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Automated customer profiling and usage splitting of electricity consumption with big data analytics (methods)

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Abstract

Currently, Switzerland is facing fundamental changes in its energy markets due to economic and technological developments as well as political decisions at home and abroad. Of the approximately 60 terawatt hours of electricity consumed annually in Switzerland, around 18 terawatt hours are consumed by private households (status as of 2011) [1]. Thus, there is a widespread interest in the electrical consumption of buildings. For example, it is of great interest to understand what purposes electricity is used for in order to set priorities for reducing its consumption.

The total yearly electrical energy demand of buildings is currently predominately used for accounting purposes. Thus, big data sets are potentially available. Within this thesis, two data sets for residential buildings in two Swiss municipalities were analysed. The age-related segmentations of the buildings in the data sets were discovered and visualized with bar graphs. In addition, the electrical energy demands were analysed and visualized with box plots.

Additionally, the specific electrical energy demands with respect to energy reference areas were calculated and visualized with empirical cumulative distribution functions. Furthermore, a new approach was used to divide the distributions of the overall specific electrical energy demands into shares for appliances, space heating and domestic hot water production. The outcomes obtained by using this method were compared with values from existing surveys concerning the electricity consumption in typical households as well as with standard values for domestic hot water demand. The comparison showed that the extracted heat demands tend to be too low. However, the new approach seems promising in terms to extract different shares from the total yearly specific electrical energy demand for buildings from big data sets. Further developments, based on this work, in terms of a comprehensive analytical methods are required.

It is important to note that an improvement of the reliability of the method or an extension of the methods requires additional data sources.

Zusammenfassung

Die Schweiz steht derzeit aufgrund der wirtschaftlichen und technologischen Entwicklung sowie der politischen Entscheidungen im In- und Ausland vor grundlegenden Veränderungen in den Energiemärkten. Von den rund 60 Terawattstunden Strom, die in der Schweiz jährlich verbraucht werden, entfallen ca. 18 Terawattstunden auf private Haushalte (Stand 2011) [1]. Daher steht der Stromverbrauch der Privathaushalte im Zentrum des Interesses. Eine zentrale Frage ist, für welche Zwecke der Strom verwendet wird, um Prioritäten für die Reduzierung des Stromverbrauchs zu setzen.

Für die Elektrizitätsrechnung wird der jährliche elektrische Energiebedarf von Gebäuden berechnet. Daher existieren sehr grosse Datensätze des elektrischen Energiebedarfs. Im Rahmen dieser Arbeit wurden zwei Datensätze von zwei Schweizer Gemeinden analysiert. Die Altersstruktur der darin enthaltenen Gebäude wurde mit Balkendiagrammen visualisiert. Zudem wurden die elektrische Energiebedarfe analysiert und mit Boxplots visualisiert.

Zusätzlich wurde der spezifische elektrische Energiebedarf in Bezug auf die Energiebezugsfläche berechnet und mit empirischen kumulativen Verteilungsfunktionen visualisiert. Darüber hinaus wurde ein neuer Ansatz zur Aufteilung der Verteilung des gesamten spezifischen elektrischen Energiebedarfs in Anteile für Geräte, Raumheizung und Warmwasser angewendet. Die Ergebnisse der Methode wurden mit Werten aus bestehenden Erhebungen zum Stromverbrauch in typischen Haushalten sowie mit Richtwerten für den Warmwasserbedarf verglichen. Der Vergleich zeigte, dass die erhalten Wärmebedarfe tendenziell zu niedrig sind. Der neue Ansatz scheint jedoch vielversprechend zu sein, um aus Datensätzen des jährlichen elektrischen Energiebedarfs von Gebäuden unterschiedliche Anteile nach Nutzungszweck zu erhalten. Es sind weitere Entwicklungen erforderlich, um auf der Grundlage dieser Arbeit eine umfassende Analysemethode zu entwickeln.

Es ist jedoch zu berücksichtigen, dass für zuverlässigere Ergebnisse und für eine Weiterentwicklung der Methode mehr Daten benötigt werden.

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Nomenclature

Latin Characters

A	Area	m^2
c_p	Specific Heat Capacity (isobaric)	$(\mathrm{W} \cdot \mathrm{h})/(\mathrm{kg} \cdot \mathrm{K})$
e	Specific Energy Demand	$(\mathrm{W} \cdot \mathrm{h})/(\mathrm{a} \cdot \mathrm{m}^2)$
E	Energy Demand	$(\mathrm{W} \cdot \mathrm{h})/\mathrm{a}$
f	ECDF Difference Function	$-$
m	Mass	kg
Q	Quantity of Heat	$\mathrm{W} \cdot \mathrm{h}$
T	Temperature	°C

Greek Characters

Δ	Difference between two Empirical Cumulative Distribution Functions	$(\mathrm{W} \cdot \mathrm{h})/(\mathrm{a} \cdot \mathrm{m}^2)$
ε	Empirical Cumulative Distribution Function of Specific Energy Demands	$(\mathrm{W} \cdot \mathrm{h})/(\mathrm{a} \cdot \mathrm{m}^2)$
Θ	Ratio of two Empirical Distribution Function Differences	$-$

Indices

DHW	Domestic Hot Water
ER	Energy Reference
HP	Heat Pump
RH	Resistance Heater
SFH	Single-Family Home

Acronyms and Abbreviations

a	Annum
C	Celsius
COP	Coefficient of Performance
CREST	Competence Center for Research in Energy, Society, and Transition
d	Day
DHW	Domestic Hot Water
FAWA	in German for: Feldanalyse von Wärmepumpenanlagen
FOE	Federal Office for the Environment
h	Hour
HP	Heat Pump
IQR	Interquartile Range
JAZ	in German for: Jahresarbeitszahl
kg	Kilogramm
LUASA	Lucerne University of Applied Sciences and Arts
ℓ	Litre
m	Meter
MFH	Multiple-Family Home
nJAZ	in German for: normierte Jahresarbeitszahl
RH	Resistance Heater
s	Second
SCOP	Seasonal Coefficient of Performance
SFH	Single-Family Home
SFOE	Swiss Federal Office of Energy
SFSO	Swiss Federal Statistical Office
TENP	Trans-Europe Natural Gas Pipeline
SHEDS	Swiss Household Energy Demand Survey
WWEA	Office of Waste, Water, Energy and Air, Canton of Zürich

Definitions

Air/Water Heat Pump	Heat Pumps which valorises energy from the environment/ambient air.
Appliances	Appliances are used to accomplish household functions such as cooking, cleaning, lighting and food preservation, and for entertainment.
Brine/Water Heat Pump	Heat Pumps which valorise energy from the ground. They are normally more efficient than air/water heat pumps, especially in winter, due to the higher temperature of the ground compared to the outside air.
COP	The Coefficient of Performance (COP) describes the efficiency of a heat pump and is defined as the ratio between the useful heat transfer for heating or cooling and the required drive energy. The useful energy can either be heating or cooling energy depending on whether the heat pump is used to provide heating or cooling. The COP is normally related to a specific operating condition [2].
DHW	Water used for domestic purposes such as drinking, food preparation, sanitation and personal hygiene
JAZ 2	The JAZ (in German for: Jahrearbeitszahl) 2 is used for evaluation of the heat pump's performance on an annual basis in real applications and it also takes the losses of hot water storages into account, refer also to [3].
Minergie-Standard	Swiss Quality standard for low-energy-consumption buildings.
nJAZ 2	The nJAZ (in German for: normierte Jahrearbeitszahl) 2 is the climate-standardized JAZ 2, refer also to [3].
Oil/RH	The expression stands for the main energy carriers for space heating (precedes the slash) and DHW production (follows the slash) in a building. For example, Oil/RH means that the space is heated with oil (oil heating), and electricity is used for DHW production (resistance heater). Note that this expression is used in the indices as well (see also Section 2.3).
Rolle	Rolle is a municipality in the Canton of Vaude in Switzerland on the north-western shore of Lake Geneva. It has about 6, 218 (2017) inhabitants [4].
SCOP	The SCOP, or Seasonal Coefficient of Performance, describes the average COP on an annual basis [2].
Wohlen	Wohlen is a municipality in the Canton of Berne in Switzerland, located approximately 5 km west to the city of Berne. It has about 9, 215 (2017) inhabitants [4].

1 Introduction

1.1 Motivation

Currently, Switzerland is facing fundamental changes in its energy markets. Buildings are responsible for a significant fraction of Switzerland's overall energy consumption [5]. Of the approximately 60 terawatt hours of electricity consumed annually in Switzerland, around 18 terawatt hours are accounted for by private households (status as of 2011) [1].

There is a widespread interest in the development and distribution of the electrical consumption of buildings. For example, it is essential to understand what purposes electricity is used for in order to set priorities for reducing its consumption.

1.2 Objective

The yearly electrical energy demand for buildings is used for accounting purposes. Thus, big data sets exist and are potentially available to researchers.

The aim of this thesis is to explore how algorithmically the shares of individual uses of electricity can be extracted from the lumped consumption signals in big data sets. The division of the electrical energy demand may result in a simplification of the electrical energy demand shares.

The approach shall be tested on two independent data sets. The outcomes shall then be compared with reference values from existing surveys regarding the electricity consumption in typical households as well as with standard values for the Domestic Hot Water (DHW) demand. Furthermore, the outcomes shall be explained via descriptive and exploratory statistical methods.

1.3 Current State of Research

In recent years, a large number of approaches to simulating and predicting building energy demand have been proposed. For example, Rahman, Srikumar, and Smith present a recurrent neural network model to generate medium- to long-term predictions of electricity consumption profiles in commercial and residential buildings [6]. Crawley, Hand, Kummert, *et al.* provide a comprehensive overview of the building energy performance simulating programs and tools developed in the past 50 years in their survey [7].

In 2012, Zhao and Magoulès stated that many statistical models have been developed to predict building energy demand. The many attempts have been made due the complexity of building energy behaviour and the influence of many factors, such as climate conditions (e.g., humidity and ambient temperature), and building structures and characteristics [8].

Daut, Hassan, Abdullah, *et al.* provide a review of the building electrical energy consumption forecasting methods which include both conventional and artificial intelligence (AI) methods [9].

Frehner, Geidl, Worlitschek, *et al.* present a methodology for predicting the thermal energy demand of residential buildings with installed heat pumps using linear regression models in combination with electricity monitoring data of the heat pump systems as well as meta data from the dwellings [10].

The Swiss Federal Office of Energy (SFOE) released a report presenting a set of consumption values for typical Swiss households. It used the raw data of a household survey on electricity consumption administered in 2011 [11].
Besides updating the values of previous studies, in particular, this report clarified open issues in methodology and calculation methods.

The Swiss Household Energy Demand Survey (SHEDS) was been developed as part of the research agenda of the Competence Centre for Research in Energy, Society, and Transition (CREST). This survey started in 2016 and has an estimated completion date in 2020. It is designed to collect a comprehensive description of Swiss households energy-related behaviours, the longitudinal changes in such behaviours and the potential for future energy demand reductions [12].

1.4 Initial Situation

Two data sets are analysed in this thesis. The data sets encompass almost all buildings in Rolle, a village on the north-western shore of Lake Geneva and Wohlen, a village located approximately 5 km west to the city of Berne.

The population sizes of the two municipalities are similar. While the village of Rolle has about $6,218$ inhabitants; Wohlen has $9,215$. The data sets provide the yearly electrical energy demand for the majority of the $1,650$ buildings in Rolle and for all $3,658$ apartments distributed over $1,945$ buildings in the data set of Wohlen. Furthermore, the datasets contain meta data categories of the buildings and usage that do not overlap completely.

2 Materials/Methods

2.1 Data Sources

The following three different collections of data were analysed in this thesis.

- A data set of building/heating system properties, estimated energy demands and measured electrical energy demands of $1,650$ buildings in the municipality of Rolle in the canton of Vaud, Switzerland (hereafter: data set Rolle).
  Each buildings was assigned to one of the group listed in Table 3.1 by the Lucerne University of Applied Sciences and Arts (LUASA). Additionally, the buildings are each assigned to one of the following four building groups; single-family homes (SFHs), multiple-family homes (MFHs), building with partially or without residential use by the Swiss Federal Statistical Office (SFSO).
  The buildings are characterized by meta data consisting of numerical variables, such as length, width, year built and energy reference area, and categorical variables, such as the afore-mentioned building groups and main energy carriers for space heating and DHW production.
  The dataset contains three different estimates of the yearly heat energy demand for most buildings performed by the LUASA, the University of Geneva and the Canton of Vaud. Moreover, the dataset contains the yearly electrical energy demand for a fraction $(1,202)$ of the buildings.

- A data set containing the yearly electrical energy demand for $3,958$ apartments distributed over $1,945$ buildings in the municipality of Wohlen in the Canton of Berne, Switzerland (hereafter: data set Wohlen^{A}). The buildings are each assigned to the same four building groups, as previously mentioned, by the SFSO. Additionally, the living areas of the apartments, year built, and main energy carriers for space heating and DHW production are provided. If an apartment is renovated, its renovation period is contained in the data set. Unfortunately, in contrast to the data set Wohlen, additional meta data concerning the apartments, such as ceiling height is missing.

- The historical developments of the population of the municipalities of Rolle and of Wohlen (hereafter: population data) were obtained from the SFSO [4].

It is important to note that the author should clarify that the estimates of the (yearly) heat energy demand in the data set Rolle are based on linear models. Therefore, it was decided to further analysed the (yearly) electrical energy demands from both data sets, which are based on measuring data. These electrical energy demands contained in the two data sets for Rolle and Wohlen were used for accounting. Unfortunately, the exact monitoring period of both data sets is not known and may even be different for two element in the same data set. Comparing the electrical energy demand for apartments or building not measured over the same period could potentially falsify the results. However, since no further information was present and no more consistent data is accessible, this data set was selected anyway.

2.2 Pre-processing

The two data sets and the population data were imported into the programming platform MATLAB and the Statistics Toolbox version 9.3.0, R2017b [13] (hereafter: MatLab). A third data set (hereafter: data set Wohlen^{B}) was generated based on the data set Wohlen^{A}. In Wohlen^{B}, the data of Wohlen^{A} are aggregated per building and not per apartment. The living area and electrical energy demand of the buildings were generated by summing up the living areas and electrical energy demands of the apartments at the same address. The buildings were assigned based on the same energy carriers for space heating and DHW production as those listed for the apartments contained in. This assumption is not critical since the main energy carriers of the apartments within the same building were identical.

2.3 Notation

For simplicity, a slash expression was introduced to combine the main energy carriers for space heating and DHW production. The main energy carrier for space heating comes first, then, the energy carrier for DHW production follows the slash. For example, Oil/Oil stand for a building in which both the space is heated and DHW is produced with oil.
Even though, strictly speaking, resistance heaters and heat pumps are not energy carriers, the notation includes their use. Here, "RH" stands for heating with resistance heaters, while "HP" stands for heating with heat pumps.

