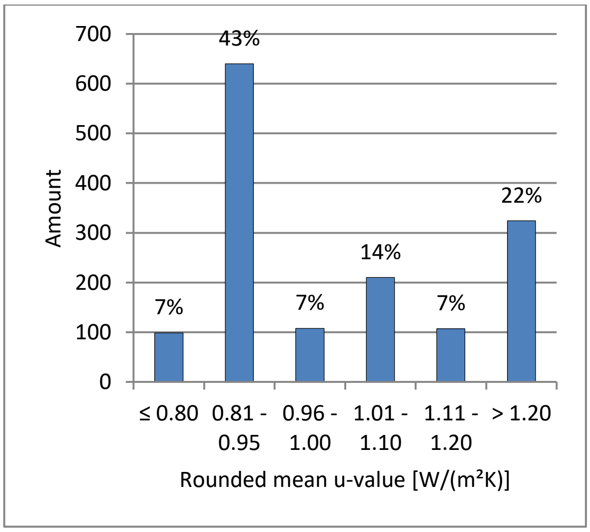

Figure 8.4 Rounded mean u-values for windows

Although the first analysis showed that half of the basement ceilings achieve the IFB requirements, only 38 % of the mean u-values for a house achieve that. This result supports the previous conclusion that a complete insulation of the floor/basement ceiling is impossible in many cases (Figure 8.3).

With 50 % the majority of the mean u-values of windows are below 0.95 W/(m²K)., but still about 22 % of the buildings tend to a mean u-value of more than 1.20 W/(m²K) (Figure 8.4).

8.2.3 Conclusion for the U-Values of the 2. Refurbishment Level

Overall the energy certificates seem often to satisfy the IFB required u-values and the advanced refurbishment measure in this Master Thesis targets these u-values as well, with the only exception of the floors/basement ceilings. In the further calculation, an insulation of 8 cm with an heat transmission coefficient of 0.035 W/(mK) that concludes to an overall u-value of about 0.30 W/(m²K) is set for floors/basement ceilings. The weak floor u-value, which is higher than the IFB-requirement of 0.25 W/(m²K), usually has to be compensated by increasing the insulation of other building parts to satisfy the requirements of the specific transmission losses of an Efficiency Building 55.

8.2.4 Additional Assumptions for the Building Envelope

In case of official energy demand calculations, the transmission losses are usually rounded to three decimal places, but as the TABULA calculation method uses simplifications towards the official calculation methods anyways, the transmission losses are rounded to two decimal places in this Thesis.

For the thermal bridging a factor of 0.035 W/(m²K) is chosen, which corresponds to the simplified assessment of thermal bridging, published by the KfW (2015, p. 8). A detailed thermal bridging coefficient can reach 0.025 W/(m²K) or even lower and offers a strong lever to decrease the overall transmission losses and therefore, the used coefficient of 0.035 is more of a conservative assumption.

8.3 System Combinations in Proposed Refurbishments

As neither the targeted incentive programmes nor the primary energy demand of the energy certificates are included in the dataset, it is difficult evaluate the proposed heating systems for refurbishment and draw conclusions for the Efficiency Standard 55 alone. It is most likely that the number of Efficiency Houses 55 is rather low like in the KfW statistics (DIEFENBACH ET AL., 2016) and thus, "more innovate" technology is underrepresented in the dataset. Nevertheless, the distribution of system combinations within the dataset is examined.

The most common system combinations for the proposed refurbishment can be seen in Figure 8.5, and again the first named boiler provides space heating, the second device is used for DHW supply (see Section 13.1.3 for EFH and MFH differences).

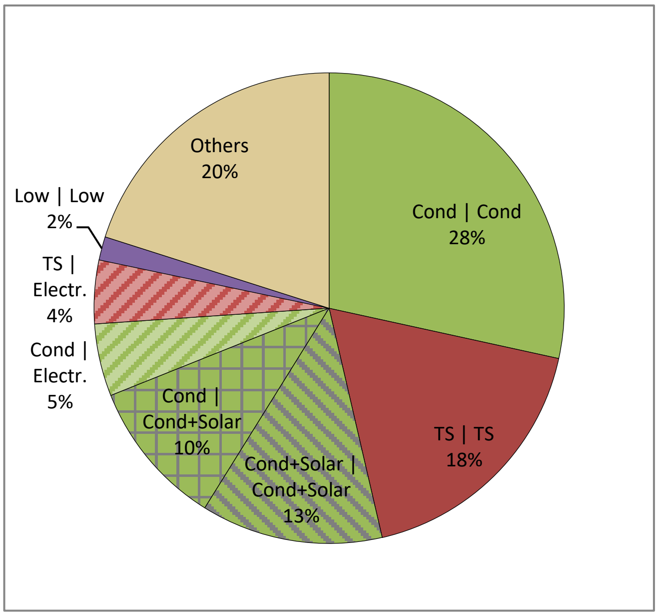

Figure 8.5 Most common system combinations for the refurbished state

Based on the colours it is obvious that the overall usage of condensing boilers increases (greens). Systems providing space heating and DHW with condensing boilers have the highest share with 28 %, followed by district heating grids (TS) with 18 %. Barely any constant temperature boilers stay in the proposed refurbishments and thus, are included in the “Others”-category.

The more “innovative” technologies do not reach high stakes within the dataset and are often used in combination with more “conservative” systems, which leads to various combinations that are summed up as “Others”:

Heat pumps are proposed for the refurbishment (9x air, 10x soil, 3x ground water, and 1 exhaust air) in 23 buildings, 13 of them cover the entire space heating demand, while in a total of 46 buildings the DHW demand is supplied byheat pumps (usually 95 % of the total DHW).

Biomass is used in 101 buildings to provide either a share of 10 % or even 90 to 100 % of the total space heating demand.

In 17 % of all buildings solar devices are used to produce usually 10 % of the space heat, whereas 30 % of the buildings use sun energy to supply their DHW demand.

Figure 8.6 and Figure 8.7 display the spatial distribution of the heating systems proposed for refurbishment[16] and show that single-family houses are more likely to use solar thermal devices than multi-family buildings. In Eimsbüttel and Hamburg-Nord no single-family buildings are connected to a heating grid, while an increase can be observed in Hamburg-Mitte. The number of buildings using electrical devices for DHW decreases and is mostly combined with other system cominations and summed up as “other” heating systems.

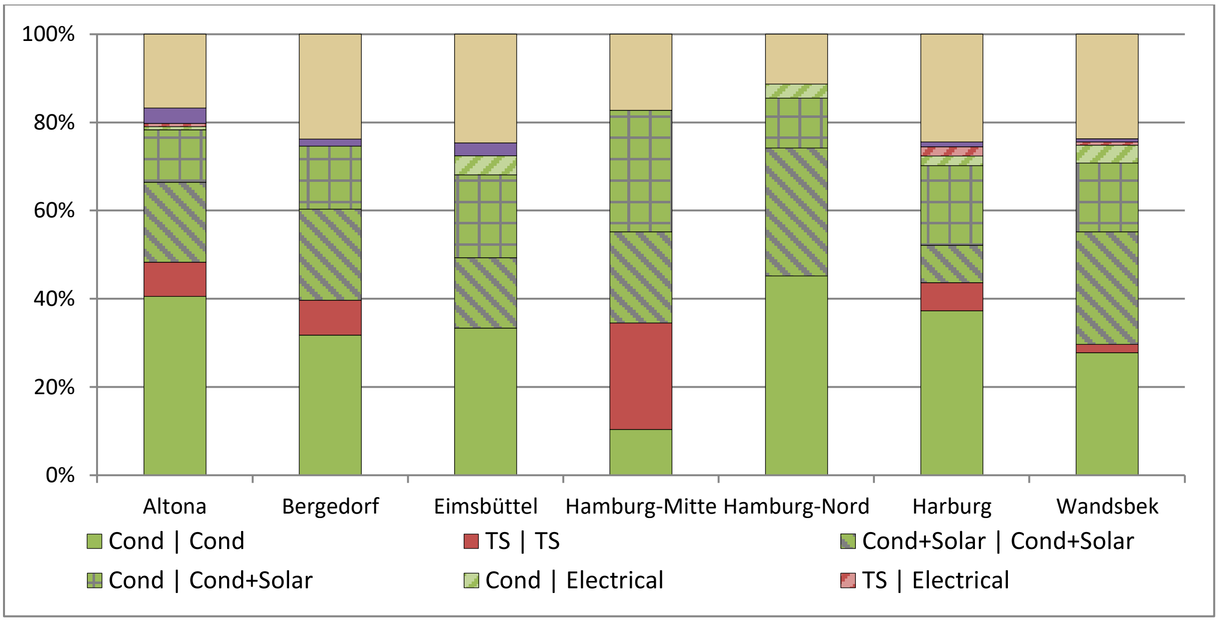

Figure 8.6 Distribution of heating systems in the districts after refurbishment: EFH & RH

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[16] The results in form of tables can be found in Appendix Section 13.1.4

The share of district heating in multi-family house increases in all districts. The amount of buildings in which the DHW is supplied by electrical appliances is higher than for single-family buildings. "Other" heating systems have the highest rates in Eimsbüttel and Harburg.

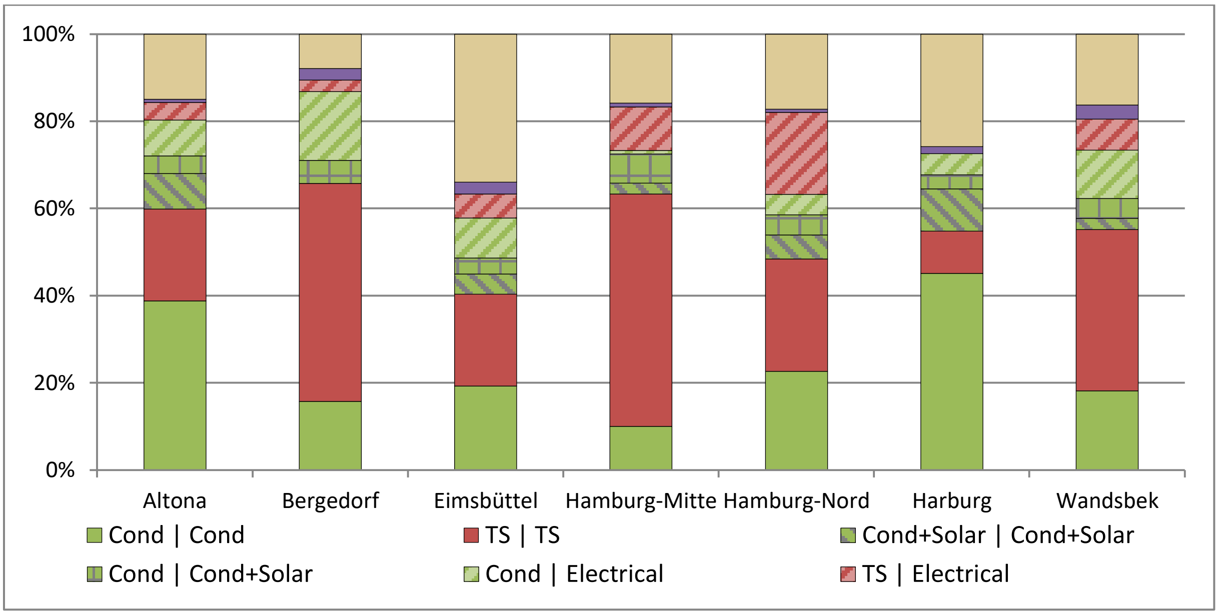

Figure 8.7 Distribution of heating systems in the districts after refurbishment: MFH, GMH & HH

The distribution of the heating systems over the building's construction epochs shows for single-family buildings a rather evenly distribution (graphics in the Appendix 13.1.5). The system combination *Condensing* | *Condensing* tends to be slightly more frequent in older epochs while *condensing boiler* in combination with *solar thermal devices* are more often proposed in younger construction epochs.