2.4 Segmentation of the Samples

In order to describe the number of the main energy carriers used in the buildings found in the the data sets of Rolle and Wohlen[B], the buildings were filtered according to their main energy carriers and counted. To visualize the results, various bar graphs were generated by using the MatLab function `bar()`.

2.5 Subgroups

The buildings of both data sets (Rolle and Wohlen[B]) were divided into various subgroups grouped according to their building groups, years built/renovation year and main energy carrier combinations (for heating space and DHW production). The apartments in the data set Wohlen[A] were also divided into subgroups organized according to their main energy carrier combinations as well as to their number of rooms.

2.6 Descriptive Data Analysis

The (yearly) electrical energy demands and specific (yearly) electrical energy demands (introduced in Section 2.8) for these subgroups were explored with typical descriptive statistics in order to obtain quantitative descriptions, such as means (averages), medians, subgroup sizes, and standard deviations. They were calculated via the the corresponding MatLab functions `mean()`, `median()`, `size()`, `quantile()` and `std()`, respectively. These functions were also used to describe the outcome of the specific electrical energy demand shares analysis. The obtained values are listed in various tables in Chapter 3.

2.7 Exploratory Data Analysis

In order to graphically present the full variation in the electrical energy demands and specific electrical energy demands for the subgroups, box plots were generated. The MatLab Regression Application was used to generate box plots for many subgroups in the same Figure efficiently. Furthermore, the electrical energy demands and specific electrical energy demands were visualized via Empirical Cumulative Distribution Functions (ECDFs). They were generated by the MatLab function `ecdf()`. The corresponding plots are shown in Chapter 3 and in the Appendix. Note that the reason why some plots are shown in the Appendix is that almost the same information in the ECDFs (with the exception of upper outliers) are contained in the box plots.

2.8 Specific Electrical Energy Demand

The aims of the subsequently described methods were:

- to find differences between various specific electrical energy demand distributions,
- to extract the shares, i.e., the ECDF differences, representing the specific electrical energy demand for appliances, space heating and DHW production from the total specific electrical energy demand distributions,
- to explore whether the Seasonal Coefficients of Performance (SCOP) can be extracted from these portions and how this is distributed.

The specific electric energy demands were introduced in order to have more comparable values. They were computed by means of the following equation:

$$e = \frac{E}{A_{\mathrm{ER}}} \left[\frac{\mathrm{kW \cdot h}}{\mathrm{a \cdot m^2}}\right], \tag{2.1}$$

where e is the total specific electrical energy demand. E stands for the total electrical energy demand for the buildings and apartments and A_{ER} is the energy reference area.

Afterwards, as previously mentioned, the specific electrical energy demands were explored with the described methods in Sections 2.6 and 2.7.

The small subsample size of various subgroups (organized according to energy carrier combinations), especially in the data set Rolle, presented a serious limitation. Therefore the following analyses were limited to the SFHs (according to the SFSO) contained in the dataset Wohlen[B].

2.8.1 Specific Electrical Energy Demand Model

In order to extract the electrical energy demand shares required by appliances, space heating and DHW production, the following model for SFHs was introduced:

$$e = e_{\mathrm{App}} + e_{\mathrm{DHW}} + e_{\mathrm{Space}}, \tag{2.2}$$

where e denotes the total specific electrical energy demand (obtained with Equation (2.2)). The terms e_{Space} and e_{DHW} represent the specific electrical energy demand required for space heating and DHW production, respectively. The term e_{App} represents the specific energy demand for (home) appliances using electricity. The model assumes that the specific electrical energy demand of a SFH consists of these three share. Additionally, it was assumed that these shares are constant for single-family homes.

To estimate the contribution of appliances e_{App}, the specific electrical energy demands for the Oil/Oil SFHs $e_{\text{Oil/Oil}}$ were considered. It was assumed that in these buildings no electricity is used for space heating and DHW production.

$$e_{\text{Oil/Oil}} = e_{\text{App}} + \cancelto{0}{e_{\text{Space}}} + \cancelto{0}{e_{\text{DHW}}} \tag{2.3}$$

Furthermore, it was assumed that the specific electrical energy demands for Oil/RH SFHs $e_{\text{Oil/RH}}$ represent the electrical energy demand for appliances and DHW production with resistance heaters.

$$e_{\text{Oil/RH}} = e_{\text{App}} + \cancelto{0}{e_{\text{Space}}} + e_{\text{DHW,RH}} \tag{2.4}$$

In contrast to an Oil/RH SFH, it was assumed that the specific electrical energy demand of an RH/RH SFH $e_{\text{RH/RH}}$ consists additionally of the share for space heating with a resistance heater. An (thermal) efficiency of 100 percent was assumed for the resistance heaters. Therefore, the electricity demands $e_{\text{Space,RH}}$ and $e_{\text{DHW,RH}}$ directly translates into heat demands.

$$e_{\text{RH/RH}} = e_{\text{App}} + e_{\text{Space,RH}} + e_{\text{DHW,RH}} \tag{2.5}$$

The electrical energy demand of a HP/HP SFH represents the electrical energy demand for appliances, heating space and producing DHW with heat pumps.

$$e_{\text{HP/HP}} = e_{\text{App}} + e_{\text{DHW,HP}} + e_{\text{Space,HP}} \tag{2.6}$$

As a building has only one energy carrier combination, these quantities can only be calculated as difference between different buildings. Thus, not the shares of the specific energy demand for single SFHs were computed, instead, the differences between different ECDFs of e were computed. An ECDF of e is denoted by ε.

The difference between two ECDFs (ECDF difference) is denoted by Δ. The ECDFs difference of two data vectors A and B was computed by subtracting their values (specific electrical energy demands) at quantiles between 0.001 and 0.999 with a step size of 0.002. The corresponding function is denoted by f. The interval was choosen as 0.002, which is slightly smaller than the step size of the ECDF containing the most observations (483), i.e. , smaller than the distance between two quantiles of two data points next to each other in these subgroup. Note that the step size ($\frac{1}{n}$) of a ECDF depends inverse proportionally on its sample size (n).

The MatLab function `quantile(X,p)` was used which returns the element of a data vector X at a cumulative probability p. The function uses linear interpolation to calculate a value at a quantile between two elements.

$$\Delta(p) = f(A, B, p) = quantile(A, p) - quantile(B, p) \quad \text{for } p = 0.001, 0.003, ..., 0.999 \tag{2.7}$$

The ECDF difference representing the specific electrical energy demand for DHW production with a resistance heater is denoted by $\Delta_{\text{DHW,RH}}$ and was computed by means of the following equation:

$$\Delta_{\text{DHW,RH}} = f(\varepsilon_{\text{Oil/RH SFHs}}, \varepsilon_{\text{Oil/Oil SFHs}}) \tag{2.8}$$

$\varepsilon_{\text{Oil/RH SFHs}}$ represents the ECDF containing the specific electrical energy demands for Oil/RH SFH, while $\varepsilon_{\text{Oil/Oil SFHs}}$ represents the ECDF containing the specific electrical energy demands for Oil/Oil SFHs.

The specific electrical energy demands for space heating with resistance heater $\Delta_{\text{Space,RH}}$ was computed by means of the following equation:

$$\Delta_{\text{Space,RH}} = f(\varepsilon_{\text{SFHs,RH/RH}}, \varepsilon_{\text{SFHs,Oil/RH}}) \tag{2.9}$$

However, to compute $\Delta_{\text{DHW,HP}}$, the ECDF of the electrical energy demands for the Oil/HP SFHs had been used. The subsample size of this subgroup is 12. The sample size of the smallest subgroup that was used to calculate other ECDF differences was 55. Because of the great difference, the ECDF difference $\Delta_{\text{DHW,HP}}$ was not considered.

Since the ECDF of HP/RH and HP/HP SFHs are nearly the same, the ECDF difference $\Delta_{\text{Space,HP}}$ had been almost zero for most probabilities p. Thus, this ECDF difference was excluded. The agreement of the two distributions was unexpected and is discussed further in Section 3.3.

The difference between the ECDF of Oil/Oil SFHs and the HP/HP SFHs represents the specific electrical energy demand for space heating and DHW production with heat pumps $\Delta_{\text{Space+DHW,HP}}$ and was computed with the following equation:

$$\Delta_{\text{Space+DHW,HP}} = f(\varepsilon_{\text{HP/HP SFHs}}, \varepsilon_{\text{Oil/Oil SFHs}}) \tag{2.10}$$

Additionally, the ECDF difference between Oil/Oil SFHs and the RH/RH SFHs was computed and represents the specific electrical energy demand for space heating and DHW production with a resistance heater.

$$\Delta_{\text{Space+DHW,HP}} = \Delta_{\text{Space,RH}} + \Delta_{\text{DHW,RH}} = f(\varepsilon_{\text{RH/RH SFHs}}, \varepsilon_{\text{Oil/Oil SFHs}}) \quad (2.11)$$

The distributions of the obtained ECDF differences were visualized in histograms by using the MatLab function `histogram(X)`, where X is a data vector. Additionally, the means and standard deviations were calculated and are listed in Sections 3.6 and 3.7. Subsequently, these measures were verified for compliance with typical electrical energy demands for Swiss apartments and buildings, as stated in the report *Typischer Haushalt-Stromverbrauch* [14].

2.8.2 SCOP Distribution

The ratio of the heat output generated by a heat pump to the electrical power required to generate this heat is defined as the Coefficient of Performance (COP).

It was assumed that the heat required for space heating and DHW production could be represented by $\Delta_{\text{Space+DHW,RH}}$. This approximation relies on the assumption that the efficiency of the RH is 100 percent. Furthermore, it was assumed that heat pump's inputs could be represented by $\Delta_{\text{Space+DHW,HP}}$. Since the ECDF differnces represent the distribution of the *yearly* specific heat/electrical energy demands, the ratio of these two ECDF differences represents the *Seasonal* COP (SCOP) distribution, denoted by Θ_{SCOP}.

$$\Theta_{\text{SCOP}} = \frac{\Delta_{\text{Space+DHW,RH}}}{\Delta_{\text{Space+DHW,HP}}} \quad (2.12)$$

The ratio of the two ECDF differences Δ_A and Δ_B was defined as the ratios of values at the respective percentage p and is denoted by Θ:

$$\Theta_C(p) = \frac{\Delta_A(p)}{\Delta_B(p)} \quad \text{for } p = 0.001, 0.003, ..., 0.999 \quad (2.13)$$

Recall that a split of SCOP for DHW production and space heating was not performed as the subsample sizes of the required subgroups were too small.

The histogram were used to represent the distributions of the Θ_{SCOP} graphically. It was assumed that the distribution of Θ_{SCOP} consists of SFHs with air/water or brine/water heat pumps due to the fact that these types account for the large majority of heat pumps sold between 2010 and 2017 [15]. For simplicity, it was assumed that the SCOP of these two heat pump types are normally distributed (with different mean values and deviations). In order to extract the contributions of these two heat pump types in the distribution of Θ_{SCOP}, a Gaussian mixture model object was fitted with two components, i.e. with two normal distributions. To fit the Gaussian mixture model, the MatLab function `fitgmdist(X,k)` was used, which returns a Gaussian mixture distribution model with a fixed number of components k to data X. Each component is defined by its mean and proportion.

3 Results

3.1 Segmentation of Data Set Rolle

It was assumed that the types of main energy carriers used to heat spaces and produce domestic heat water (DHW) influence the electrical energy demand strongly. For example, it was assumed that heating space or producing DHW with a resistance heater results in a greater electrical energy demand than heating for example, with oil.

The two bar graphs in Figures 3.1 and 3.2 display the histograms of the energy carriers for space heating and DHW production for the buildings contained in the data set Rolle built between 1877 and 2017. Unfortunately, the renovation years of the buildings could not be considered due to missing data in the data set Rolle. However, since it was assumed that the population and the newly constructed buildings are correlated, the population data was added to the diagrams. The left vertical axis shows the number of buildings, while the right vertical axis shows the number of inhabitants.

Each of the 15 bars represents one decade (counted from xxx7 to xxx7). The height of each bar is the number of construction objects completed within this decade. The coloured segments on each bar represent the buildings according to their main energy carrier for space heating in Figure 3.1 and for DHW production in Figure 3.2.

A clear upward trend can be observed over the past 70 years in the number of inhabitants. Since more inhabitants require more living space, it is not surprising that the number of new buildings increased as well. Oil is the prevalent energy carrier for both space heating and DHW production in buildings built between 1927 and 1987, while between 1987 and 2017, gas is the most common energy carrier. The causes for this change are presumably the two oil crises in 1973 and 1979, which led to the planning and, in the years that followed, construction of new buildings with gas heating systems. The reason for the shift between the oil crises and the change in the energy carriers preferences is presumably that buildings under construction or in planning (with oil heatings) were completed prior to the planning and construction of new buildings with gas heatings.

Another noteworthy fact that may have contributed or led to this shift is that new gas deposits were discovered and developed in Europe in the 1960s. The natural gas transit pipeline Trans-Europe Natural Gas Pipeline (TENP) from Holland to Italy enabled in the 1970s the supply of sufficient natural gas for Swiss cities and to meet the growing demand for gas heating systems [16].

Solar energy, as the "main energy carrier" for DHW production and the electricity used to operate heat pumps in space heating systems, has become more popular in the last two decades. Reasons for this popularity may well include increased environmental awareness, the introduction of the Minergie standard and further developments in heat pump and collector technologies (e.g., higher reliability, reduction in operating costs) as well as cantonal and federal financial contributions.

Furthermore since 1987, there has been a decrease in the number of resistance heater producing DHW. The major driver for this decline is probably a policy change which resulted in an announced ban for newly installed heating systems.

It can be recognized that the number of inhabitants fell slightly from $3,658$ in 1970 to $3,409$ in 1981, then strongly increased in the following decades to $6,168$ in 2017. There is a significant difference in population growth between Rolle and Switzerland. The population of the municipality grew by 130 percent between 1950 and 2017, whereas the population of Switzerland grew by 78 percent in the same period, i.e., the population of the municipality of Rolle has grown almost twice as fast as the population of Switzerland.

An interesting fact is that the Swiss voters approved the total revision of the energy law with a majority of 58 percent of the total votes. This law aims at developing the existing potential for energy efficiency and taking advantage of renewable energies (solar, wind, geothermal, biomass) [17]. The voters of the municipality of Rolle approved this law with a majority of 77 percent. This larger majority could be an indication that the people entitled to vote in the municipality of Rolle are more environmentally conscious than an average Swiss voter is [18].

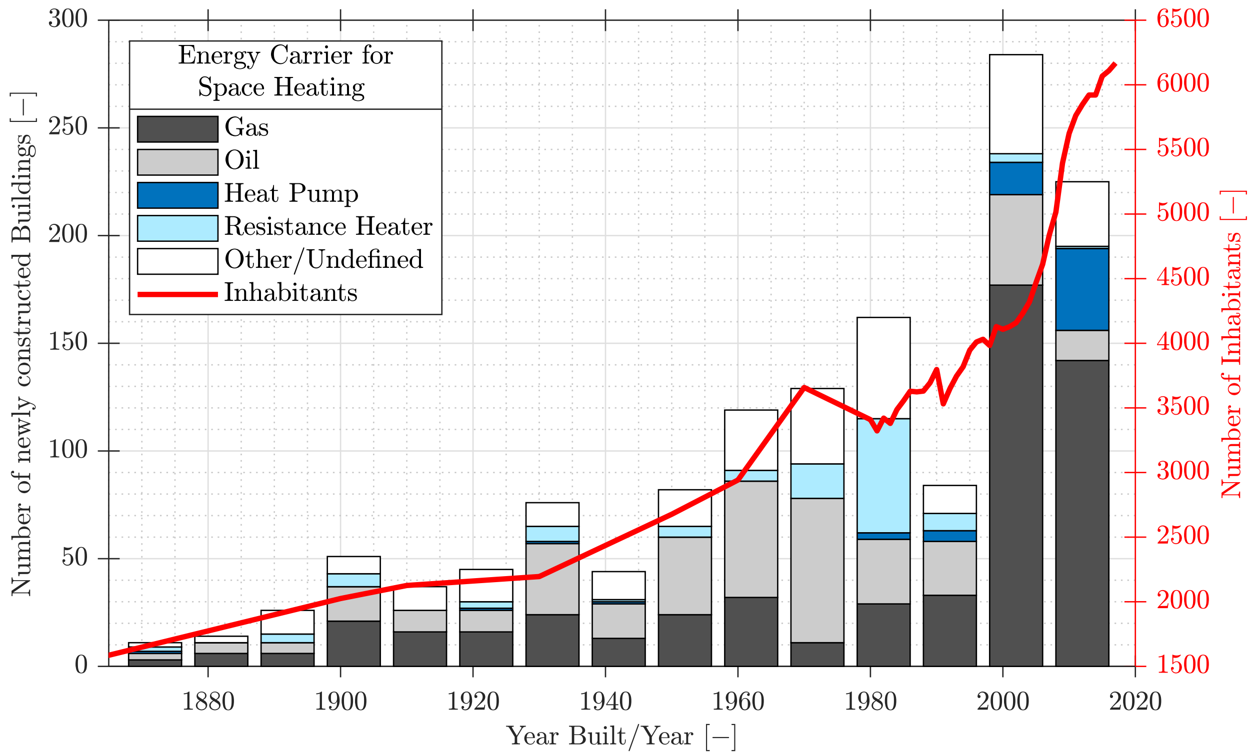

Figure 3.1: Population and Buildings According to Space Heating Energy Carrier, 1867-2017, Data set Rolle[1]

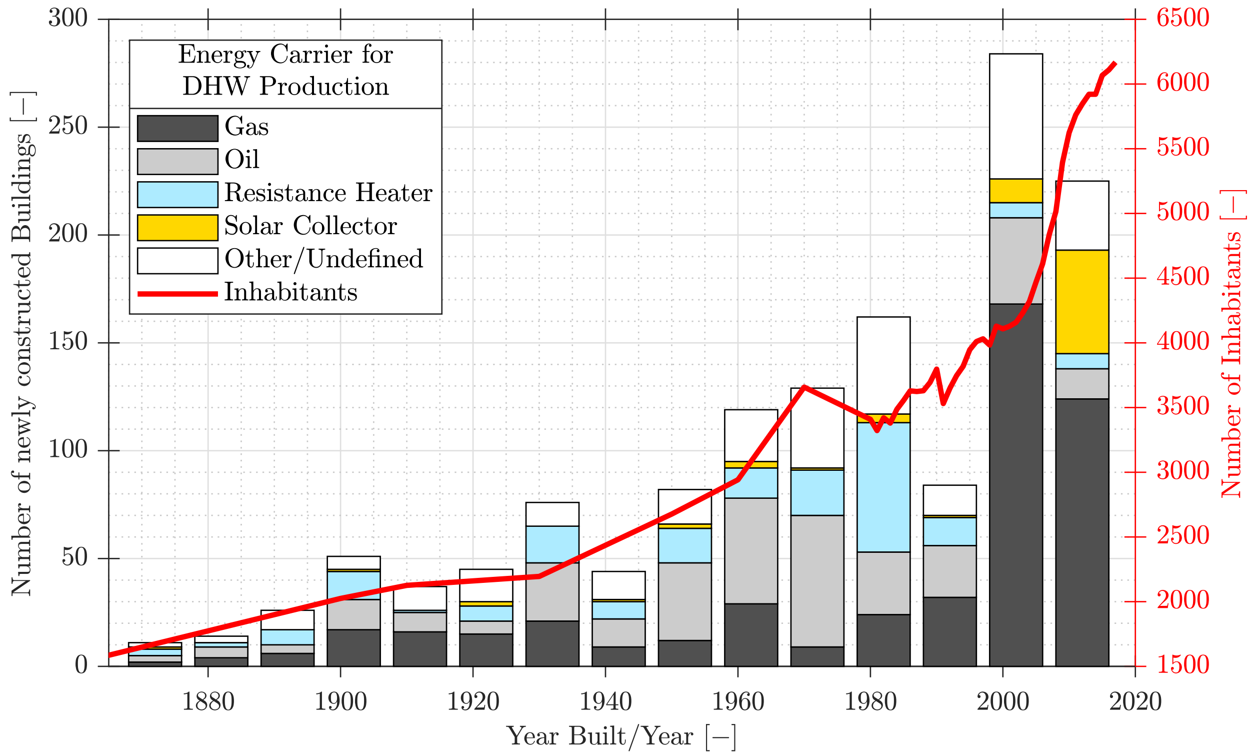

Figure 3.2: Population and Buildings According to DHW Production Energy Carrier, 1867-2017, Data set Rolle

[1]Note that while gas is listed uppermost in the legend, it is at the bottom of each stack bar in the bar charts

The segmentation of the building groups assigned by the LUASA (e.g., SFH or MFH) in the data set Rolle is discussed hereafter.

Table 3.1 shows the percentage of all 1,650 buildings in the LUASA-building groups listed. The majority of the buildings in the municipality of Rolle (1,203 of 1,650) are used for residential purposes, about 37.5 percent are used as SFHs, 24.5 percent as MFHs and 10.6 percent as mixed-use buildings. Assuming that the mixed-use buildings are counted as buildings used solely for residential purpose, 52 percent of the 1,203 buildings used for residential purposes are SFHs and 33 percent are MFHs. The latest *Buildings and Dwellings Statistics 2017* report, released in November 2018, states that 57 percent of the buildings in Switzerland, which are used solely for residential purposes, are SFHs [19]. The ratio of SFHs to residential buildings is thus slightly lower in Rolle compared to the Swiss average.

Figure 3.3 displays the distribution of the same buildings as in Figures 3.1 and 3.2, but grouped according to their LUASA-building groups. It can be recognized that the ratio of newly built SFHs to newly built MFHs is highest between 1997 and 2007. Generally, the number of newly built buildings has increased over the last decades with the maximums in the last two decades. These trends may be explained by the economic growth in this period. In fact, the real gross domestic product per capita of Switzerland increased by approximately 30 percent between 1997 and 2007 [20], while the interest rates on mortgages in Switzerland dropped by approximately 1.5 percent [21].

Table 3.1: Buildings according to their LUASA-building class, Data Set Rolle

Class	Number [−]	Percentage [%]
Single-Family Homes	619	37.5
Multiple-Family Homes	406	24.6
Garages	217	13.2
Mixed Use	175	10.6
Light Industry	88	5.3
Sales	30	1.8
Clubhouses	25	1.5
Administration	20	1.2
Industry	18	1.1
Schools	15	0.9
Agriculture	11	0.7
Retirement homes	8	0.5
Restaurants	8	0.5
Hotels	3	0.2
Grammar Schools	3	< 0.2
Castles	1	< 0.2
Churches	1	< 0.2
Hospital	1	< 0.2
Indoor Swimming Pools	1	< 0.2
Sum of all buildings	1,650	100

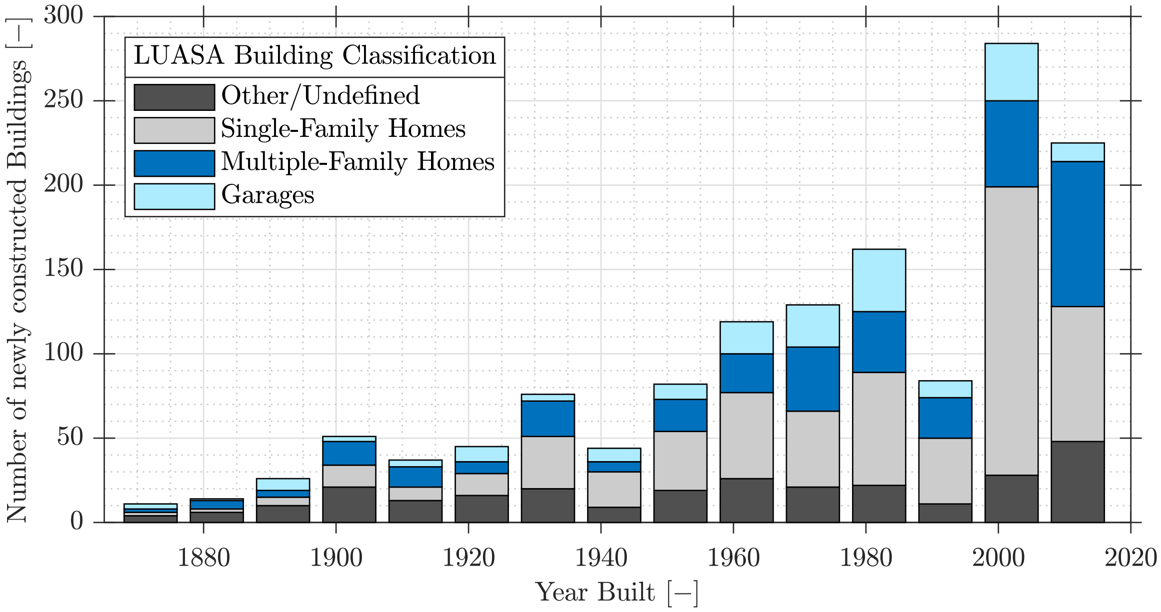

Figure 3.3: Number of Buildings According to their Building Groups, 1867-2017, Data set Rolle

3.2 Segmentation of Data Set Wohlen

In this section three bar graphs are shown. They represent the histograms of the data set Wohlen^{B}.

Figure 3.5 displays the population of the municipality of Wohlen, presented as a red line, and the number of constructed objects, i.e., buildings, organized according to their building year. The left vertical axis shows the number of newly constructed buildings, while the right vertical axis shows the number of inhabitants.

It can be recognized that the number of inhabitants increased continuously between 1960 and 1990, then remained at the same level of approximately $9,000$ inhabitants.

There is a significant difference in population growth between Rolle and Wohlen. The number of inhabitants of Wohlen grew by approximately 215 percent between 1950 and 2017 while the number of inhabitants in Rolle grew by 130 percent during the same time period (Switzerland had a growth of 78 percent during this period).
The reason for this strong growth in Wohlen is that the nearby Bremgartenwald and the Aare River acted as natural barriers to construction activity until 1960. Prior to 1960, most of the population was made up of farming families and their servants. Employees represented a minority, and industry was almost completely missing. After 1961, the demand for living space increased tremendously. The Hinterkappeln district, in particular, started to strongly grow from a base of about 600 inhabitants.

Today, about half of the inhabitants of Wohlen live in Hinterkappelen [22]. Figure 3.4 shows building activities in this district. Thus, it is not surprising that the majority of buildings in Wohlen were built or renovated between 1960 and 1990.

Figure 3.4: Construction of Buildings in Hinterkappelen, probable in the 60s or 70s, Wohlen [22]

Figures 3.6 and 3.7 display the distribution of the energy carriers for space heating and DHW production of the buildings built or renovated between 1960 and 2017.

The buildings are grouped according to year built or, in contrast to Figures 3.1, 3.2 and 3.3, according to their renovation year (if they were renovated). The bar width is not uniform since the buildings are organized in the data set Wohlen^{B} according to building periods of different lengths.

As mentioned previously, in Rolle, oil is the prevalent energy carrier for both space heating and DHW production for buildings built between 1927 and 1987, while between 1987 and 2017, gas dominates. In Wohlen, the most prevalent energy carrier for DHW production is clearly electricity used for resistance heaters. A possible reason for the difference observed between the two municipalities might be that most buildings in Wohlen were built between 1960 and 1990, while, in Rolle, most buildings were built between 1997 and 2017. Another reason might be that the Mühleberg hydroelectric power station and Mühleberg nuclear power stations are approximately 5 km from Wohlen. Another interesting factor that may contribute to the large number of resistance heaters in Wohlen is that the inhabitants of Wohlen seem less environmentally conscious than those in Rolle. This observation is based on the fact that voters in Wohlen approved the total revision of the energy law with a majority of 63 percent of the total votes cast, whereas the voters of in the municipality of Rolle approved this law with a majority of 77 percent [18].

The large number of systems producing DHW with resistance heaters indicates that there is energy-saving potential in Wohlen if the resistance heaters in buildings, built or renovated between 1970 and 2000, will be replaced with heat pumps or solar (thermal) collectors in the future. This energy-saving potential is estimated in Subection 3.6.1.

In about 50 percent of the buildings in Wohlen, space is heated with oil, while only approximately 5 percent of the buildings have their space heated by gas.
Recall that in Rolle, approximately 35 percent of the buildings have their space heated with gas and approximately 24 percent remarkably have their space heated with oil. These differences may be due to gas being more common in Rolle, as discussed in Section 3.1. Another interesting fact is that solar collectors make up a smaller share of DHW production in Wohlen than Rolle. The reason is presumably that fewer buildings were built (or renovated) in the last two decades in Wohlen compared to Rolle.