In the dataset, multi-family buildings from 1979-1994 (epochs G and H), do not use solar thermal devices at all, despite it has to be noted that the sample size are rather small.

More than half of the dataset's entries use natural ventilation, while about a quarter of the buildings have a ventilation system with heat recovery. As previously explained, probably not all buildings aim for an Efficiency House Standard 55, but the necessity of a ventilation system depends on the efficiency level because with increasing insulation measures the air-tightness rises, which needs to be compensated with a ventilation system with heat recovery. The typical heat recovery rates found in the dataset lies at 80, 85, and 94 %, whereas the highest rate included in the TABULA Calculation Tool is 80 %, which is set for the advanced refurbishment level in this Master Thesis.

8.4 Existing Heating System to Proposed Heating System

This section examines the relations between existing heating systems and the proposed heating systems for refurbishment. The following tables show the frequencies of changes from one system into another. For example in case a single-family building that heats with the system combination *TS | Electrical* in the existing state has a tendency of 50 % of not changing the system, while another 30 % change to building-central systems.

Tabelle 8.1 Proposed Replacement of the heating system

		Refurbishment: Combinations							
		TS | Electrical	**TS | TS**	**Cond | Cond**	**Cond | Cond/Solar**	**Cond/Solar | Cond/Solar**	**Cond | Electrical**	**Low | Low**	**Others**
EFH & RH Existing State: Combination	**TS | Electrical**	50%	20%	10%	0%	0%	0%	0%	20%
	TS | TS	0%	86%	0%	0%	0%	0%	0%	14%
	Electrical | Electrical	0%	4%	46%	17%	8%	0%	0%	25%
	Cond | Cond	0%	0%	54%	16%	24%	0%	0%	6%
	Cond | Electrical	0%	0%	38%	25%	17%	17%	0%	4%
	Constant | Constant	0%	1%	33%	19%	23%	0%	0%	25%
	Constant| Electrical	0%	9%	22%	9%	23%	16%	0%	20%
	Low | Electrical	0%	3%	22%	9%	22%	13%	0%	31%
	Low | Low	0%	1%	31%	14%	19%	0%	13%	23%
	Others	0%	4%	21%	18%	20%	1%	0%	37%
	Total	1%	5%	33%	15%	21%	3%	2%	21%
MFH, GMH & HH Existing State: Combination	**TS | Electrical**	59%	21%	3%	0%	2%	1%	0%	13%
	TS | TS	0%	91%	2%	0%	0%	0%	0%	8%
	Electrical | Electrical	5%	32%	23%	0%	0%	9%	0%	32%
	Cond | Cond	0%	13%	63%	16%	3%	0%	0%	5%
	Cond | Electrical	0%	3%	17%	7%	7%	59%	0%	7%
	Constant | Constant	0%	15%	44%	8%	10%	0%	0%	22%
	Constant| Electrical	0%	7%	25%	3%	5%	27%	0%	33%
	Low | Electrical	0%	11%	15%	2%	9%	24%	4%	35%
	Low | Low	0%	16%	40%	5%	9%	0%	20%	9%
	Others	1%	8%	37%	10%	7%	3%	0%	35%
	Total	8%	31%	24%	5%	5%	7%	2%	19%

In general, for nearly all buildings with night storage heaters and electrical DHW supply it was proposed to change to mostly building-central DHW systems.

Buildings that use electric appliances for DHW supply have a tendency of 20 % to change to a building central system during the refurbishment.

In about 8 % of the multi-family buildings a non-DH space heating changes to a DH space heating, while it is only ca. 2 % of the single-family buildings.

These frequencies show the typical proposed replacements during the refurbishment which allows a more diverse computation of the buildings refurbishment. It delivers a first approach to assume the heating system after refurbishment, based on the assigned baseline heating system. A combination of these findings with the results on district distribution might be necessary, as e.g. the connection to a district heating grid depends on its availability, but were not performed in scope of this Master Thesis.

8.5 Results on Energy Demand – Refurbishment Level 2

A list of different systems combinations is calculated for the advanced refurbishment level (as displayed in Table 8.3). On the one hand, it is based on the dataset's most frequent heating systems, while, on the other hand, it also includes different system combinations with heat pumps, to enable the comparison with more conventional systems, despite of small sample sizes within the dataset,

Table 8.3 The following building systems are simulated

Heating Sys. | DHW Sys.	
1) Condensing & Solar | Condensing & Solar[17]	(*)
2) Condensing | Condensing & HP (Soil)[18]	(*)
3) Condensing | Condensing & HP (Air)	(*)
4) HP (Soil) | HP (Soil)	
5) HP (Air) | HP (Air)	(*)
6) Pellets | Pellets	
7) TS | TS	
8) TS | Solar	
9) TS | TS&HP (Soil)	
10) TS | TS&HP (Air)	(*)
11) TS | Electrical	
12) Pellets | Electrical	(*)

The German strategy on energy efficiency in buildings aims on a primary energy demand of 40 kWh/(m²a) on average in 2050 and expects a final energy demand between 74 and 104 kWh/(m²a) depending on whether the strategy focusses on the energy efficiency or the usage of renewable energies (BMWI, 2015, 47-48, 51).

The final energy demand of the considered heating system in this Master Thesis is often below 80 kWh/(m²a) and thus, would meet the values of the national strategy. However, most single-family and row houses exceed the primary energy demand of 40 kWh/(m²a) and have even trouble to reach the Efficiency House Standard 55. Especially systems using condensing boilers exceed the primary energy demand by up to 15 kWh/(m²a) towards the Efficiency House, while the other systems surpass the requirements by only about 1 kWh/(m²a). All systems that do not reach the primary energy demand of an Efficiency House 55 are tagged with an asterisk in Table 8.3.

Although the official calculation programmes offer additional setting options, which allow a more detailed calculation resulting into lower primary energy demands, it would be still difficult to reduce the primary energy demand by a total of 15 kWh/(m²a). But as all available means of the TABULA Calculation Tool are exhausted (with the exception of the thermal bridging factor, which is expected to

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[17] Solar thermal devices produce 10 % of the demand for space heating, while the share for DHW supply amounts to 60 % for EFH and 40 % for MFH

[18] Heat pump provides 95 % of the heat demand and is supplemented by an electrical heater rod

help, but not solve the problem entirely) and a further increase of insulation thickness is neither realistic nor would it have enough impact on the final results, exceedance of required primary energy demand is tolerated. They display the best possible results, on basis of the used calculation tool and available information. Table 8.4 shows the coefficients to calculate the final energy demand based on the reference system *Condensing & Solar | Condensing & Solar*.

Table 8.4 Coefficients to calculate the final energy demand for the advanced refurbishment level

Basis: Cond+Sol | Con+Sol	**EFH & RH**		**MFH, GMH & HH**	
Heating Sys. | DHW Sys.	**Coefficient**	**Absolute Error Demand**	**Coefficient**	**Absolute Error Demand**
Cond+Sol | Cond+HP(Soil)	0.964	-0.05 ± 1.15	0.820	-0.07 ± 0.73
Cond+Sol | Cond+HP(Air)	0.984	-0.03 ± 1.11	0.848	-0.06 ± 0.62
HP(Soil) | HP(Soil)	0.502	0.20 ± 1.56	0.463	0.06 ± 0.65
HP(Air) | HP(Air)	0.569	0.21 ± 1.59	0.531	0.06 ± 0.67
Pellets | Pellets	1.839	0.42 ± 3.27	1.658	8.37 ± 2.15
TS | TS	1.246	0.19 ± 1.50	1.242	0.06 ± 0.70
TS | TS+HP(Soil)	0.976	-0.07 ± 0.56	0.855	-0.08 ± 0.87
TS | TS+HP(Air)	0.996	-0.05 ± 0.41	0.884	-0.07 ± 0.75
TS | Electrical	1.052	0.00 ± 0.02	1.050	-0.02 ± 0.18
Pellets | Electrical	1.465	0.05 ± 0.37	1.383	0.02 ± 0.17
HP | Electrical	0.571	0.27 ± 2.07	0.658	0.13 ± 1.41

9 Comparison of Results with the IWU Typology

9.1 Baseline Condition

In this section the resulting energy demands of this Master Thesis are compared with the values of the IWU-typology to assess the influence of the adaptations made.

A look on the usable heat demand of the baseline condition enables the observation of the effect caused mainly by the modification of the climate (Hamburg instead of Potsdam) because only minor changes were made for the heating systems. On average the usable heat demand decreases by ca. 7 kWh/(m²a). Hamburg's climate is milder than Potsdam's, at least according to the data of DIN V 18599.

Figure 9.1 displays the final energy demand for the baseline condition. The grey bars show the range between the different considered heating systems, with *electrical* | *electrical* having the lowest final energy demand and *constant* | *constant* having the highest. Single-family buildings have a range of 124 kWh/(m²a) on average while multi-family buildings have a mean range of 75 kWh/(m²a). The final energy demand of the *low* | *low* heating system – represented by red dots –is usually higher than the corresponding *low* | *low* variant computed in this Thesis (green squares).

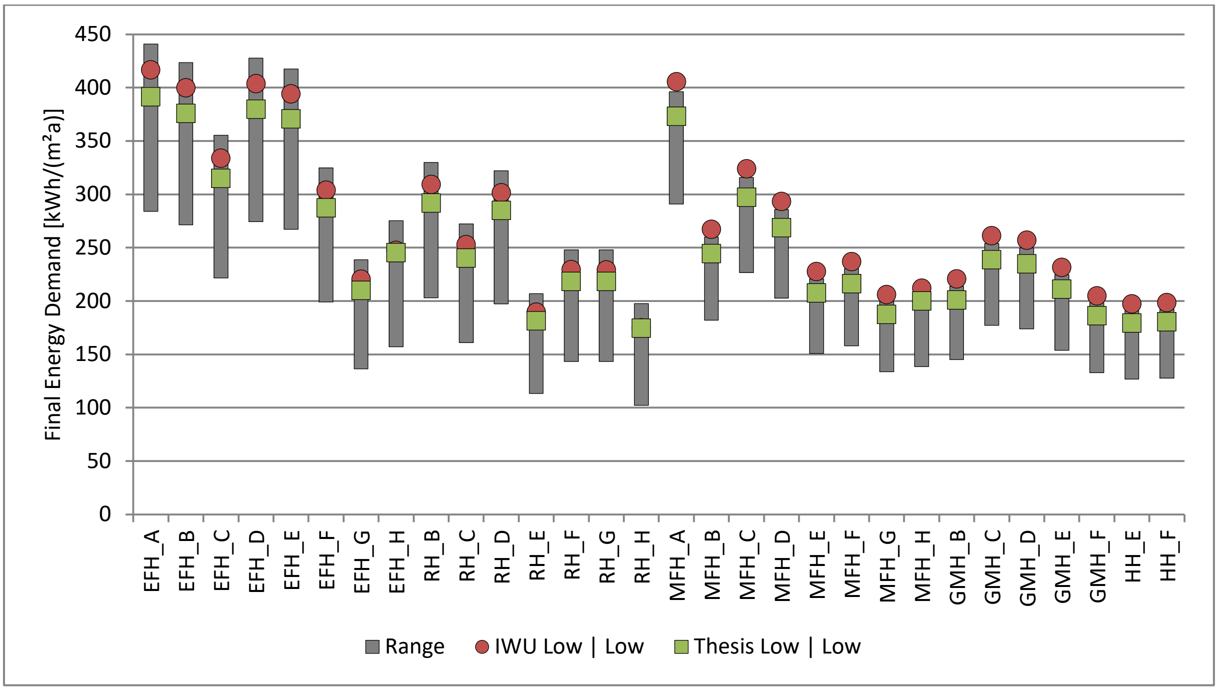

Figure 9.1 Comparison of final energy demand for the baseline condition

The ranges between the heating systems show the value of this Master Thesis: Until now, only limited means to display the final energy demand of residential buildings were available[19], but the insights of this Master Thesis enable a more differentiated final energy demand calculation. And based on the ranges between the considered heating systems, it is assumed that the effects on neighbourhood- or city-scale will be noticeable.