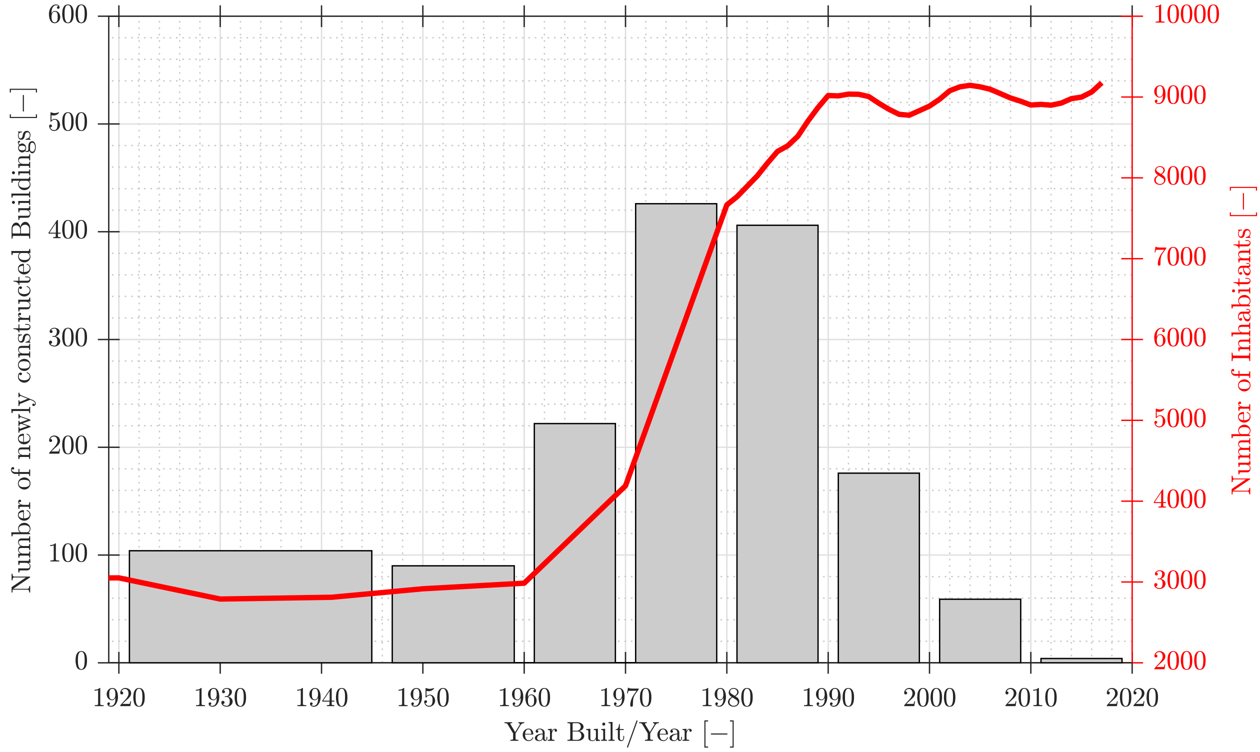

Figure 3.5: Population and Number of newly constructed Buildings, 1919-2017, Data set Wohlen[B]

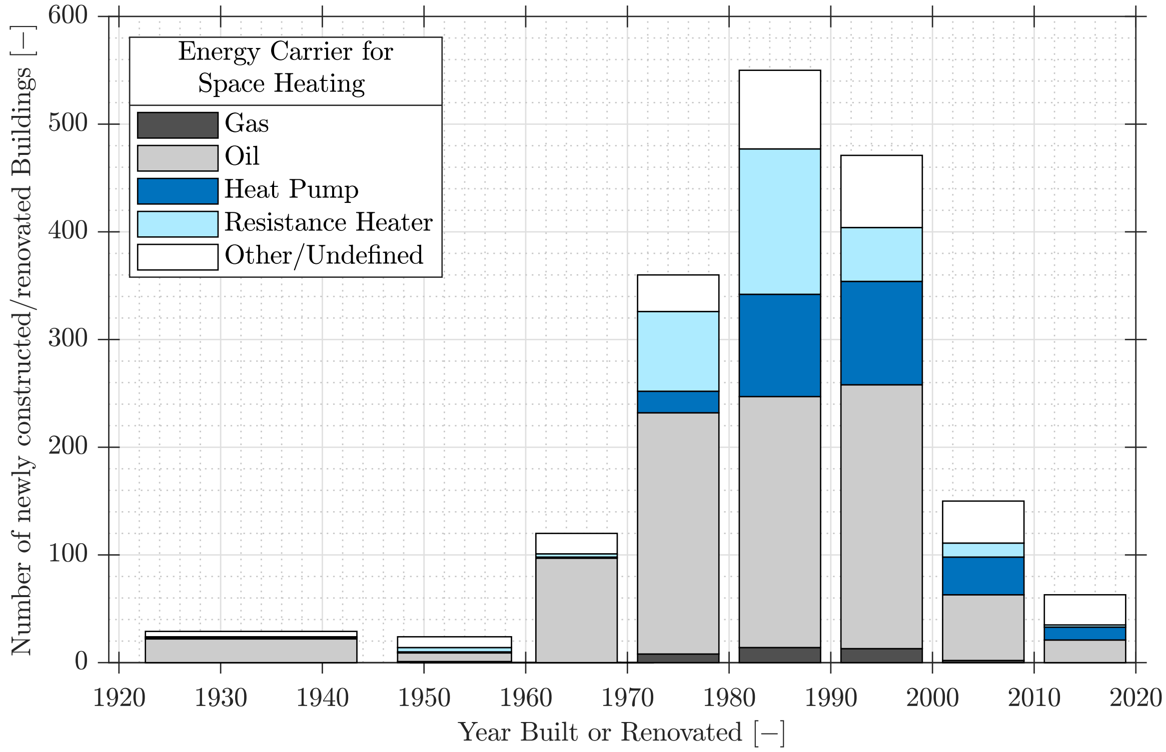

Figure 3.6: Population and Buildings According to Space Heating Energy Carrier, 1919-2017, Data set Wohlen[B]

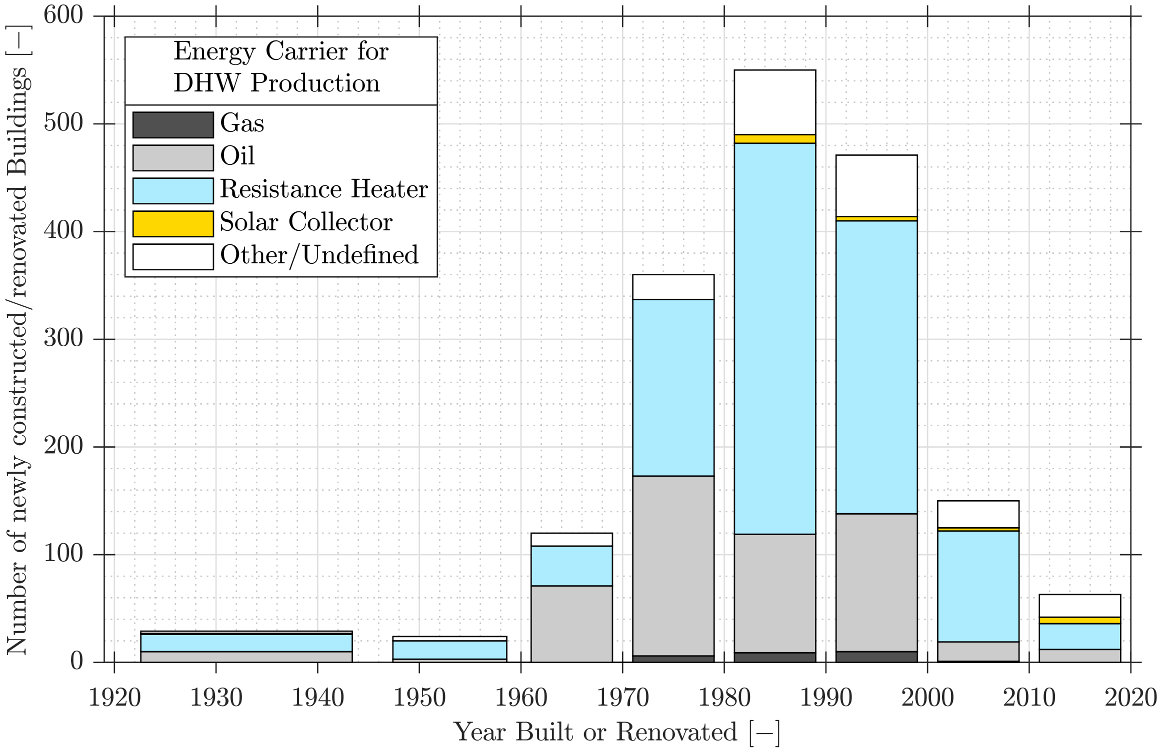

Figure 3.7: Population and Buildings According to DHW Production Energy Carrier, 1919-2017, Data set Wohlen[B]

3.3 Electrical Energy Demand

Various box plots representing the electrical energy demands for SFH subgroups, grouped according to their main energy carrier combinations, are shown in Figures 3.8 (data set Rolle) and 3.9 (data set Wohlen^{B}). Note that only the subgroups with the nine most common (according to data set Wohlen in SFHs) energy carrier combinations (for space heating and DHW production) are shown. The number in the legend represents the subsample size.
The vertical axis presents the (yearly) electrical energy demand. The boxplots's central rectangle spans the first quartile to the third quartile (Interquartile Range, IQR), i.e., 25 to the 75 quantile. The segment inside the rectangle shows the median. The dashed lines extending parallel from the boxes are used to visualize the "minimum" and "maximum". The minimum and maximum visualize the lowest and highest observation still within 1.5 IQR. Outliers are sample value beyond the minimum or maximum and plotted as individual crosses. These box plots are shown in order to display the full range of variation of the total electrical energy demand and to compare the subgroups in the two data sets. Note that the ECDFs of a portion of the same sugroups can be found in the Appendix (Figures A1 and A2).

The corresponding descriptive statistics (quartiles) are listed in Table 3.2. Two outliers are not shown because they are beyond the range of the vertical axis, namely, one Gas/Gas SFH with an electrical energy demand of $9.83 \cdot 10^{5}\ \frac{\mathrm{MW \cdot h}}{\mathrm{a}}$ and one HP/HP SFH with an electrical energy demand of $2.60 \cdot 10^{6}\ \frac{\mathrm{MW \cdot h}}{\mathrm{a}}$, both in the data set Rolle. It could be clarified that the first-mentioned outlier represent a villa on the Lake Geneva. A possible reason for the high electricity consumption may be an indoor pool. The reason for the high electricity consumption of the other outlier could not be clarified. Also the use of satellite pictures led not to an explanation.

Recall that, in general, the potentially different measuring periods of the electrical energy demands for the two data sets as well as the different geographical location (weather conditions) of the two municipalities could be responsible for part of the differences between the subgroups. According to MeteoSwiss, the mean annual temperature in 2017 in Nyon (approximately 8 km south-west of Rolle) was 11.2° C, whereas the mean annual temperature in the City of Bern (approximately 5 km east of Wohlen) was 9.7° C. The heat demand inverse proportionally depends on the ambient temperature. Thus, a higher energy demand for space heating in Wohlen can potentially explained in part by the fact that the ambient temperatures in Rolle tends to be higher than in Wohlen. However, since the mean annual temperatures differ from year to year and the measuring periods are not known, this cannot be concluded unequivocally.

SFHs using electricity as the main energy carrier for both space heating and DHW production (RH/RH, HP/RH and HP/HP) have, generally speaking, the biggest electrical energy demand. This is not surprising since electricity is used for appliances, space heating and DHW production in contrast to other subgroups, such as Oil/Oil and Gas/Gas.
The descriptive measures of the RH/RH SFHs are highest. This again is no surprise since resistance heaters are less efficient than heat pumps.
Surprisingly, the difference between HP/RH and HP/HP within the data set Wohlen^{B} is relatively small although heat pumps are supposed to generated heat more efficiently. This finding is confirmed by the distributions of the *specific* electrical energy demands for HP/RH and HP/HP SFHs and will be further discussed in Section 3.4. The subsample sizes of these two subgroups in Rolle are relatively small to enable a statistically reliable statement with.

The discrepancy in the quartiles of the two subgroup RH/RH SFHs is relatively small. This indicates that the electrical energy demand distribution in Rolle and Wohlen are similar despite the potentially different measuring period and energy reference areas.

Outliers can be recognized mainly for subgroups with relatively high numbers of observations. Remarkable is that the subgroup RH/RH SFHs in the data set Wohlen, although the subsample size is 238, has only three outliers.
Generally, outliers represent buildings which have a relatively high electrical energy demand. Large demands can have various reasons, such as a big energy reference area requiring more electricity (e.g., to heat or run entertainment system), a high number of inhabitants or, as in the subgroups Oil/Oil and Gas/Gas, SFHs in which resistance heaters are used as supplementary heating systems (in winter). Other reasons for a high electrical energy demand include a large number of electrical appliances, private handcrafts which require much electricity are performed or the use of electricity is less efficient (e.g., incandescent lamps instead of energy-saving lamps). Note that outliers can not have an electrical energy demand less than 0 $\frac{\mathrm{kW \cdot h}}{\mathrm{a \cdot m^2}}$ (would mean electricity generation), while they have virtually no upper limit.

The subgroup Oil/Oil SFHs contains the most observations in the data set Wohlen and the second most observations in the data set Rolle. Recall that the

electrical energy demand of these SFHs represents mainly the electrical energy demand for appliances.
All three quantiles are higher for the subgroup of the data set Rolle than they are for the subgroup of the data set Wohlen^{B}. A possible reason may be that the age distribution of the two subgroups is different. Gas is more common in newer buildings in Rolle, whereas gas is generally not common in Wohlen. That is, in newer SFHs in Wohlen oil is commonly used as main energy carrier for space heating in contrast to Rolle where mostly gas is used. This difference in fuels may influence the electrical energy demand and contribute to the difference. In [14], it is stated that the electrical energy demand for appliances is dependent mainly on the number of inhabitants. Thus, another factor is that the number of inhabitants per SFH is higher in Wohlen than in Rolle. Social factors which lead to a higher "density of inhabitants" such as statistically higher rents in Wohlen than in Rolle, may be responsible as well.

The comparison between Wood/RH and Oil/RH in the data set Wohlen shows that the descriptive statistics are of the same magnitude. This is not surprising since, in these SFHs, the electricity is "only" used for appliances and DHW production. Wood/Wood SFHs have even a slightly higher electrical energy demand. This however is not the outcome that should be expected since no electricity is used for DHW production.
A possible explanation is that supplementary resistance heaters for space heating and DHW production systems are used or that a portion of these SFHs are likely farmhouses. It seems possible that, at farmhouses, activities are carried out that require electrical energy not carried in Oil/Oil SFHs, such as repair works (e.g., welding). Another factor that may influence the result here as well is the small subsample size.

The difference between Oil/Oil and Oil/RH represents the electrical energy demand for DHW production. This difference will be discussed further in the Sections 3.4 and 3.6.

In summary, the analysis showed that the electrical energy demand for the considered subgroups is either similar or explainable although important information about the data is missing such as the measuring period and SFHs sugbroups of different energy reference areas were compared.
In the next section the specific electrical energy demand of various subgroups will be analysed.