9.2 Usual Refurbishment

The usable heat demand of the usual refurbishment calculated in this Master Thesis is smaller than the IWU-typology, while in some cases the final energy demand of the *condensing* | *condensing* system is nearly identical (Figure 9.2). However, the difference between the most and least efficient system stays the same compared to the baseline condition with heat pumps (soil) having the lowest demand and pellet boilers the highest. Furthermore, the figures show that the final energy demand of the individual building types for the baseline condition fluctuates considerably compared to the usual refurbishment level, which reduces the variance remarkably.

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[19] The online TABULA tool offers four different scenarios of the heating system in existing state and in proposed refurbishment http://webtool.building-typology.eu/

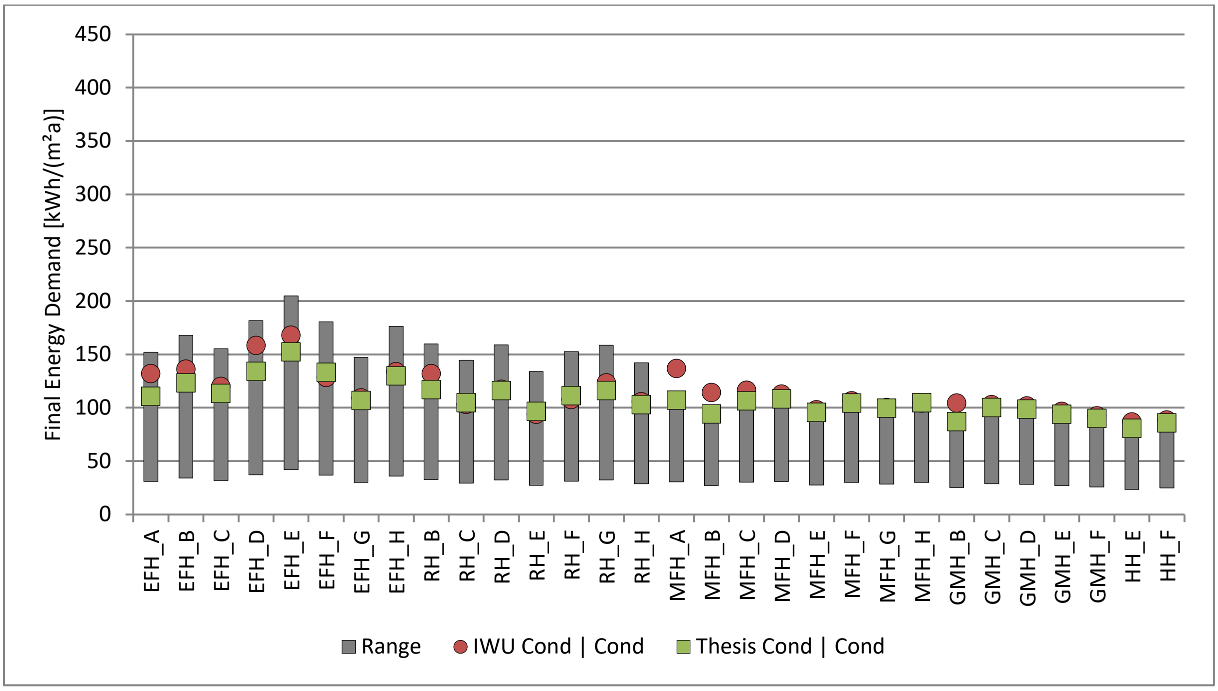

Figure 9.2 Comparison of final energy demand for the usual refurbishment

9.3 Advanced Refurbishment

While the advanced refurbishment of the IWU targets the Passive House Standard, this Master Thesis used the Efficiency House Standard 55 as role model, causing a slight increase of the usable energy demand by ca. 2 kWh/(m²a) on average. For some buildings the final energy demand of the IWU *cond | cond+solar* variant is smaller than the *cond+solar | cond+solar* system computed in this Master Thesis, in other cases it is vice versa (Figure 9.3). The range of the considered heating systems decreases: it is 78 kWh/(m²a) on average for single-family buildings and 57 kWh/(m²a) for multi-family buildings. Again, the most efficient system is the heat pump with soil as heat source, whereas pellet boilers have the highest final energy demand.

As the IWU-version has a similar high final energy demand as calculated in this Thesis, the IWU possibly has the same difficulties to satisfy the requirements regarding the non-renewable primary energy demand of the Efficiency House 55. However, the Passive House Standard works unlike the KfW Efficiency Buildings. Until 2015 a non-renewable primary energy demand of 120 kWh/(m²a) must not be exceeded[20], which would be satisfied by all considered heating systems of this Master Thesis.

The calculation of the final and primary energy demand does not seem to have errors, as the IWU does not achieve the required fianl energy demands as well, it confirms the calculations performed in this Thesis.

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[20] since 2015 certain conditions regarding the renewable primary energy demand have to be met (PASSIVHAUS INSTITUT, 2016, p. 5)

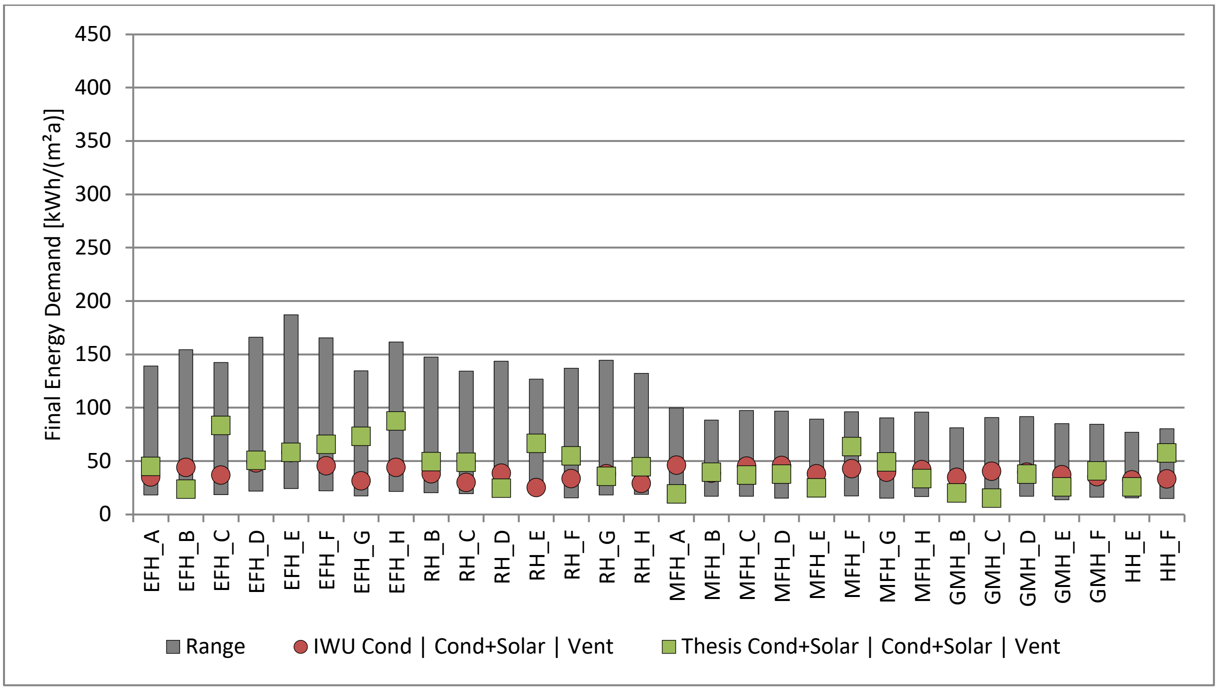

Figure 9.3 Comparison of final energy demand for the advanced refurbishment

10 Estimation of Refurbishment Costs

10.1 Building Envelope

Within this Master Thesis the costs for the building envelope and heating system are separated. The costs for the enhancement of the building envelope are calculated with a small tool based on the regression analysis of Hinz in 2015 and are dependent on the thickness of the insulation that has to have a thermal conductivity of 0.035 W/(mK). In addition, the costs include the scaffolding, energy consulting, and the work of the architect.

Table 10.1 shows the costs for the refurbishment of the building envelope for single-family houses. The average costs are calculated from the regression function developed by Hinz, and in addition the lower and upper costs of the 50 and 95 % confidence intervals are provided. The complete table is available in the Appendix Section 13.3.

Table 10.1 Excerpt of the costs of the building envelope for single-family buildings

	Costs in €/m²$_{Ref}$	**EFH_A**	**EFH_B**	**EFH_C**	**EFH_D**	**EFH_E**	**EFH_F**	**EFH_G**
Usual Refurbishment	**Lower Costs 95%**	233.84	316.00	262.85	254.77	437.56	305.67	203.14
	Lower Costs 50%	285.32	382.78	317.76	337.07	529.02	376.58	246.90
	Average Costs	319.56	422.83	350.21	385.16	582.16	418.26	274.18
	Upper Costs 50%	359.18	469.10	387.47	439.98	642.01	465.71	306.77
	Upper Costs 95%	461.26	587.41	482.10	578.34	788.11	584.85	395.00

Figure 10.1 and Figure 10.2 show that the refurbishment costs vary significantly depending on the building type, which can be ascribed to the rather different building properties in the baseline condition. Due to economies of scale the costs are smaller for multi-family buildings than for single-family buildings. Compared to the usual refurbishment the advanced refurbishment is 11 % more expensive on average.