Table 3.2: Descriptive Statistics for the Electrical Energy Demands of SFHs, Data sets Rolle and Wohlen^{B}

Energy Carrier for Space	Energy Carrier for DHW	25%-Quantile		Median		75%-Quantile	
		Rolle $\frac{MW\cdot h}{a}$	Wohlen $\frac{MW\cdot h}{a}$	Rolle $\frac{MW\cdot h}{a}$	Wohlen $\frac{MW\cdot h}{a}$	Rolle $\frac{MW\cdot h}{a}$	Wohlen $\frac{MW\cdot h}{a}$
Resistance Heater	Resistance Heater	9.92	8.02	14.2	12.6	18.4	18.0
Gas	Resistance Heater	3.27	4.16	4.91	4.76	8.93	6.32
Gas	Gas	3.34	2.89	4.39	4.36	6.86	5.77
Heat Pump	Resistance Heater	12.1	5.50	19.9	7.70	25.3	10.4
Heat Pump	Heat Pump	8.50	4.86	13.6	8.99	18.3	12.7
Oil	Resistance Heater	4.09	4.38	5.05	5.70	6.31	7.59
Oil	Oil	3.27	2.71	5.34	4.05	8.93	6.14
Wood	Resistance Heater	2.33	3.16	6.54	5.59	15.0	8.30
Wood	Wood	2.79	4.18	4.92	6.28	8.32	7.50

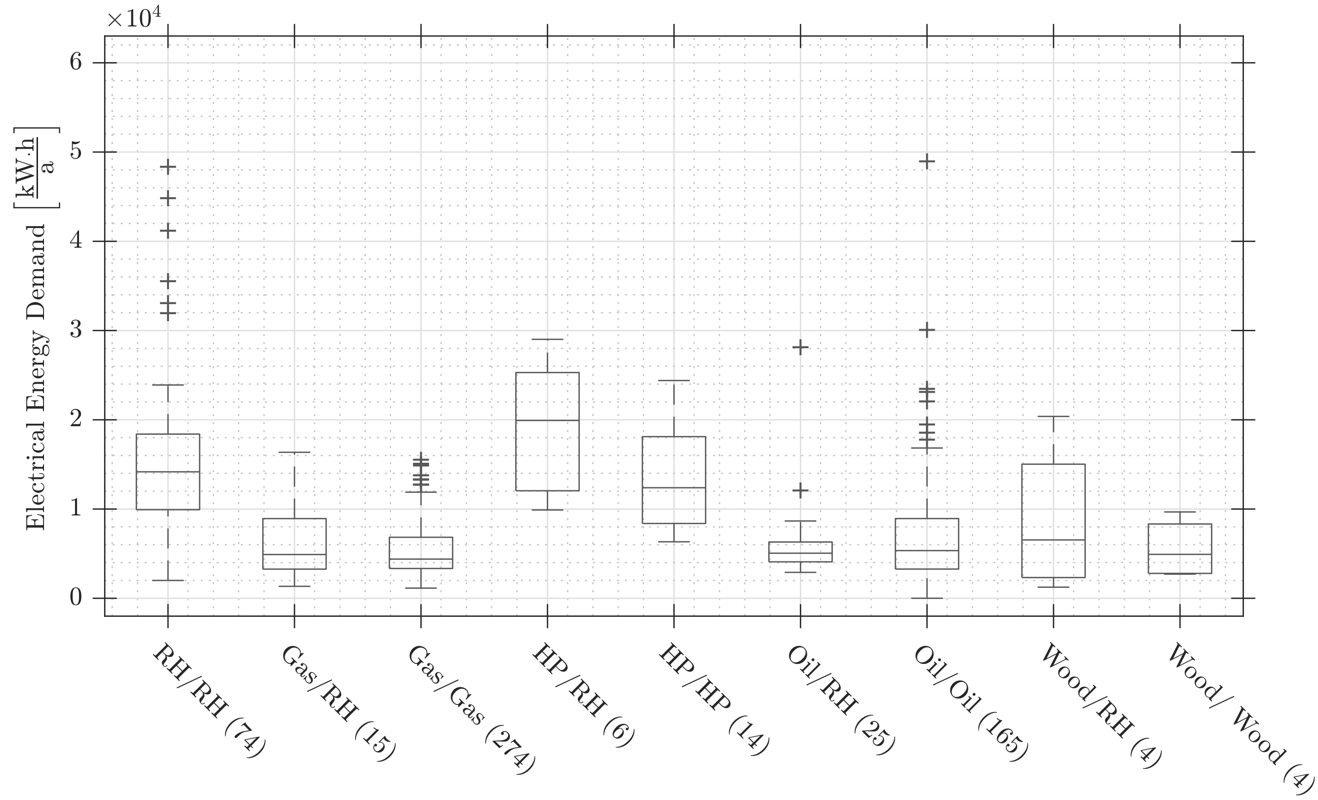

Figure 3.8: Box Plots representing Electrical Energy Demands for SFHs, Data set Rolle

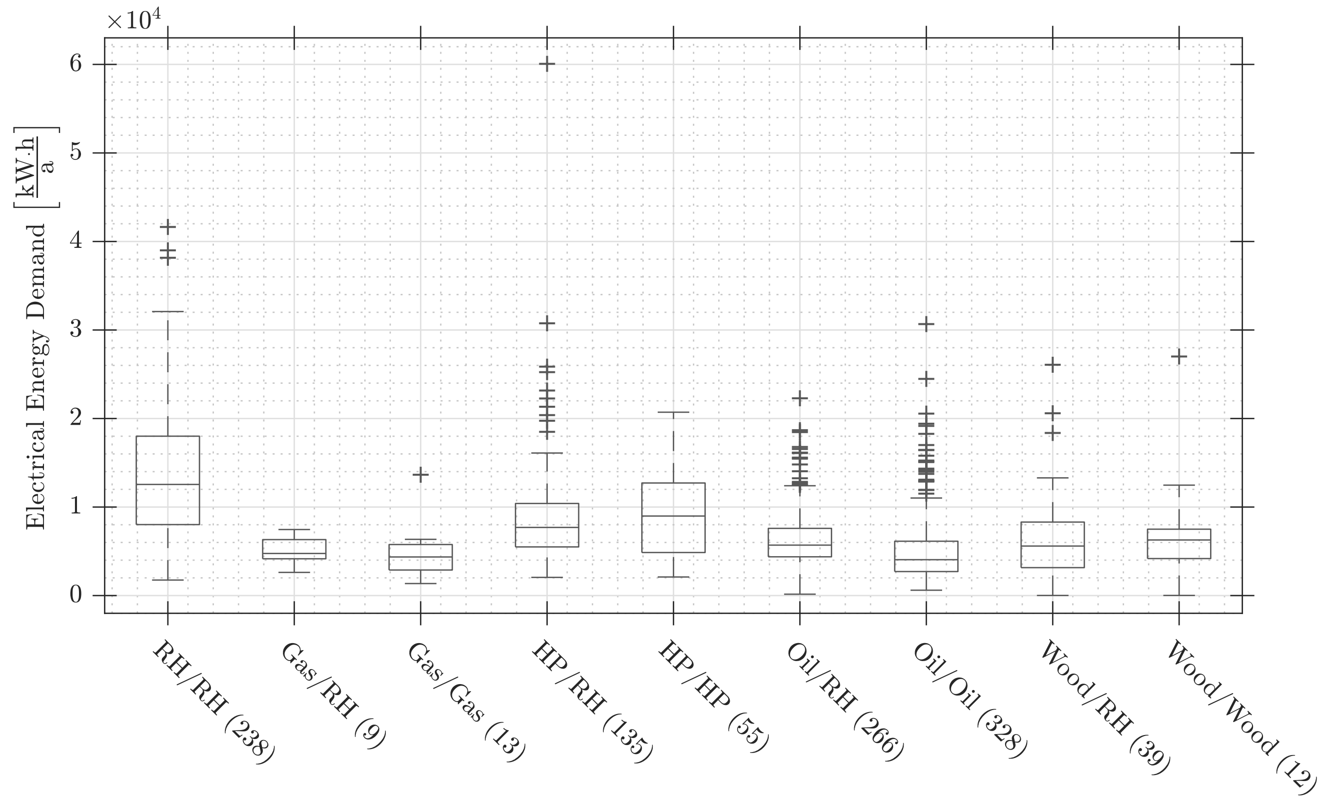

Figure 3.9: Box Plots representing Electrical Energy Demands for SFHs, Data set Wohlen[B]

3.4 Specific Electrical Energy Demand

The following results were obtained via the methods described in Section 2.8.

For the calculation of the specific electrical energy demands the energy reference area was used. For the two data sets, it was not possible to confirm whether the same source and same reference for the area calculation was employed. Therefore, the available areas are employed due to unavailable alternatives. Another possibility considered was to define a specific energy demand based on the dwelling area or number of inhabitant. The promising alternative representation based on the number of inhabitants could not be pursuit due to missing data.

Various ECDFs representing the (yearly) electrical energy demands for subgroups in both data sets are shown in this section and the following Sections. The horizontal axes of these Figures represent the specific electrical energy demand while the vertical axes represent the cumulative probability.

The subsample size required to represent a subgroup accurately was unknown and is a much discussed subject in research. Various factors such as the power of the study, level of significance, effect size, precision and variability affect the sample size required for an empirical study. Important factors, such as the measuring period for both data sets are unknown. Thus, the required subsample size could not be conclusively clarified.

In Figures 3.10 and 3.11 five and six ECDFs of SFH subgroups, gathered according to their main energy carrier combinations, with more than 20 samples, are shown. The ECDFs represent the specific electrical energy demands for these SFHs subgroups for the data sets Rolle and Wohlen[B]. Note that the corresponding box plots can be found in the Appendix (Figures A3 and A4).

Since only subgroups with more than 20 observations are shown, different combinations for the two data sets are shown. In Table 3.3 the corresponding means, medians, 75 percent quantiles and standard deviations are listed.

The curve representing Oil/Oil SFHs is closest to the vertical axis at a probability of 50 percent (median) in Figure 3.11. This is not surprising, as these buildings consume no or almost no electrical energy neither for heating space nor for DHW production. Thus, this curve represents the distribution of e_{App}. The subgroup's medians and 75 percent quantiles are of the same order of magnitude. Most of these buildings have a specific electrical energy demand between approximately 10 and 40 $\frac{\text{kW·h}}{\text{a·m}^2}$ since the curve is steepest in this range. The specific electrical energy demand for appliances will be further discussed in the next Section.

The curve of Oil/RH SFHs in Figure 3.11 is further to the right (approximately 15 $\frac{\text{kW·h}}{\text{a·m}^2}$) than the curve for Oil/Oil. This difference represents the additional electrical energy demand for DHW production with resistance heaters $e_{\text{DHW,RH}}$, instead of oil. This additional energy demand will be discussed further in Section 3.6. In contrast to Figure 3.11, the curve of Oil/RH SFHs in Figure 3.10 runs almost identically as the Oil/Oil SFHs curve. This result is surprising and indicates that buildings in Rolle in which DHW is produced with oil or RH have almost the same specific electrical energy demand. The same can be observed for the curves HP/RH and HP/HP in Figure 3.11, which are nearly the same. This result is highly counter-intuitive, since heat pumps heat more efficiently than resistance heaters. This results can not be further explained with the available data. The differences in the subsample size (135 to 55 and 25 to 165) might have a slight impact on the results.

In Figure 3.10, the curve representing Gas/Gas SFHs has a similar shape to the Oil/Oil SFHs. The medians, and 75 percent quantile confirm this observation. This was expected, since electricity is used in both subgroups only for appliances. Note that, in Figure 3.11, Gas/Gas SFHs are not shown due to a subsample size of less than 20. The fact that gas is more common Wohlen than in Rolle was already discussed in Sections 3.1 and 3.2.

The difference between the curves Oil/Oil and RH/RH SFHs represents the specific energy demands for space heating and DHW production with resistance heaters. It can be assumed that this difference is equal to the overall specific thermal energy demands for space heating and DHW production.

Interestingly, the curve Wood/RH is shifted to a higher specific energy demand than Oil/RH in Figure 3.11. A possible explanation for this might be the discussed reasons given in Section 3.3.

Surprisingly, the median of HP/Collector SFHs in Rolle is almost identically to the median of HP/HP SFHs in Wohlen even tough the main energy carrier for DHW production is not electricity.
The observation that the difference between the SFHs using electricity for DHW production and SFHs not using electricity to produce DHW is unexpected relatively small and is previously discussed.

An additional explanation for the small difference between a party of the curves representing HP/HP and HP/Collector SFHs may be that almost no electricity is used in summer to produce DHW but in winter the DHW is produced mainly with supplementary RH. Doing so, results in an inefficient use of electricity in winter, leading to higher specific electrical energy demands for HP/Collector SFHs.

From both figures, it can be recognized that RH/RH SFH have by far the greatest specific electrical energy demands. The reason is that both space heating and DHW production account for the specific electrical energy demand in contrast to other SFHs in which electricity is only used for appliances (e.g., Oil/Oil) or only for appliances and DHW (e.g., Oil/RH).
It should be noted that the shapes of the curves for Rolle and Wohlen are different. The shape of the RH/RH curve from the data set Wohlen is almost a line, i.e., almost the same probability for the specific electrical energy demand in a range from 30 to 160 $\frac{\text{kW}\cdot\text{h}}{\text{a}\cdot\text{m}^2}$ indicating a plateau distribution. The shape of the RH/RH curve for Rolle indicates a positive-skew normal distribution, since the highest probability is in a range from 40 to 80 $\frac{\text{kW}\cdot\text{h}}{\text{a}\cdot\text{m}^2}$, whereas a lower probability (curve is less steep) is in a ranges from 20 $\frac{\text{kW}\cdot\text{h}}{\text{a}\cdot\text{m}^2}$ to 40 and from 80 to 200 $\frac{\text{kW}\cdot\text{h}}{\text{a}\cdot\text{m}^2}$. A reason may be that the age structure of buildings is different between Rolle and Wohlen.

The slopes of most curves become smaller at approximately 90 percent of the way through the data. This means that there is a similar percentage of upper outliers in most groups. Another interesting finding is that most ECDFs start between 0 and 10 $\frac{\text{kW}\cdot\text{h}}{\text{a}\cdot\text{m}^2}$. This start indicates that there are SFHs in almost all subgroups which have relative small specific electrical energy demands. These SFHs may be vacant or holiday homes.

The big difference between the medians and means in Table 3.3 shows the effects of the upper outliers. Thus, most means are higher than the corresponding medians.