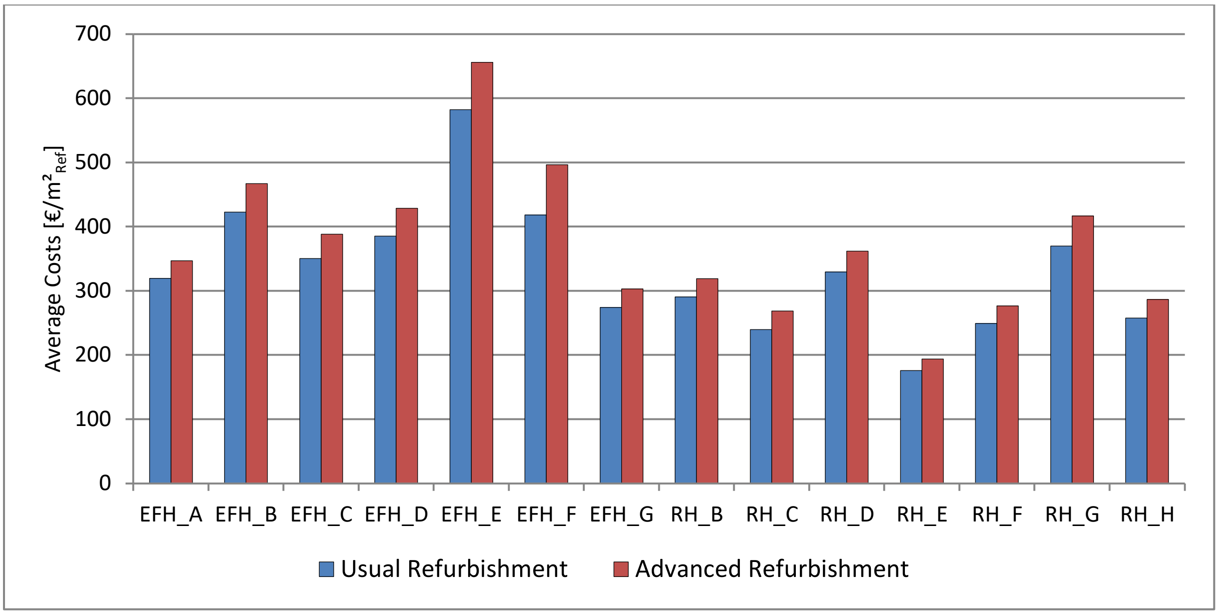

Figure 10.1 Average costs for the refurbishment of the building envelope: EFH & RH

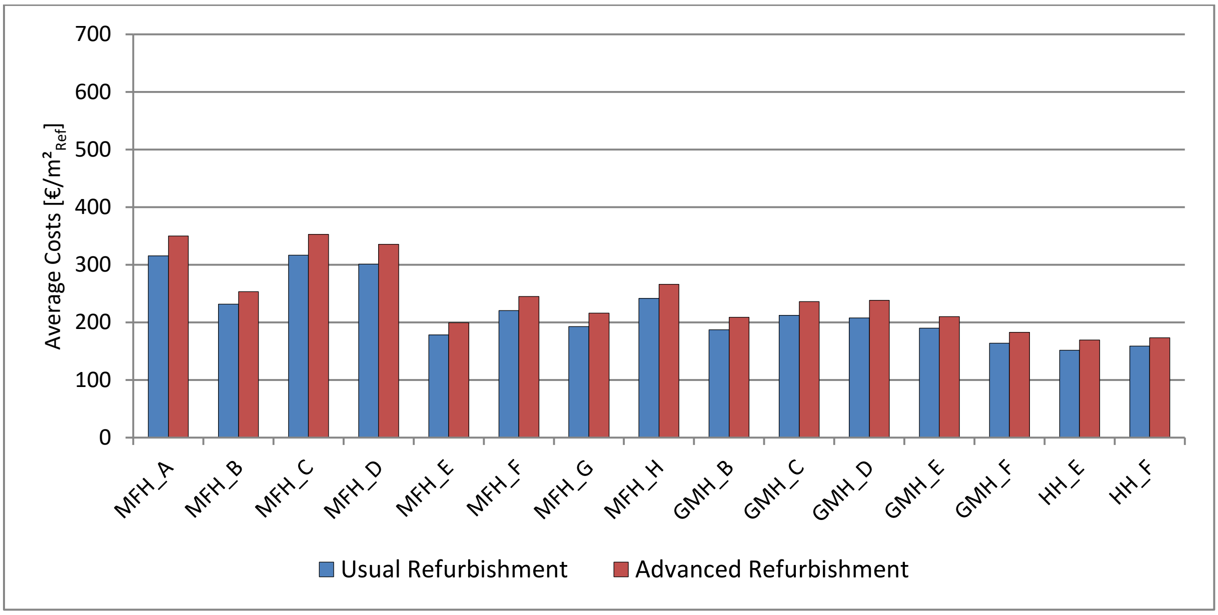

Figure 10.2 Average costs for the refurbishment of the building envelope: MFH, GMH & HH

10.2 Heating Systems

Hinz found a non-linear correlation of the heating system costs towards the living space. Therefore, the costs calculated in the scope of this Master Thesis cannot be delivered as coefficients but need to be in form of functions as well.

However, Hinz did not have enough information on heat pumps in 2015. The gap is filled by older data from his previous research in 2012 despite the sample was rather small (54 buildings) and no available confidence interval (BMVBS, 2012). In addition it cannot be assessed to which extent the costs of heat pumps might have changed over the years.

Building-decentral heating systems, in which two different heaters provide heating and DHW respectively, are not available in Hinz' publications and thus, need to be assumed.
In this regard it is necessary to take into account that the boiler does usually not need to have a greater output to cover the DHW demand in single-family buildings. When the hot water storage empties, the boiler usually prioritises the DHW supply for about an hour, while the warmth of the radiators slightly declines without a noteworthy reduction in comfort (BOSCH THERMOTECHNIK GMBH, n.d.; MINERGIE & ENERGIE SCHWEIZ, 2007; ÖKO-ZENTRUM NRW, 2011b). Hence, installation costs of the boiler for space heating stay the same, even if it does not produce DHW, while additional costs occur as another heater has to be installed for DHW supply, which makes *building-decentral* systems financially more unattractive compared to *building-central* systems that are based on one boiler.

In the usual refurbishment level the average share of DHW of the overall useful heat demand amounts to ca. 20 %, while it makes ca. 25 % for the advanced refurbishment level. The shares are applied on the living space which is the basis for the boiler cost estimation. In case of the heating system: *TS | electrical* 100 % of the living space is supplied by the transfer station of the district heating grid, while additional 20 % or respectively 25 % are supplied by instant hot water heater.

The costs for electric instantaneous water heater are assumed to be 600 € on average in single-family buildings, based on current heater costs between 250 and 500 € plus a surcharge for the installation. It is expected that the value applies on a dwelling unit with a living space of 60 m² and is extrapolated accordingly.

Figure 10.3 shows exemplarily the functions derived for *building central heating* systems in case of a "usual" refurbishment. The functions include all costs related to the exchange of the heater and the improvement of the peripheral system and then are converted to be based on the buildings usable area[21].

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[21] Additional costs for the change from building-decentral DHW to central DHW are not included, due to lack of data

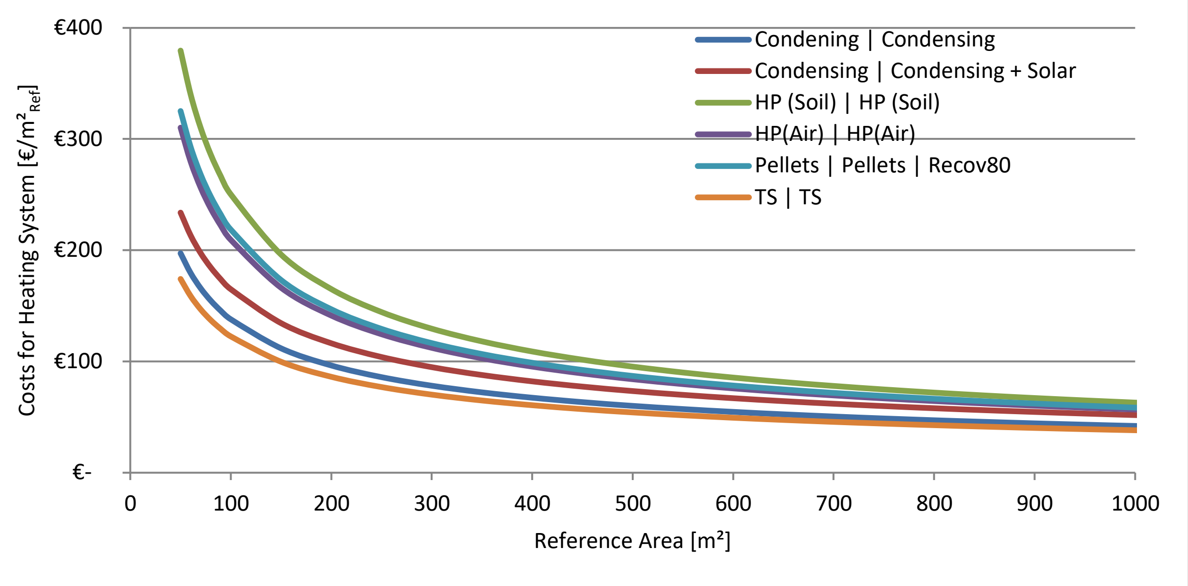

Figure 10.3 Comparison of the cost functions for usual refurbishment of non-electrical heating systems

Table 10.2 and Table 10.3 show the functions for the costs for both refurbishment levels, based on the usable area.

Table 10.2 Cost functions for the usual refurbishment level

Heating System	**Cost function**
Condensing | Condensing	$y = 1487.9x^{-0.517}$
Condensing | Condensing & Solar	$y = 1673.4x^{-0.503}$
HP (Ground) | HP (Ground)	$y = 3945.8x^{-0.599}$
HP (Air) | HP (Air)	$y = 2849.0x^{-0.567}$
Pellets | Pellets	$y = 3052.1x^{-0.573}$
TS | TS	$y = 1265.5x^{-0.507}$
Condensing | Electrical	$y = 1184.2x^{-0.454}$
HP (Ground) | Electrical	$y = 3262.8x^{-0.551}$
HP (Air) | Electrical	$y = 756.91x^{-0.38}$
Pellets | Electrical	$y = 2515.1x^{-0.523}$
TS | Electrical	$y = 993.91x^{-0.44}$

Table 10.3 Cost functions for the advanced refurbishment level

Heating System	**Cost function**
Cond+Sol | Con+Sol	$y = 2225.8x^{-0.441}$
Cond | Con+HP(Soil)	$y = 3020.7x^{-0.507}$
Cond | Con+HP(Air)	$y = 2697.5x^{-0.489}$
HP(Soil) | HP(Soil) |	$y = 3741.7x^{-0.536}$
HP(Air) | HP(Air) |	$y = 2854.3x^{-0.507}$
Pellets | Pellets |	$y = 3024.5x^{-0.512}$
TS | TS	$y = 1508.5x^{-0.45}$
TS | TS+HP(Soil)	$y = 2990.7x^{-0.503}$
TS | TS+HP(Air)	$y = 2486.9x^{-0.484}$
TS | Electrical	$y = 1328.0x^{-0.413}$
Pellets | Electrical	$y = 2687.7x^{-0.481}$
HP | Electrical	$y = 3323.4x^{-0.505}$

However, the costs for a new connection to either the natural gas or the district heating grid are not included in the expenses presented above as they need to be applied depending on whether a building is changing the energy carrier or not. The functions are taken from Hinz and adapted to be based on the usable area instead of the living space (Table 10.4).

Table 10.4 Costs to connect a building to a grid based energy carrier

Natural gas grid:	$y = 155.43x^{0.51}$
District heating grid:	$y = 538.77x^{0.386}$

11 Conclusion and Outlook

For the development of digital heat cadastres with as planning tools for the future transition of the heat supply in cities, it is helpful to have data on heating systems as they form a crucial point in the estimation of the greenhouse gas emissions, which need to be eventually decreased in regard of the climate change.

This Master Thesis examines a set of energy certificates of buildings located in Hamburg (*Hamburger Energiepass*) and draws conclusions regarding the heating systems that are currently used by mainly non-refurbished residential buildings and their typical replacement during refurbishment.

First, it delivers frequencies that describe a tendency of buildings to possess a certain heating system in a certain district. In addition these frequencies show differences between the heating systems of single-family buildings and multi-family buildings. A significant relation between the construction year of the building and the heating system could not be found. Due to the rather small dataset it is not possible to combine more attributes because the samples for each category would become too small and therefore not significant.

In the next step the final energy demand of the considered heating systems was calculated on basis of the TABULA Tool. It is figured that the final energy demand of the heating systems can be compared with each other and thus, coefficients were formed that display the change from a reference system towards another system, e.g. a non-refurbished building supplied by district heating has a 26 % smaller final energy consumption than the same building heating with a constant boiler. These factors will allow a methodical approach to assess the final energy demand of heating systems without the need to have all final energy demands listed in a table. The simplification causes a small error which is tolerable, considering that the whole calculation is based on assumptions and generalisations.

Finally, the costs for the assumed insulation of the building envelop was estimated for each building type and functions were generated to calculate the costs of the heating systems in dependency on the usable area. This last step completes the data on heating systems in refurbishment.

The results can be used in digital heat cadastres to generate primary energy demand and greenhouse gas emissions of the existing state and to simulate the effects of different refurbishment scenarios on larger scales. In combination with the estimated refurbishment costs, this data on heating systems will allow a holistic assessment of future scenarios.

However, further verification of this heating system data should be considered, before implementing. For example the effect of the heating system assignment using the frequencies presented in this Master

Thesis has to be evaluated. Especially the consequences of assigning the different gas-based heating systems should be assessed, for example by running a Monte-Carlo Simulation.

Still, there is much material left for further research and more final papers. For example the dataset could not provide information on current refurbishment rate in Hamburg or frequencies of the different refurbishment standards that are targeted during the refurbishment. Moreover, the energetic standard of the future are not considered. What might be the legal requirements for refurbished buildings and new buildings in the future? How might the refurbishment costs develop? How do current incentive programmes affect the economies of the refurbishments?
However, the values and calculation tools included in this Master Thesis can provide a foundation to conquer those questions in in the future.

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13 Appendix

13.1 Supplementary Results on the Dataset

13.1.1 Peripheral Heating System in the Building Stock

Figure 13.1 shows that about 59 % of the buildings have moderate insulation of distribution pipes, 4 % are not insulated, and another 4 % do not have further information (usually night storage heating or wooden fuelled boilers do not have distribution pipes). About 11 % of the pipes are insulated according EnEV requirements; roughly 17 % meet the requirements of "half EnEV", i.e. between moderate and EnEV.

With 79 % the majority of buildings do not have a hydraulic balancing (German: *hydraulischer Abgleich)*. Furthermore, the power of pumps is usually not regulated.

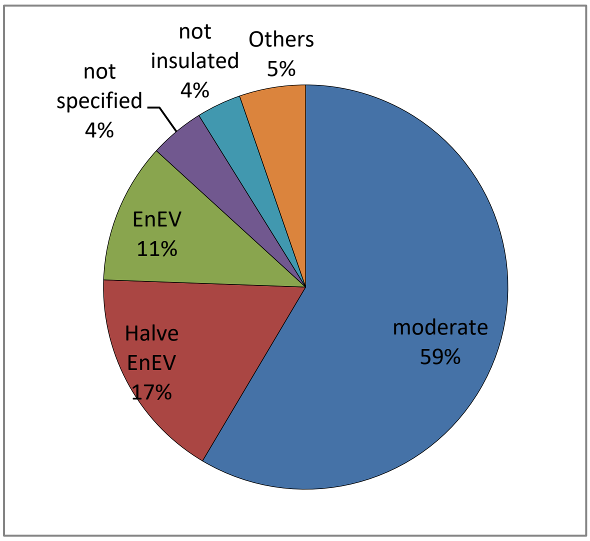


Figure 13.1 Distribution of pipe insulation

13.1.2 System Combinations in EFH and MFH – Baseline Condition

The analysis of system combinations was performed on single- and multi-family buildings. In ca. 20 % of single-family buildings the DHW is provided electrically, while it is 35 % for multi-family buildings (Figure 13.2 and Figure 13.3).

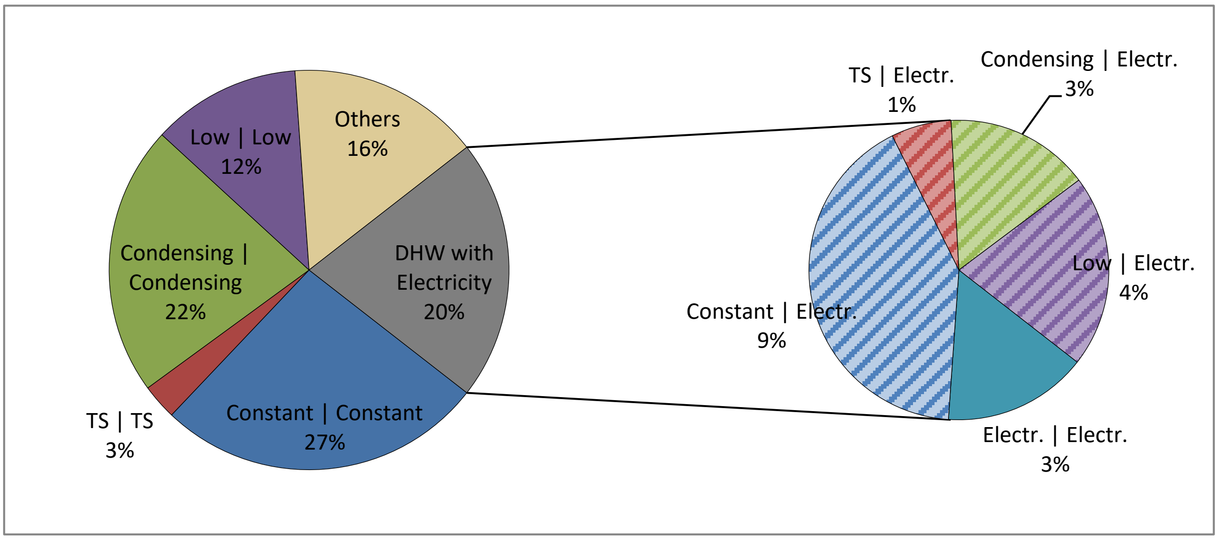


Figure 13.2 Distribution of system combinations for single-family buildings

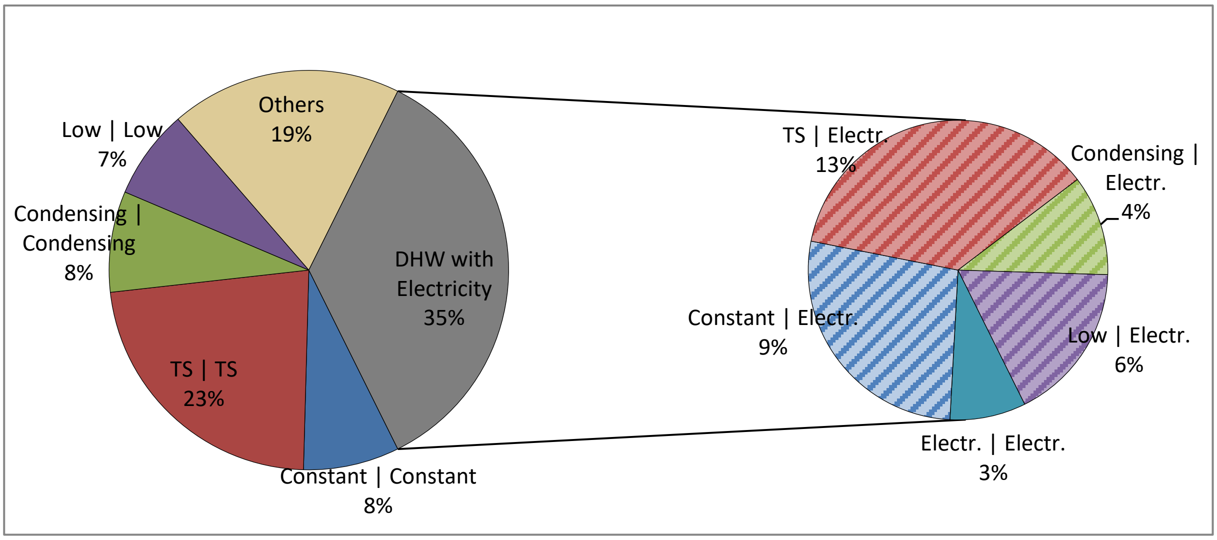
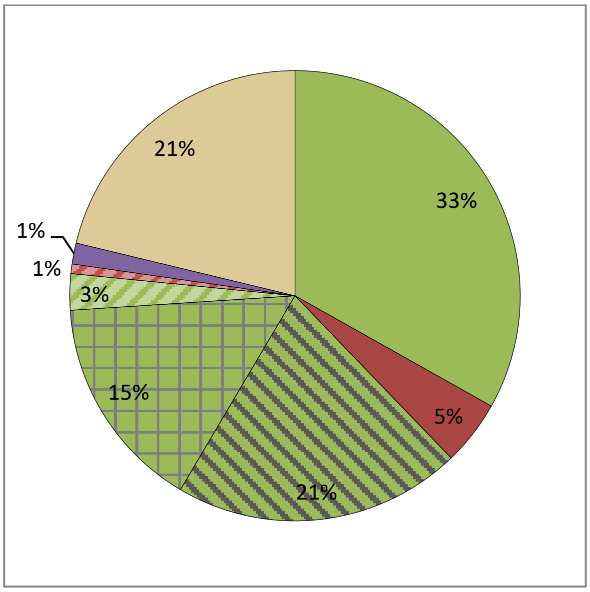


Figure 13.3 Distribution of system combinations for multi-family buildings

13.1.3 System Combinations in EFH and MFH – Refurbishment



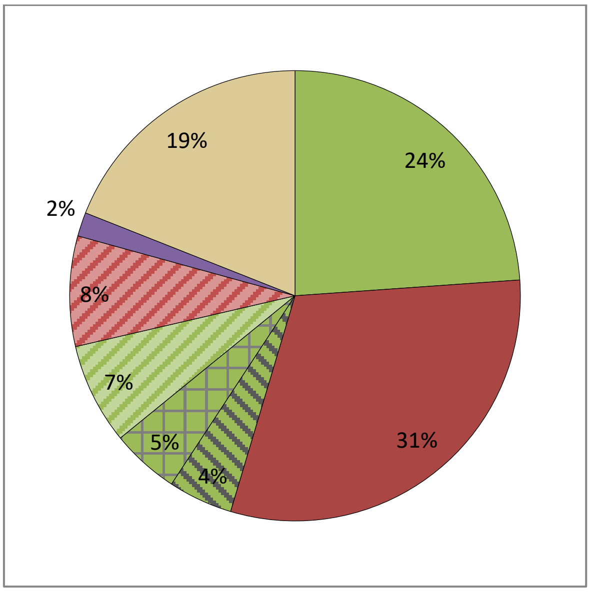


Figure 13.4 Distribution of heating systems after refurbishment in single-family buildings