Table 3.3: Descriptive Statistics for the Specific Electrical Energy Demands for SFHs, Data sets Rolle and Wohlen$^{\text{B}}$

Energy Carrier for Space	Energy Carrier for DHW	Data Set	Mean $\frac{\text{kW}\cdot\text{h}}{\text{a}\cdot\text{m}^2}$	Median $\frac{\text{kW}\cdot\text{h}}{\text{a}\cdot\text{m}^2}$	75%-Quantile $\frac{\text{kW}\cdot\text{h}}{\text{a}\cdot\text{m}^2}$	Standard Deviation $\frac{\text{kW}\cdot\text{h}}{\text{a}\cdot\text{m}^2}$
Oil	Resistance Heater	Rolle	30.8	20.2	36.7	26.3
Oil	Oil	Rolle	27.7	22.2	30.8	31.5
Gas	Gas	Rolle	46.6	25.5	37.9	257
HP	Collector	Rolle	52.0	48.6	57.4	19.0
Resistance Heater	Resistance Heater	Rolle	80.0	65.2	81.1	61.1
Oil	Oil	Wohlen$^{\text{B}}$	34.6	26.9	42.6	24.6
Oil	Resistance Heater	Wohlen$^{\text{B}}$	46.6	41.3	56.2	25.6
Wood	Resistance Heater	Wohlen$^{\text{B}}$	63.2	46.9	69.7	54.5
HP	Resistance Heater	Wohlen$^{\text{B}}$	58.1	48.0	68.1	35.8
HP	HP	Wohlen$^{\text{B}}$	57.9	52.3	74.6	31.8
Resistance Heater	Resistance Heater	Wohlen$^{\text{B}}$	97.1	87.3	125.5	60.0

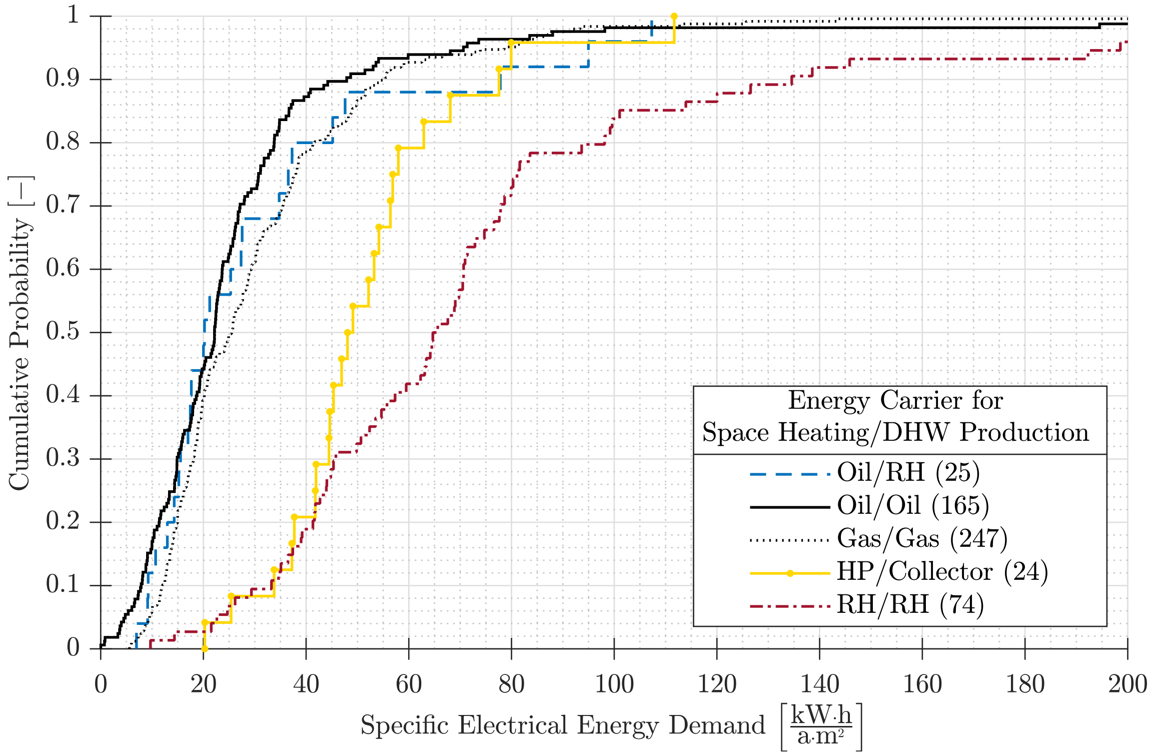

Figure 3.10: ECDFs representing Specific Electrical Energy Demands for SFHs, Data set Rolle[2]

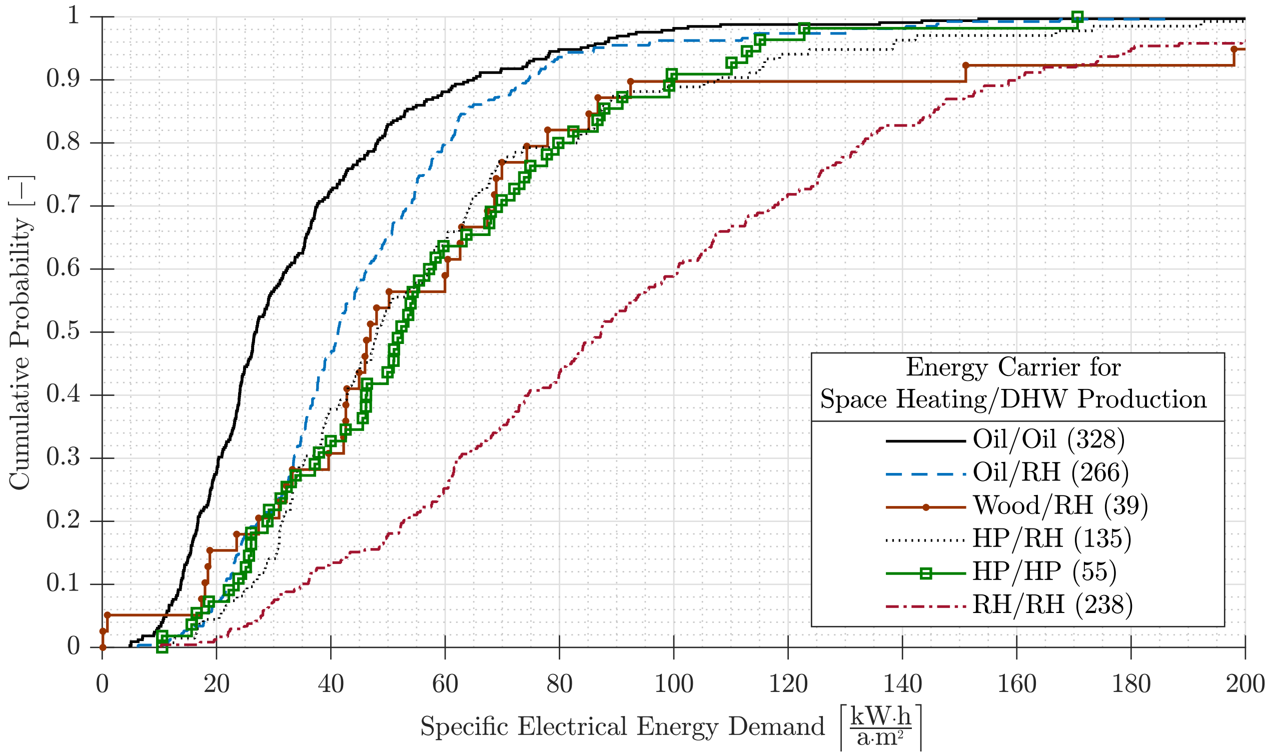

Figure 3.11: ECDFs representing Specific Electrical Energy Demands for SFHs, Data set Wohlen[B]

[2] Note that while Oil/RH and Oil/Oil are listed uppermost in the legend, they are closest to the vertical axis at a cumulative probability of 0.5 (median).

3.5 Contribution from Appliances

3.5.1 Contribution from Appliances for Multiple-Family Homes

In this and the following Subsections, the specific electrical energy demand contribution from Appliances is discussed.

Figure 3.12 shows four ECDFs representing the specific electrical energy demand for all apartments in Oil/Oil MFHs contained in the data set Wohlen^{A} organized according to their number of rooms ranging from 5 to 45 $\frac{kW \cdot h}{a \cdot m^2}$.
In these apartments, the *total* specific electrical energy demand represents the energy demand for appliances e_{App}. Due to the number of observations it was decided to use the specific electrical energy demands of Oil/Oil MFHs to represent e_{APP}. The corresponding means, medians and standard deviations are listed in Table 3.4. As previously stated, upper outliers are responsible for the relatively large differences between the means and medians.

The ECDF closest to the vertical axis represents two-room apartments and indicates the lowest specific electrical energy demand. The dashed curve representing three-room apartments and lies further to the right than the curve representing two-room apartments. The curves of four- and five-room apartments are almost the same, indicating a similar specific electrical energy demand distribution. Recall that the electrical energy demand for appliances depends mainly on the number of inhabitants, according to [14]. Hence, data points of the ECDFs above the median likely represent apartments with a high ratio of inhabitants to the energy reference area and vice versa.

Figure 3.13, adopted from the *Typischer Haushalt-Stromverbrauch report* [14], displays the number of persons living in 549 apartments in MFHs in Switzerland organized by the number of rooms. The report used the raw data of an household survey on electricity consumption.

It shows that most of the 549 apartments have four-rooms. These apartments have mostly two or three inhabitants. Three-room apartments have mostly two, followed by one inhabitant, while two-room apartments have mostly one inhabitant.
Hence, a possible explanation for the higher electrical energy demand in three-room apartments compared to four-room apartments is that there are more persons per room (or energy reference area), resulting in a higher energy demand per square meter. Another factor perhaps leading to this result could be that a portion of the two-room apartments are used by weekly residents or persons who do not cook (e.g., due to more sparse cooking facilities in two-room apartments or lifestyle-related reasons).

For interpretation, the above results are compared with "reference" values of the *Typischer Haushalt-Stromverbrauch report* [14].
This report states that the electrical energy demand E for appliances of apartments in a MFH correlates linearly with the number of persons x by means of the following equation (see also Figure A9 in the Appendix):

$$E = 1320 + 531 \cdot x \left[\frac{\mathrm{kW \cdot h}}{\mathrm{a}}\right] \tag{3.1}$$

In consequence, the electrical energy demand for a two-person household is $2,380 \frac{kW \cdot h}{a}$.
According to the SFSO, the average living space in three-room apartments in the Canton of Berne with two inhabitants is 31 square meters per person, which increases to 37 square meters per person for four-room apartments [11].

Hence, the resulting area for an average three-room apartment is 62 square meters, increasing to 74 square meters for an average four-room apartment. Assuming that the calculated areas are equal to the energy reference area results in a specific electrical energy demand of 38 $\frac{kW \cdot h}{a \cdot m^2}$ for a three-room apartment and 32 $\frac{kW \cdot h}{a \cdot m^2}$ for a four-room apartment. If the calculation is conducted for a four-room apartment with three inhabitant, then the specific electrical energy demand is 26 $\frac{kW \cdot h}{a \cdot m^2}$.

Recall that the ECDFs as well as the medians in Table 3.4 are based on measurements, whereas the reference values are obtained from a household survey on electricity consumption.
The comparison indicate, that the ECDFs are plausible and that the assumption that the specific electrical energy demand for Oil/Oil apartments represents the demand for specific electrical energy demand appliances is plausible.

Table 3.4: Descirptive Statistics for Oil/Oil Apartments, Data Set Wohlen^{A}

Number of Rooms	Mean $\frac{kW \cdot h}{a \cdot m^2}$	Median $\frac{kW \cdot h}{a \cdot m^2}$	Standard Deviation $\frac{kW \cdot h}{a \cdot m^2}$
2	22.2	18.7	18.2
3	26.3	19.9	27.4
4	31.7	22.1	38.2
5	30.3	22.2	31.2

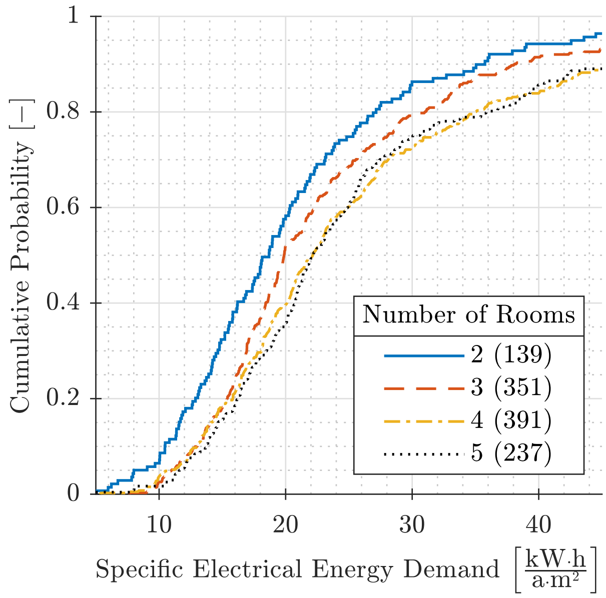

Figure 3.12: ECDFs representing Specific Electrical Energy Demands for Oil/Oil Apartments, Data set Wohlen[A]

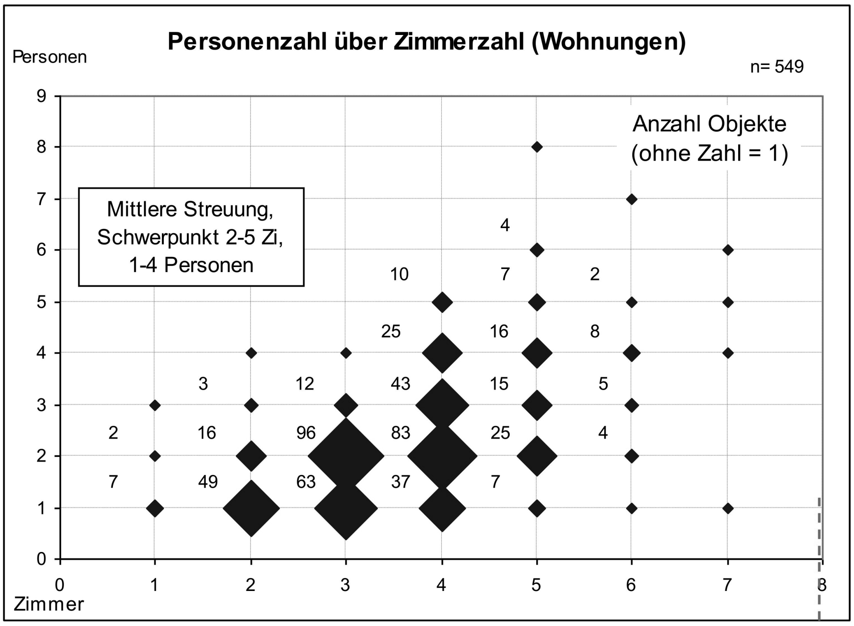

Figure 3.13: 549 Apartments Organized by Number of Rooms and Inhabitants [14]

3.5.2 Contribution from Appliances for Single-Family Homes

Figure 3.14 shows the four ECDFs representing the specific electrical energy demands for Oil/Oil and Gas/Gas SFHs contained in the two data sets (Rolle and Wohlen^{B}). The same ECDFs are shown in Figures 3.10 and 3.11, with the exception of Gas/Gas Wohlen due to its small subsample size. The ECDFs are shown on the same graph in order to better highlight the differences between them.

Recall that the ECDFs represent the distribution of the specific energy demand for the appliances e_{App}. The corresponding means, medians and standard deviations are listed in Table 3.5. It can be recognized that the curves are almost identical. The sample sizes indicate that gas is much less popular in Wohlen than in Rolle. This fact was discussed in Section 3.2. The medians are roughly similar in the range of 25 $\frac{\text{kW·h}}{\text{a·m}^2}$, except for Gas/Gas in Wohlen. This difference can be explained by the relatively small subsample size, which does not allow a reliable comparison. The shapes of the curves suggest that the underlying distributions of e_{App} are almost the same and are independent of the locations of the single-family homes and main energy carriers (oil or gas).