Figure 13.5 Distribution of heating systems after refurbishment in multi-family buildings

13.1.4 Tables with System Combination for Hamburg’s Districts

Table 13.1 Frequencies of heating system combinations in the baseline condition in Hamburg’s districts part 1

	Hamburg			Altona			Bergedorf			Eimsbüttel		
Gas or Oil Firing Systems:	**EFH**	**MFH**	**Total**	**EFH**	**MFH**	**Total**	**EFH**	**MFH**	**Total**	**EFH**	**MFH**	**Total**
Constant | Constant	35%	18%	29%	25%	14%	20%	21%	27%	22%	37%	22%	30%
Condensing | Condensing	28%	19%	25%	33%	22%	29%	46%	7%	35%	26%	18%	22%
Low | Low	16%	17%	16%	14%	21%	16%	10%	7%	9%	20%	18%	19%
Constant | Electrical	11%	23%	15%	15%	38%	24%	10%	13%	11%	9%	20%	14%
Low | Electrical	6%	14%	9%	8%	3%	6%	8%	20%	11%	2%	16%	9%
Condensing | Electrical	4%	9%	6%	5%	3%	4%	5%	27%	11%	6%	8%	7%
DH Systems:												
TS | TS	68%	64%	64%	80%	57%	61%	86%	95%	93%	0%	55%	55%
TS | Electrical	32%	36%	36%	20%	43%	39%	14%	5%	7%	0%	45%	45%

Table 13.2 Frequencies of heating system combinations in the baseline condition in Hamburg’s districts part 2

	Hamburg-Mitte			Hamburg-Nord			Harburg			Wandsbek		
Gas or Oil Firing Systems:	**EFH**	**MFH**	**Total**	**EFH**	**MFH**	**Total**	**EFH**	**MFH**	**Total**	**EFH**	**MFH**	**Total**
Constant | Constant	37%	32%	34%	45%	21%	33%	39%	10%	30%	38%	14%	32%
Condensing | Condensing	11%	23%	18%	25%	19%	22%	32%	24%	30%	25%	16%	23%
Low | Low	16%	6%	10%	15%	15%	15%	10%	10%	10%	18%	23%	20%
Constant | Electrical	16%	10%	12%	9%	13%	11%	6%	21%	11%	12%	23%	14%
Low | Electrical	0%	26%	16%	6%	23%	14%	6%	14%	9%	5%	12%	7%
Condensing | Electrical	21%	3%	10%	0%	8%	4%	6%	21%	11%	2%	11%	4%
DH Systems:												
TS | TS	50%	74%	74%	0%	44%	44%	67%	75%	69%	50%	65%	64%
TS | Electrical	50%	26%	26%	0%	56%	56%	33%	25%	31%	50%	35%	36%

Table 13.3 Frequencies of refurbishment heating system combinations in Hamburg's districts part 1

	Hamburg			Altona			Bergedorf			Eimsbüttel		
Gas or Oil Firing Systems	**EFH**	**MFH**	**Total**	**EFH**	**MFH**	**Total**	**EFH**	**MFH**	**Total**	**EFH**	**MFH**	**Total**
Condensing | Condensing	45%	56%	49%	54%	65%	59%	47%	40%	45%	44%	49%	46%
Condensing | Condensing/Solar	21%	12%	18%	16%	14%	15%	21%	0%	16%	25%	12%	19%
Condensing | Electrical	4%	17%	9%	1%	14%	7%	0%	40%	10%	6%	23%	14%
Low | Low	2%	4%	3%	5%	1%	3%	2%	7%	3%	4%	7%	5%
Condensing/Solar | Condensing/Solar	28%	11%	22%	24%	7%	16%	30%	13%	26%	21%	9%	16%
DH Systems:												
TS | Electrical	13%	20%	20%	8%	16%	14%	0%	5%	4%	0%	21%	21%
TS | TS	87%	80%	80%	92%	84%	86%	100%	95%	96%	0%	79%	79%

Table 13.4 Frequencies of refurbishment heating system combinations in Hamburg's districts part 2

	Hamburg-Mitte			Hamburg-Nord			Harburg			Wandsbek		
Gas or Oil Firing Systems	**EFH**	**MFH**	**Total**	**EFH**	**MFH**	**Total**	**EFH**	**MFH**	**Total**	**EFH**	**MFH**	**Total**
Condensing | Condensing	18%	48%	36%	51%	59%	55%	56%	70%	61%	38%	46%	40%
Condensing | Condensing/Solar	47%	12%	26%	13%	14%	13%	27%	15%	22%	21%	7%	18%
Condensing | Electrical	0%	4%	2%	4%	12%	8%	3%	8%	5%	6%	28%	11%
Low | Low	0%	4%	2%	0%	2%	1%	2%	3%	2%	1%	8%	3%
Condensing/Solar | Condensing/Solar	35%	32%	33%	33%	12%	23%	13%	5%	10%	35%	11%	29%
DH Systems:												
TS | Electrical	0%	16%	14%	0%	42%	42%	25%	0%	14%	29%	16%	17%
TS | TS	100%	84%	86%	0%	58%	58%	75%	100%	86%	71%	84%	83%

13.1.5 System Combinations over the Epochs

In section 6.4 the distribution of either the system for space heating or for DHW over the building construction epochs was examined. The following charts show the distribution of the system combinations over the epochs, first for the existing state, then for the proposed refurbishment.

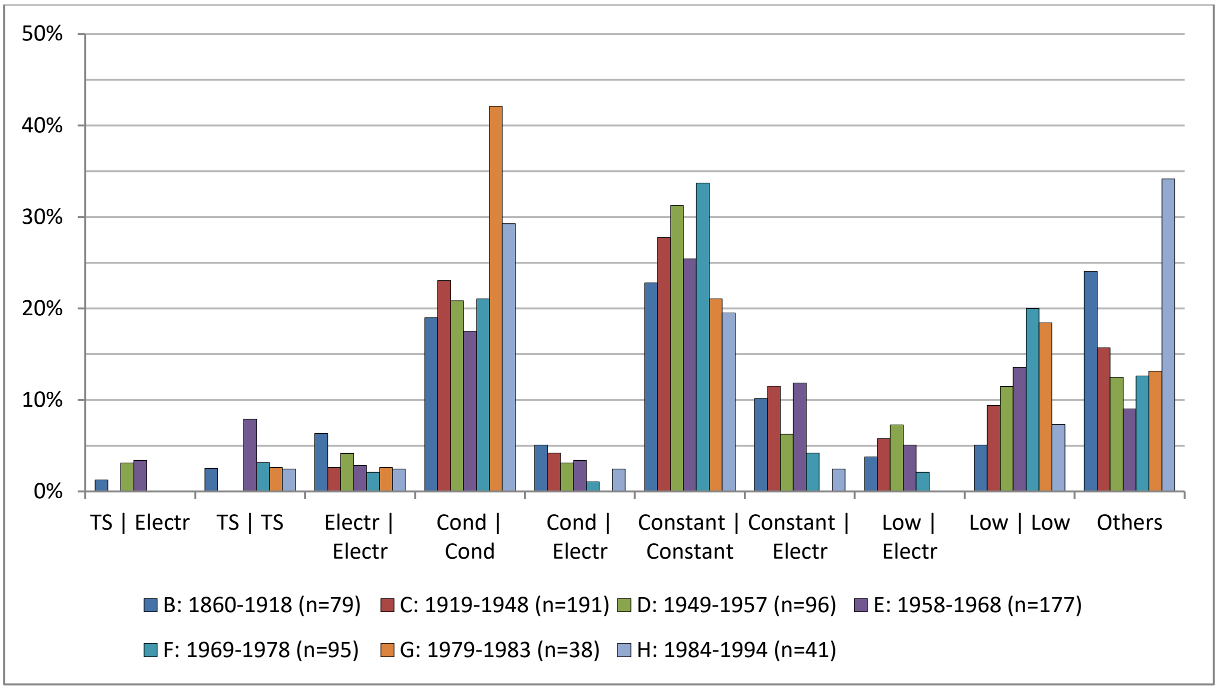


Figure 13.6 Existing state of system combinations over the construction epochs: EFH & RH

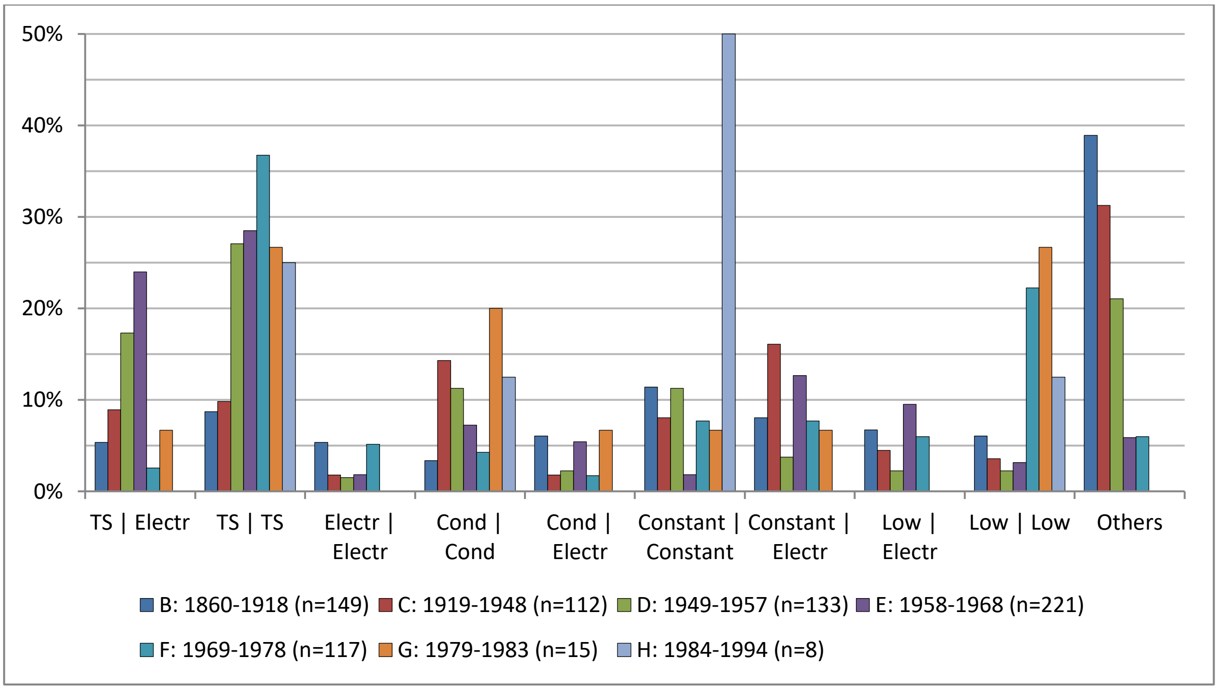


Figure 13.7 Existing state of system combinations over the construction epochs: MFH, GMH & HH

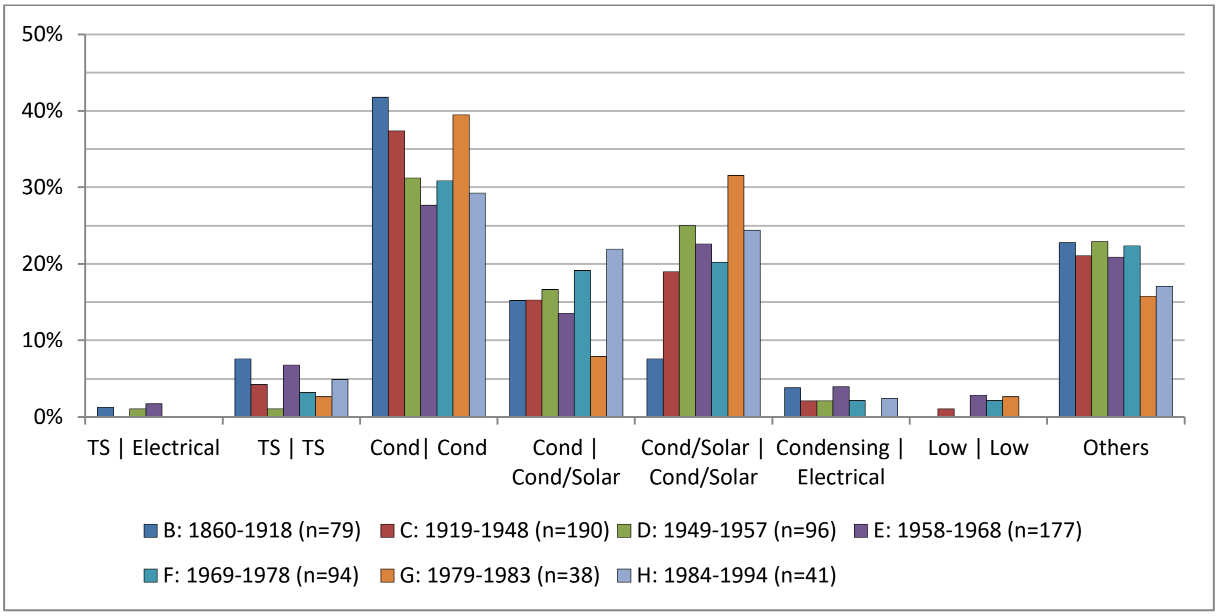


Figure 13.8 Proposed replacement of system combinations over the construction epochs – single-family houses

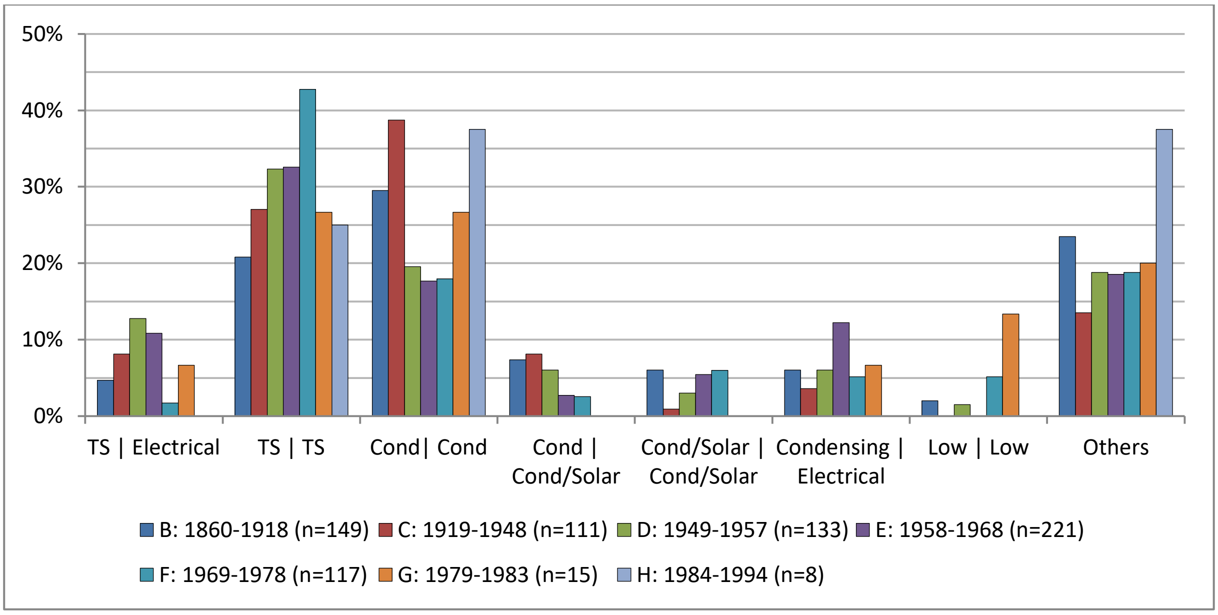


Figure 13.9 Proposed replacement of system combinations over the construction epochs – multi-family houses

As before, slight tendencies can be seen for a few system combinations, but none of them seem to reliable enough, especially when considering the uncertainty during the assignment of IWU types to the entries of the dataset. The additional value of a differentiation of the heating system based on the construction year of the building for the estimation of the final energy demand of neighborhoods or cities is considered to be minor.

13.2 Tables with Useful Energy Demand and Reference system

Tabelle 13.1 Useful and final energy demand of the reference system in baseline condition

IWU Type	Useful heat DHW	Useful heat Space Heating	Gas or Oil | Constant | Constant				Gas or Oil | Constant | Electrical			
			Final Energy: DHW	Final Energy: Heating	Aux	Total Final Energy	Final Energy: DHW	Final Energy: Heating	Aux	Total FinalEnergy
EFH_A	10	273.4	38.0	402.8	6.5	447.3	11.4	406.8	6.1	424.3
EFH_B	10	260.8	38.0	385.6	6.5	430.1	11.4	389.6	6.1	407.1
EFH_C	10	211.2	38.0	317.6	6.5	362.0	11.4	321.6	6.1	339.1
EFH_D	10	263.9	38.0	389.8	6.5	434.2	11.4	393.8	6.1	411.3
EFH_E	10	256.5	38.0	379.7	6.5	424.2	11.4	383.7	6.1	401.2
EFH_F	10	188.7	38.0	286.7	6.5	331.2	11.4	290.8	6.1	308.3
EFH_G	10	125.8	38.0	200.6	6.5	245.1	11.4	204.7	6.1	222.2
EFH_H	10	146.5	38.0	237.3	6.5	281.8	11.4	241.5	6.1	259.0
EFH_I	10	94.7	38.0	158.0	6.5	202.5	11.4	162.1	6.1	179.6
RH_B	10	192.5	38.0	292.0	6.5	336.5	11.4	296.1	6.1	313.6
RH_C	10	150.4	38.0	234.3	6.5	278.8	11.4	238.4	6.1	255.9
RH_D	10	186.8	38.0	284.2	6.5	328.7	11.4	288.3	6.1	305.8
RH_E	10	102.8	38.0	169.1	6.5	213.6	11.4	173.2	6.1	190.7
RH_F	10	132.7	38.0	210.1	6.5	254.5	11.4	214.1	6.1	231.6
RH_G	10	132.6	38.0	210.0	6.5	254.4	11.4	214.0	6.1	231.5
RH_H	10	91.7	38.0	159.5	6.5	204.0	11.4	163.8	6.1	181.3
RH_I	10	66.9	38.0	119.9	6.5	164.4	11.4	124.0	6.1	141.5
MFH_A	15	275.5	33.8	362.5	2.6	398.9	16.4	300.1	1.8	318.3
MFH_B	15	166.4	33.8	226.2	2.6	262.6	16.4	188.9	1.8	207.1
MFH_C	15	211.1	33.8	282.1	2.6	318.5	16.4	234.5	1.8	252.7
MFH_D	15	187.0	33.8	252.0	2.6	288.4	16.4	209.9	1.8	228.1
MFH_E	15	135.1	33.8	187.1	2.6	223.5	16.4	157.0	1.8	175.2
MFH_F	15	142.6	33.8	196.4	2.6	232.8	16.4	164.6	1.8	182.8
MFH_G	15	118.1	33.8	165.8	2.6	202.2	16.4	139.6	1.8	157.8
MFH_H	15	123.0	33.8	177.4	2.6	213.8	16.4	144.6	1.8	162.8
MFH_I	15	77.4	33.8	114.9	2.6	151.3	16.4	98.1	1.8	116.3
GMH_B	15	129.6	33.8	180.2	2.6	216.5	16.4	151.4	1.8	169.6
GMH_C	15	161.6	33.8	220.2	2.6	256.5	16.4	184.0	1.8	202.2
GMH_D	15	158.3	33.8	216.1	2.6	252.5	16.4	180.7	1.8	198.9
GMH_E	15	138.1	33.8	190.8	2.6	227.2	16.4	160.1	1.8	178.3
GMH_F	15	117.2	33.8	164.7	2.6	201.1	16.4	138.7	1.8	156.9
HH_E	15	111.3	33.8	157.3	2.6	193.7	16.4	132.7	1.8	150.9
HH_F	15	112.2	33.8	158.5	2.6	194.9	16.4	133.7	1.8	151.9

Table 13.5 Relationship between different building central heating systems and constant temperature boiler as reference heating system

Heating Sys. | DHW Sys.	EFH & RH		MFH, GMH & HH	
Basis: Constant | Constant	**Coefficient**	**Absolute Error Demand**[22]	**Coefficient**	**Absolute Error Demand**[21]
Condensing | Condensing	0.835	-0.36 ± 1.50	0.903	-0.02 ± 0.83
TS | TS	0.742	-0.08 ± 1.59	0.825	0.16 ± 1.15
Low | Low	0.883	-0.46 ± 1.49	0.940	-0.08 ± 0.47
Low & Stove (Wood) | Low	0.905	-0.63 ± 1.92	-	-

Table 13.6 Relationship between different systems with decentralized electrical DHW and constant temperature boiler and instant water heater as reference system

Heating Sys. | DHW Sys.	EFH & RH		MFH, GMH& HH	
Basis: Constant | Electrical	**Coefficient**	**Absolute Error Demand**[21]	**Coefficient**	**Absolute Error Demand**[21]
TS | Electrical	0.762	0.61 ± 2.23	0.832	0.31 ± 1.43
Low| Electrical	0.907	0.31 ± 1.13	0.950	0.07 ± 0.55
Condensing | Electrical	0.857	0.37 ± 1.34	0.912	0.16 ± 0.97
Electrical | Electrical	0.611	-4.08 ± 11.56	0.708	-1.74 ± 6.05

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[22] Error means the difference between the final energy demand calculated according to TABULA method compared to simplified method of this thesis [kWh/(m^2·a)

Table 13.7 Useful and final energy demand of the reference system in usual refurbishment