Moreover, the relatively small differences between the three curves (except Gas/Gas Wohlen) indicate that, although the data acquisition method to collect the data from Rolle and the measurement periods are unknown, the specific electrical energy demands for the same subgroups (SFHs grouped according to main energy carrier combinations) in the two data sets are similar. Furthermore, an electrical energy demand for appliances of 25 $\frac{\text{kW·h}}{\text{a·m}^2}$ meets the specific electrical energy demands in MFHs based on the *Typischer Haushalt-Stromverbrauch report* [14], as calculated previously.

Table 3.5: Descirptive Statistics for Oil/Oil and Gas/Gas SFHs, Data sets Rolle and Wohlen^{B}

Main Energy Carriers	Mean $\frac{\text{kW·h}}{\text{a·m}^2}$	Median $\frac{\text{kW·h}}{\text{a·m}^2}$	Standard Deviation $\frac{\text{kW·h}}{\text{a·m}^2}$
Oil/Oil Rolle	27.7	22.2	31.5
Gas/Gas Rolle	46.6	25.5	257
Oil/Oil Wohlen	34.6	26.9	24.6
Gas/Gas Wohlen	66.8	35.4	117

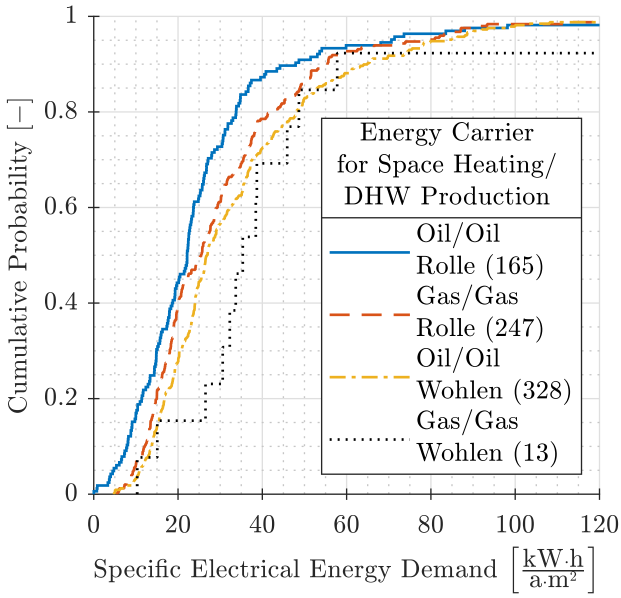

Figure 3.14: ECDFs representing Specific Electrical Energy Demands for Oil/Oil and Gas/Gas SFHs, Data sets Rolle and Wohlen^{B}

3.5.3 Contribution from Appliances for Single-Family Homes Grouped by Age

Figure 3.15 shows four ECDFs representing the specific electrical energy demands for Oil/Oil SFHs contained in the data set Wohlen^{B} grouped by the year they were built or their year of renovation (if renovated). The corresponding means, medians and standard deviations are listed in Table 3.6.

The sample sizes indicate that there are only a few SFHs which were either not renovated after or built before 1961. Furthermore, it can be recognized that the lower quartile of SFHs built or renovated since 1961 on are almost the same. Whereas, the SFHs built from 1996 on have, in the upper quartile, a higher specific electrical energy demand. The high mean of SFHs built or renovated from 1996 on compared to the other means confirms this observation. Reasons for this might be that in a portion of the SFHs built or renovated between 1996 and 2017, more electricity is used for appliances, such as entertainment electronics, or that the user behaviour of inhabitants in newer SFHs is different from the user behaviour of inhabitants in older buildings. Another factor that may lead to this result is that the building technology of these newer SFHs, such as ventilation or automatic sun shading consume more electricity than they do in older SFHs or are missing in older SFHs.

Table 3.6: Descriptive Statistics for Oil/Oil SFHs organized by Year Built or Year of Renovation, Data set Wohlen[B]

Year Built/ Renovation Year	Mean $\frac{kW\cdot h}{a\cdot m^2}$	Median $\frac{kW\cdot h}{a\cdot m^2}$	Standard Deviation $\frac{kW\cdot h}{a\cdot m^2}$
before 1961	34.1	36.7	14.1
1961 – 1980	33.4	27.0	24.8
1981 – 1995	30.2	24.3	19.5
after 1995	39.9	29.3	29.2

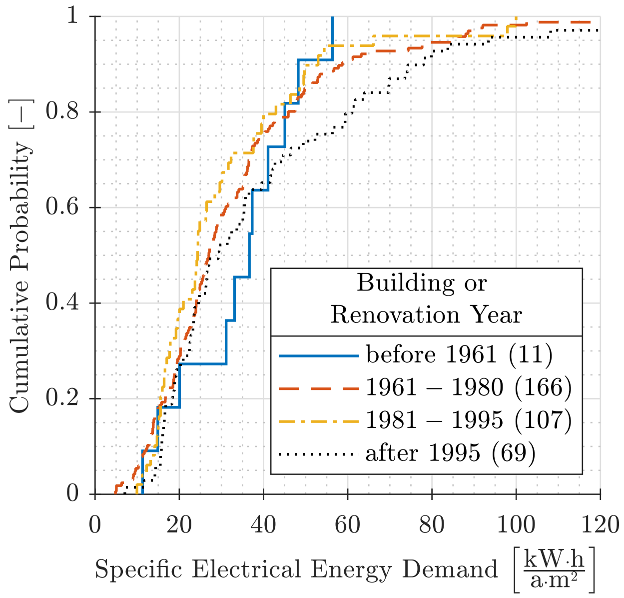

Figure 3.15: ECDFs representing Specific Electrical Energy Demands for Oil/Oil SFHs Organized by Age, Data Set Wohlen[B]

3.5.4 Contribution from Appliances for Multiple-Family Homes Grouped by Age

Figure 3.16 shows four ECDFs representing the specific electrical energy demand for three- and four-room apartments in Oil/Oil MFHs contained in the data set Wohlen[A]. The apartments are organized by the year they were built or renovation year (if renovated). Their corresponding means, medians and standard deviations are listed in Table 3.7. This figure visualizes the differences in the specific electrical energy demands for appliances in apartments from different building periods. Figure 3.12 shows that two- and three-room apartments have noticeably lower specific electrical energy demands for appliances than four- and five-room apartments. However, four and five-room apartment have almost the same specific electrical energy demands for appliances. To eliminate the impact of this trend in the analysis, only three- and four-room apartments are shown. From Figure 3.15, it can be recognized that a portion of the newer SFHs (later built or renovated) have higher specific electrical energy demands. The pattern is even more pronounced in apartments newer than 1995. These MFHs have a significantly higher electricity consumption for appliances than apartments in older MFHs. The reason for the higher specific electrical energy demand in apartments in MFH may be the same, as discussed previously for SFHs. This result is a surprising aspect of the data. It was assumed that newer or more recently renovated buildings would have a lower specific energy demand than older residential buildings due to the use of more energy-efficient appliances.

Table 3.7: Descriptive Statistics for Oil/Oil Apartments, Data set Wohlen[A]

Year Built/ Renovation Year	Mean $\frac{kW\cdot h}{a\cdot m^2}$	Median $\frac{kW\cdot h}{a\cdot m^2}$	Standard Deviation $\frac{kW\cdot h}{a\cdot m^2}$
before 1961	29.2	20.9	30.3
1961 – 1980	30.8	21.0	40.1
1981 – 1995	31.0	23.1	22.1
after 1995	44.6	32.1	39.3

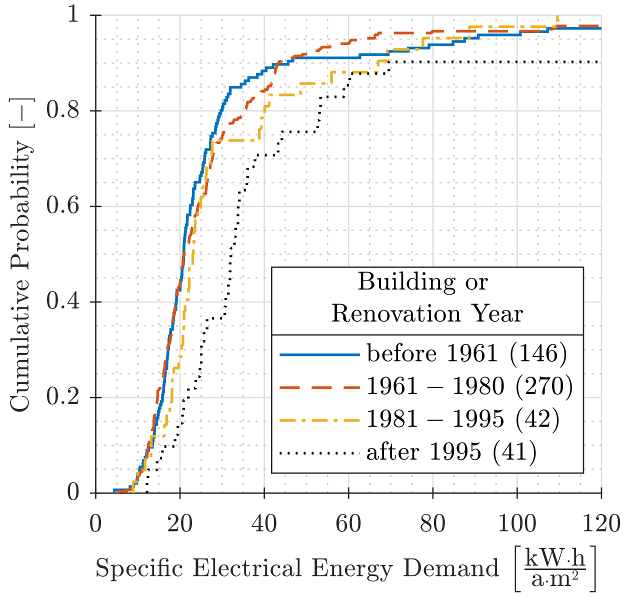

Figure 3.16: ECDFs representing Specific Electrical Energy Demands for Oil/Oil Apartments, Organized by Age, Data set Wohlen[A]

3.6 Contributions from Space Heating and DHW Production for Single-Family Homes

In this Section, the contributions from space heating and DHW production to the total specific electrical energy demand are discussed.

Figure 3.18 on the left shows three ECDFs representing the specific electrical energy demand for Oil/Oil, Oil/RH and RH/RH SFHs in the data set Wohlen^{B}. The diagram on the right in this figure shows the ECDF differences between Oil/RH and Oil/Oil, namely $\Delta_{\mathrm{DHW,RH}}$ and between Oil/RH and RH/RH, namely $\Delta_{\mathrm{Space,RH}}$.

The ECDF difference $\Delta_{\mathrm{DHW,RH}}$ represents the electrical energy demand for DHW production with resistance heater, while $\Delta_{\mathrm{Space,RH}}$ represents the energy demand for space heating with a resistance heater.

The distributions of the ECDF differences $\Delta_{\mathrm{Space,RH}}$ and $\Delta_{\mathrm{DHW,RH}}$ are shown via the histograms in Figure 3.19. The same data are shown via the histogram in Figures A5 and A6 in the Appendix but with bin widths of 2.5 and 7.5 $\frac{\mathrm{kW \cdot h}}{\mathrm{a \cdot m^2}}$

The histogram plot shows that the distribution of $\Delta_{\mathrm{Space,RH}}$ is more widely spread out compared to the distribution of $\Delta_{\mathrm{DHW,RH}}$.

The distribution of $\Delta_{\mathrm{DHW,RH}}$ is asymmetrical to the left, indicating a negatively skewed distribution and lower specific energy demand for DHW production than space heating. The report *Typischer Haushalt-Stromverbrauch* [14] states that the energy demand for DHW production depends mainly on the number of inhabitants. Hence, the left-tailed observations may be SFHs with a below-average ratio of inhabitants per energy reference area. Another reason for the limited specific energy demand for DHW production, i.e., no upper outliers, may be that the specific energy demand for DHW production with a resistance heater depends only on user behaviour (DHW demand). Furthermore, the electrical energy demand for space heating with resistance heating depends on several other factors, such as building envelope area, window area and building insulation what presumably explains the wider spread of the distribution $\Delta_{\mathrm{Space,RH}}$.

In order to check the plausibility of the results, the specific electrical energy demand for DHW production, according to the *Typischer Haushalt-Stromverbrauch report* [14], was calculated as described hereafter.

The report graphically represents the number of rooms and inhabitants of 215 Swiss SFHs. The corresponding graph is shown in Figure 3.17. According to this figure, the largest number of the analysed SFHs have two inhabitants and five or six rooms.

Furthermore, the report states that the electrical energy demand for DHW production with resistance heating $E_{\mathrm{DHW,RH}}$ correlates linearly with the number of inhabitants x according to the following equation (see also Figures A10 and A11 in the Appendix):

$$E_{\mathrm{DHW,RH}} = 1400 + 800 \cdot x \left[\frac{\mathrm{kW \cdot h}}{\mathrm{a}}\right] \tag{3.2}$$

The relative high offset represents the thermal losses, for example, in the water pipes between the boiler and the shower or the bathroom. A part of these thermal losses may contribute to space heating. Interestingly, according to the *Typischer Haushalt-Stromverbrauch* report [14], the offset, i.e., average thermal losses for a MFH is 200 $\frac{\mathrm{kW \cdot h}}{\mathrm{a}}$ lower due to the fact that the boilers of MFHs are less often installed in the basement. It follows that the electrical energy demand for a SFH with two inhabitants is 3000 $\frac{\mathrm{kW \cdot h}}{\mathrm{a}}$. As a numerical illustration the 3 MWh energy are converted to a mass of DHW by the following equation:

$$m = \frac{Q}{\Delta T \cdot c_p}, \tag{3.3}$$

where Q represents the heat quantity which, in our example, is equal to $3\,\mathrm{MW \cdot h}$. Note that since the DHW is produced with a resistance heater (thermal efficiency of 100%), the electrical energy is equal to the heat quantity. c_p represents the specific heat capacity of water and is approximately $4,200\,\frac{\mathrm{J}}{\mathrm{kg \cdot K}}$ or $1.17\,\frac{\mathrm{W \cdot h}}{\mathrm{kg \cdot K}}$.
If the water is heated from $15\,°\mathrm{C}$ to $60\,°\mathrm{C}$, the temperature difference ΔT is $45\,\mathrm{K}$. Energy of $3\,\mathrm{MW}$ results in a DHW mass of approximately $19,000\,\mathrm{kg}$ equal to $156\,\frac{\ell}{\mathrm{d}}$.

The average energy reference area of the SFHs contained in the data set Wohlen^{B} is approximately 181 square meters. The resulting specific electrical energy demand for producing DHW $e_{\mathrm{DHW,RH}}$ in an average size SFH with two inhabitants in Wohlen is approximately 17 $\frac{\mathrm{kW \cdot h}}{\mathrm{a \cdot m^2}}$. The result of the same calculation for three inhabitants is 21 $\frac{\mathrm{kW \cdot h}}{\mathrm{a \cdot m^2}}$, and, for four inhabitants, it is 25 $\frac{\mathrm{kW \cdot h}}{\mathrm{a \cdot m^2}}$. The mean of $\Delta_{\mathrm{DHW,RH}}$ is 12.0 $\frac{\mathrm{kW \cdot h}}{\mathrm{a \cdot m^2}}$, and the median is 12.8 $\frac{\mathrm{kW \cdot h}}{\mathrm{a \cdot m^2}}$, per Table 3.8. The distribution of the ECDF difference $\Delta_{\mathrm{DHW,RH}}$ seems to be approximately 30 percent lower compared to the result obtained with the values from the *Typischer Haushalt-Stromverbrauch report* [14].

Table 3.8: Descriptive Statistics for $\Delta_{\text{DHW,RH}}$ and $\Delta_{\text{Space,RH}}$

Distribution	Mean	Median	Standard Deviation
	$\frac{kW \cdot h}{a \cdot m^2}$	$\frac{kW \cdot h}{a \cdot m^2}$	$\frac{kW \cdot h}{a \cdot m^2}$
$\Delta_{\text{DHW,RH}}$	12.0	12.8	4.35
$\Delta_{\text{Space,RH}}$	50.3	46.0	34.7

The calculation of the ECDF difference is based on assumption that the Oil/Oil and Oil/RH SFHs have the same specific electrical energy demand for appliances e_{App}. Thus, a possible explanation for the rather small ECDF difference might be that the specific electrical energy demand for appliances in Oil/Oil is slightly higher than in Oil/RH, SFHs resulting in a smaller specific electrical energy demand for producing DHW.