			Condensing | Condensing			
IWU Type	**Useful heat DHW**	**Useful heat Space Heating**	**Final Energy: DHW**	**Final Energy: Heating**	**Aux**	**Total Final Energy**
EFH_A	10	70.9	24.2	86.3	6.5	117.0
EFH_B	10	82.6	24.2	98.9	6.5	129.6
EFH_C	10	73.4	24.2	89.0	6.5	119.7
EFH_D	10	92.6	24.2	109.7	6.5	140.4
EFH_E	10	109.5	24.2	128.0	6.5	158.7
EFH_F	10	91.8	24.2	108.9	6.5	139.6
EFH_G	10	67.4	24.2	82.5	6.5	113.2
EFH_H	10	88.7	24.2	105.5	6.5	136.2
EFH_I	10	69.4	24.2	84.7	6.5	115.4
RH_B	10	76.7	24.2	92.6	6.5	123.3
RH_C	10	65.4	24.2	80.4	6.5	111.1
RH_D	10	75.9	24.2	91.7	6.5	122.4
RH_E	10	57.9	24.2	72.3	6.5	103.0
RH_F	10	71.4	24.2	86.8	6.5	117.5
RH_G	10	75.8	24.2	91.6	6.5	122.3
RH_H	10	63.8	24.2	78.6	6.5	109.3
RH_I	10	51.4	24.2	65.2	6.5	95.9
MFH_A	15	73.3	26.2	80.7	2.6	109.5
MFH_B	15	61.2	26.2	67.8	2.6	96.7
MFH_C	15	72.7	26.2	80.0	2.6	108.9
MFH_D	15	74.5	26.2	81.9	2.6	110.8
MFH_E	15	62.5	26.2	69.2	2.6	98.1
MFH_F	15	70.7	26.2	77.9	2.6	106.8
MFH_G	15	66.3	26.2	73.3	2.6	102.1
MFH_H	15	71.0	26.2	78.2	2.6	107.1
MFH_I	15	57.4	26.2	63.8	2.6	92.7
GMH_B	15	54.3	26.2	60.5	2.6	89.4
GMH_C	15	66.8	26.2	73.8	2.6	102.6
GMH_D	15	65.3	26.2	72.2	2.6	101.0
GMH_E	15	60.9	26.2	67.5	2.6	96.4
GMH_F	15	57.2	26.2	63.6	2.6	92.4
HH_E	15	48.4	26.2	54.3	2.6	83.1
HH_F	15	53.3	26.2	59.5	2.6	88.3

Table 13.8 Relationship between different heating systems towards the reference system in usual refurbishment

Basis: Condensing | Condensing	**EFH & RH**		**MFH, GMH & HH**	
Heating Sys. | DHW Sys.	**Coefficient**	**Absolute Error Demand**	**Coefficient**	**Absolute Error Demand**
Condensing | Condensing & Solar	0.883	-0.21 ± 1.76	0.898	-0.08 ± 0.87
HP (Soil) | HP (Soil)	0.319	0.09 ± 0.77	0.306	0.02 ± 0.28
HP (Air) | HP (Air)	0.373	0.09 ± 0.74	0.362	0.02 ± 0.27
Pellets | Pellets	1.354	0.15 ± 1.29	1.045	0.03 ± 0.38
TS | TS	0.947	0.00 ± 0.04	0.966	0.00 ± 0.03
Condensing | Electrical	0.895	-0.18 ± 1.57	0.914	-0.06 ± 0.73
HP (Soil) | Electrical	0.361	0.16 ± 1.39	0.398	0.09 ± 1.06
HP (Air) | Electrical	0.405	0.14 ± 1.21	0.442	0.08 ± 0.95
Pellets | Electrical	1.180	-0.16 ± 1.33	0.925	-0.06 ± 0.64
TS | Electrical	0.854	-0.16 ± 1.36	0.887	-0.06 ± 0.64

Table 13.9 Useful and final energy demand of the reference system in advanced refurbishment

			Cond+Sol | Con+Sol | Recov80			
IWU Type	**Useful heat DHW**	**Useful heat Space Heating**	**Final Energy: DHW**	**Final Energy: Heating**	**Aux**	**Total Final Energy**
EFH_A	10	50.0	9.7	35.2	7.3	52.2
EFH_B	10	58.0	9.7	43.2	6.1	59.0
EFH_C	10	51.2	9.7	36.6	6.1	52.3
EFH_D	10	61.8	9.7	47.2	6.1	62.9
EFH_E	10	69.9	9.7	55.6	6.5	71.8
EFH_F	10	62.4	9.7	47.9	6.5	64.1
EFH_G	10	46.7	9.7	31.9	6.5	48.1
EFH_H	10	60.5	9.7	46.0	7.3	63.0
EFH_I	10	58.6	9.7	44.5	7.3	61.4
RH_B	10	53.7	9.7	39.0	7.3	56.0
RH_C	10	45.8	9.7	31.5	7.3	48.5
RH_D	10	54.6	9.7	40.6	6.1	56.3
RH_E	10	40.1	9.7	25.8	6.1	41.6
RH_F	10	50.0	9.7	35.5	6.1	51.3
RH_G	10	51.7	9.7	37.2	6.5	53.3
RH_H	10	43.8	9.7	29.3	6.5	45.5
RH_I	10	41.1	9.7	27.0	6.5	43.2
MFH_A	15	49.3	15.7	28.5	7.3	51.5
MFH_B	15	41.9	15.7	21.9	7.3	45.0
MFH_C	15	48.4	15.7	27.7	2.6	46.1
MFH_D	15	50.2	15.7	29.2	3.1	48.1
MFH_E	15	42.5	15.7	22.4	1.8	40.0
MFH_F	15	48.2	15.7	27.5	1.8	45.0
MFH_G	15	44.7	15.7	24.3	1.8	41.8
MFH_H	15	48.9	15.7	28.3	2.6	46.7
MFH_I	15	46.9	15.7	26.5	2.6	44.8
GMH_B	15	36.8	15.7	17.6	2.6	35.9
GMH_C	15	45.3	15.7	25.0	2.6	43.3
GMH_D	15	43.3	15.7	23.2	2.6	41.5
GMH_E	15	41.7	15.7	21.8	2.6	40.1
GMH_F	15	39.1	15.7	19.5	3.1	38.3
HH_E	15	35.6	15.7	16.7	1.8	34.3
HH_F	15	37.8	15.7	18.3	1.8	35.9

Table 13.10 Relationship between the different heating systems in advanced refurbishment

Basis: Cond+Sol | Cond+Sol	**EFH & RH**		**MFH, GMH & HH**	
Heating Sys. | DHW Sys.	**Coefficient**	**Absolute Error Demand**	**Coefficient**	**Absolute Error Demand**
Cond | Cond+HP(Soil)	0.964	-0.05 ± 1.15	0.820	-0.07 ± 0.73
Cond | Cond+HP(Air)	0.984	-0.03 ± 1.11	0.848	-0.06 ± 0.62
HP(Soil) | HP(Soil)	0.502	0.20 ± 1.56	0.463	0.06 ± 0.65
HP(Air) | HP(Air)	0.569	0.21 ± 1.59	0.531	0.06 ± 0.67
Pellets | Pellets	1.839	0.42 ± 3.27	1.658	8.37 ± 2.15
TS | TS	1.246	0.19 ± 1.50	1.242	0.06 ± 0.7
TS | TS+HP(Soil)	0.976	-0.07 ± 0.56	0.855	-0.08 ± 0.87
TS | TS+HP(Air)	0.996	-0.05 ± 0.41	0.884	-0.07 ± 0.75
TS | Electrical	1.052	0.00 ± 0.02	1.050	-0.02 ± 0.18
Pellets | Electrical	1.465	0.05 ± 0.37	1.383	0.02 ± 0.17
HP | Electrical	0.571	0.27 ± 2.07	0.658	0.13 ± 1.41

13.3 Tables of Refurbishment Costs

Table 13.11 Estimated specific costs for insulation of the building envelope: EFH & RH

	Costs in €/m²$_{Ref}$	EFH_A	EFH_B	EFH_C	EFH_D	EFH_E	EFH_F	EFH_G	RH_B	RH_C	RH_D	RH_E	RH_F	RH_G	RH_H
Usual Refurbishment	**Lower Costs 95%**	233.84	316.00	262.85	254.77	437.56	305.67	203.14	205.17	168.99	245.70	116.06	175.22	270.51	185.55
	Lower Costs 50%	285.32	382.78	317.76	337.07	529.02	376.58	246.90	257.08	211.74	297.24	151.59	219.83	332.03	229.25
	Average Costs	319.56	422.83	350.21	385.16	582.16	418.26	274.18	290.32	239.87	329.31	175.86	249.05	369.94	257.56
	Upper Costs 50%	359.18	469.10	387.47	439.98	642.01	465.71	306.77	330.62	274.67	367.55	206.63	285.13	414.72	292.28
	Upper Costs 95%	461.26	587.41	482.10	578.34	788.11	584.85	395.00	441.49	373.27	470.24	296.96	386.84	532.87	389.38
Advanced Refurbishment	**Lower Costs 95%**	250.53	344.44	286.26	330.00	481.28	361.15	221.81	227.69	191.25	273.33	130.47	197.51	298.70	203.42
	Lower Costs 50%	308.53	421.53	350.60	390.82	592.57	446.89	272.03	283.56	238.16	327.84	168.36	245.51	372.37	254.25
	Average Costs	346.72	467.06	388.09	428.58	656.13	496.41	302.78	319.09	268.66	361.83	193.97	276.75	416.72	286.39
	Upper Costs 50%	390.26	518.77	430.36	472.95	726.41	551.54	338.79	361.51	305.67	401.74	226.00	314.65	467.92	324.90
	Upper Costs 95%	499.98	647.50	534.55	589.94	892.49	685.65	433.56	476.46	408.53	507.59	318.74	419.87	598.35	429.23

Table 13.12 Estimated specific costs for insulation of the building envelope: MFH, GMH & HH

	Costs in €/m²$_{Ref}$	MFH_A	MFH_B	MFH_C	MFH_D	MFH_E	MFH_F	MFH_G	MFH_H	GMH_B	GMH_C	GMH_D	GMH_E	GMH_F	HH_E	HH_F
Usual Refurbishment	**Lower Costs 95%**	243.21	171.56	239.89	227.32	139.01	164.44	145.16	188.79	141.99	166.33	164.60	152.66	130.25	123.93	128.73
	Lower Costs 50%	288.64	208.42	287.73	273.71	163.54	199.18	174.55	221.52	169.79	194.90	191.58	175.96	151.28	141.49	147.78
	Average Costs	315.12	231.49	316.17	300.74	177.89	220.59	192.77	241.30	186.90	211.89	207.69	189.57	163.78	151.62	158.50
	Upper Costs 50%	345.21	259.27	349.03	331.46	194.33	246.02	214.54	264.50	207.36	231.62	226.46	205.16	178.36	163.16	170.38
	Upper Costs 95%	420.68	335.42	433.46	408.58	236.73	314.89	274.29	326.05	263.19	283.25	275.91	245.17	216.93	192.50	199.21
Advanced Refurbishment	**Lower Costs 95%**	266.72	186.91	264.05	249.82	156.30	184.13	163.37	208.68	157.16	186.02	187.92	169.67	145.90	138.76	140.88
	Lower Costs 50%	319.52	227.60	319.72	304.23	183.20	221.82	195.87	244.32	189.18	217.43	219.47	195.08	168.90	157.89	161.45
	Average Costs	349.98	252.86	352.41	335.55	198.98	244.96	215.88	265.86	208.64	236.13	238.17	209.99	182.63	169.04	173.11
	Upper Costs 50%	383.99	282.73	389.45	370.52	216.73	271.97	239.33	290.65	231.39	257.41	259.40	226.77	198.31	181.51	185.85
	Upper Costs 95%	466.94	362.84	481.84	455.77	261.60	343.89	302.27	355.23	291.55	312.01	313.54	269.00	238.95	212.53	216.28