However, the relatively small difference between the "reference values" and the extracted ECDF differences, although main factors, such as the measurement period could not be considered, suggests that the calculation method and underlying assumptions to obtain the share for DHW producing led to a plausible result.

3.6.1 Energy-Saving Potential in Wohlen

In the data set Wohlen, there are 693 SFHs in which DHW is produced with a resistance heater. They have an approximate total energy reference area of 102,000 square meter energy reference area. In order to estimate the savings potential for the SFHs contained in the data set Wohlen^{B} roughly, the following assumption is made:
The mean specific electrical energy demand for heating DHW with resistance heater will be conservatively assumed to be almost halved when DHW is produced with heat pumps (SCOP=1.75) instead. Then the median for heating DHW with HP would be approximately 6.9 $\frac{kW \cdot h}{a \cdot m^2}$. The savings potential, if all resistance heaters in SFHs were to be replaced with heat pumps, would be 5.1 $\frac{kW \cdot h}{a \cdot m^2}$, respectively 520,000 $\frac{kW \cdot h}{a}$ for Wohlen. The same assumptions for MFHs lead to a savings potential of approximately 232,000 $\frac{kW \cdot h}{a}$.

The municipality of Wohlen stated that it has set itself the target of reducing the share of non-renewable energies by 25 percent by 2025. In order to achieve this goal, various measures have been defined. If an additional 25 percent of the resistance heater boilers were to be replaced with heat pump boilers in SFHs and MFHs, the municipality could save a minimum of 188,000 $\frac{kW \cdot h}{a \cdot m^2}$ in electricity. According to Messmer and Frischknecht, 1 $kW \cdot h$ consumed electricity in Switzerland corresponds to 0.182 kg CO_2 greenhouse gas emissions (see also Figure A12 in the Appendix) [23]. It follows that the greenhouse gas emissions of Wohlen could be reduced by approximately 34,200 kg CO_2.

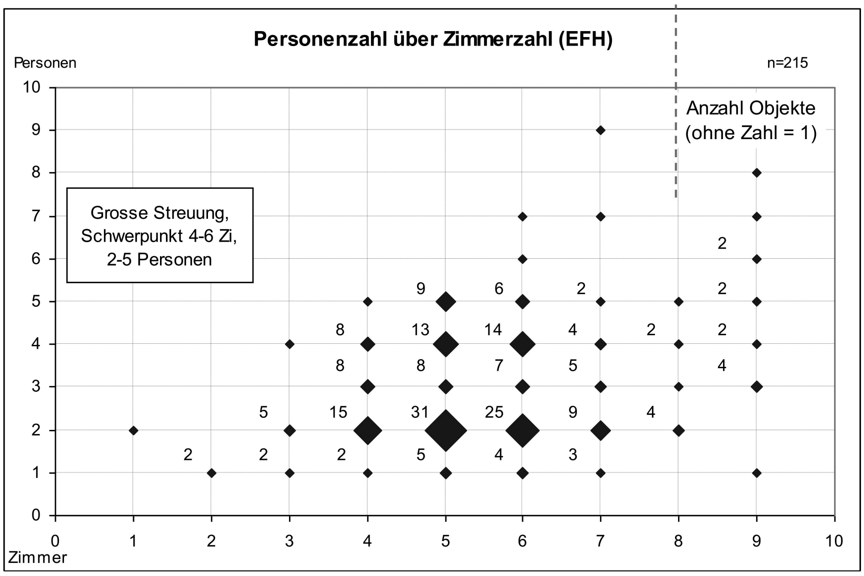

Figure 3.17: 215 SFHs organized by number of Rooms and Persons [14]

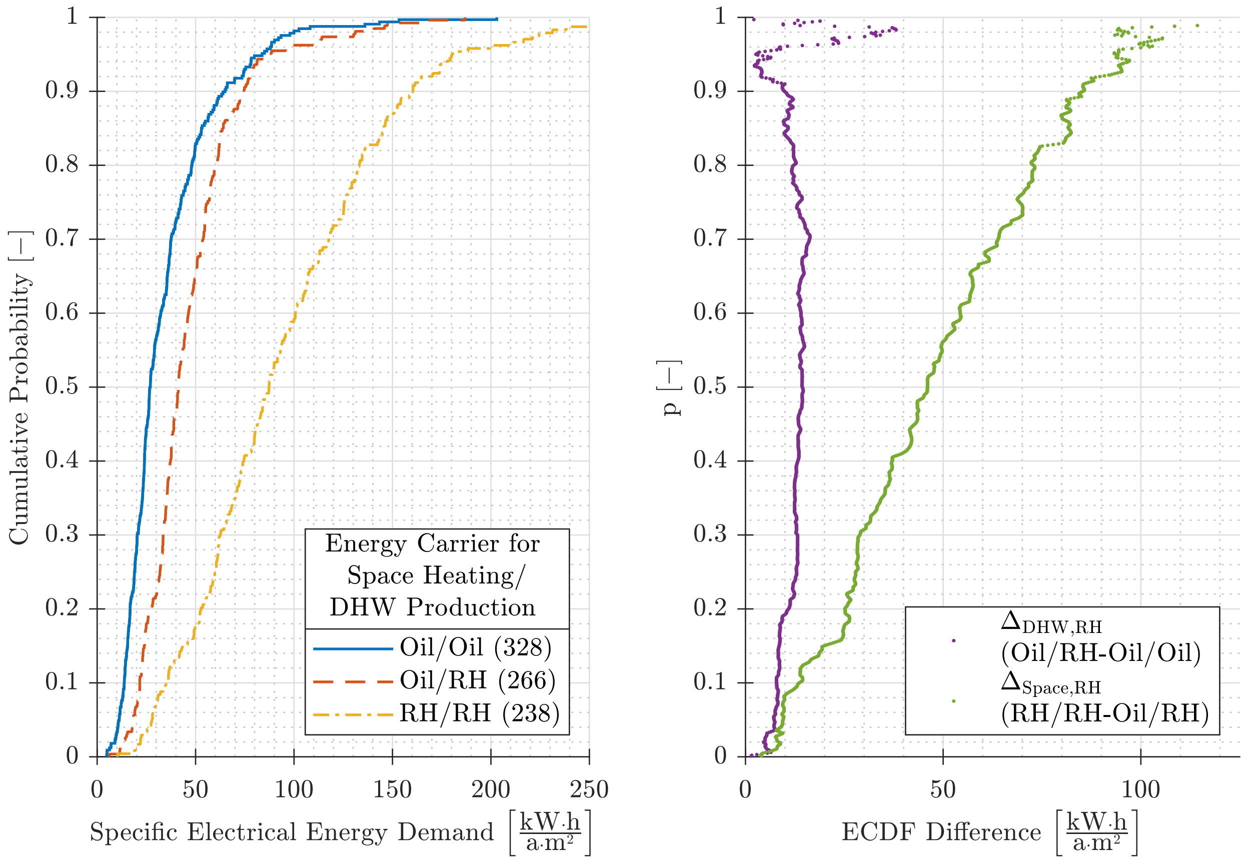

Figure 3.18: Left: ECDFs representing Specific Electrical Energy Demands for Oil/Oil, Oil/RH and RH/RH SFHs, Right: The corresponding Differences $\Delta_{\mathrm{DHW,RH}}$ and $\Delta_{\mathrm{Space,RH}}$, Data set Wohlen[B] [3]

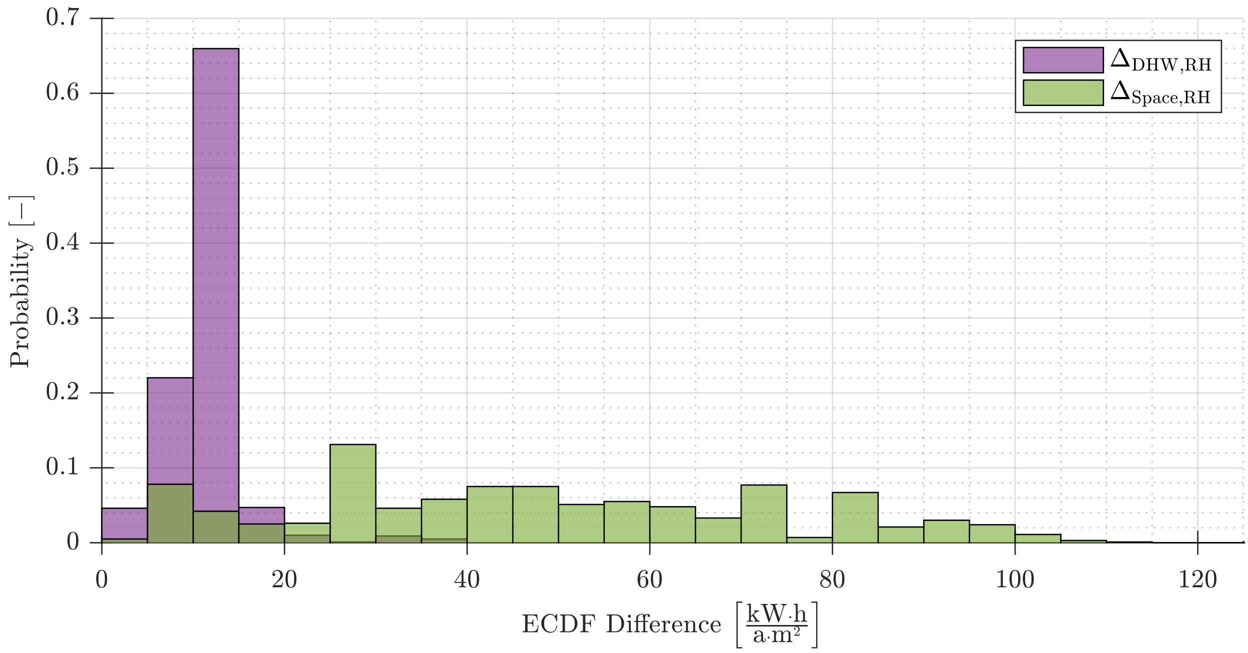

Figure 3.19: Histograms of $\Delta_{\mathrm{DHW,RH}}$ and $\Delta_{\mathrm{Space,RH}}$

[3] Note that the scale for the horizontal axis is twice as large in the left diagram compared to the right diagramm.

3.7 Contribution from Total Heat Demand for Single-Family Homes

In this Section, the contribution from the total heat demand (space heating and DHW production) to the total specifc electrical demand is discussed.

The ECDF representing the specific electrical energy demand for Oil/Oil, HP/HP and RH/RH SFHs are shown in Figure 3.21 on the left. The corresponding ECDF differences between the Oil/Oil SFHs and RH/RH SFHs $\Delta_{\text{Space+DHW,RH}}$ and between the Oil/Oil SFHs and HP/HP SFHs $\Delta_{\text{Space+DHW,RH}}$ are shown in Figure 3.21 on the right. The distributions of the ECDF differences are shown in Figure 3.22. Additional histograms with different bin widths are displayed in the Appendix (Figures A7 and A8). The corresponding means, medians and standard deviations are listed in Table 3.9.

The curves for $\Delta_{\text{Space+DHW,RH}}$ and $\Delta_{\text{Space+DHW,HP}}$ in Figure 3.21 when p is between 0.95 and 1 can be explained by outliers in the subgroups Oil/Oil, HP/HP and RH/RH SFHs.

The distribution of the ECDF difference $\Delta_{\text{Space+DHW,RH}}$ has various peaks indicating that the distribution is a combination of several distributions representing buildings with different attitudes (e.g., building's period, insulation or user behaviour).

The two peaks in the distribution of $\Delta_{\text{Space+DHW,HP}}$ may be an indication of a combination of two different distributions. The distinguishing feature of the two distributions may be the heat source of the heat pumps (air- or ground-source).

The centre of the distribution of $\Delta_{\text{Space+DHW,RH}}$ is significantly higher compared to the centre of the distribution of $\Delta_{\text{Space+DHW,HP}}$ (as per Table 3.9). This result is not surprising since heat pumps heat more efficiently than resistance heaters.

Table 3.9: Descriptive Statistics for $\Delta_{\text{Space+DHW,RH}}$ and $\Delta_{\text{Space+DHW,HP}}$

Distribution	Mean $\frac{\text{kW·h}}{\text{a·m}^2}$	Median $\frac{\text{kW·h}}{\text{a·m}^2}$	Standard Deviation $\frac{\text{kW·h}}{\text{a·m}^2}$
$\Delta_{\text{Space+DHW,RH}}$	23.3	25.2	10.1
$\Delta_{\text{Space+DHW,HP}}$	62.4	60.4	35.6

The *Energieplanungsbericht 2013, Bericht des Regierungsrats über die Energieplanung des Kantons Zürich* [24] shows the (total) specific heat demand for space heating and DHW production (Energiekennzahl Wärme) averaged over four years and a total energy reference area of 87 square kilometres energy reference area for residential buildings in the Canton of Zurich. The specific heat demands were organized by the building periods of the residential buildings. The red curve represents the status of the specific heat demand in 2011. The corresponding graph is shown in Figure 3.20.

The ECDF difference $\Delta_{\text{Space+DHW,RH}}$ represents the heat demand. Thus, the curve, representing the status as of 2011, can be compared with the distribution of $\Delta_{\text{Space+DHW,RH}}$ in Figure 3.22.

The averaged specific heat demand of the analysed building in the Canton of Zurich is between approximately 80 and 175 $\frac{\text{kW·h}}{\text{a·m}^2}$. The median of $\Delta_{\text{Space+DHW,RH}}$ is 60.4 $\frac{\text{kW·h}}{\text{a·m}^2}$. The reason for the difference may be that the specific electrical energy demand for appliances in Oil/Oil is higher than in RH/RH SFHs resulting in a smaller specific electrical energy demand for space heating and DHW production when using resistance heaters (as described in Section 3.6). Another factor may be that $\Delta_{\text{Space+DHW,RH}}$ is calculated based on the electricity demand over one year while the specific energy demands of the *Energieplanungsbericht 2013, Bericht des Regierungsrats über die Energieplanung des Kantons Zürich* [24] are averaged over four years.

Figure 3.20 shows that buildings which have *Minergie Standard 2009* have a specific heat demand of approximately 60 $\frac{\text{kW·h}}{\text{a·m}^2}$, respectively 30 $\frac{\text{kW·h}}{\text{a·m}^2}$ for buildings built from 2001 on.

The average of $\Delta_{\text{Space+DHW,HP}}$ is 23.2 $\frac{\text{kW·h}}{\text{a·m}^2}$. Assuming that optimistically the heat output of heat pumps is approximately three times higher than the (electrical) input, the mean of the specific heat demand of $\Delta_{\text{Space+DHW,HP}}$ would be 69.9 $\frac{\text{kW·h}}{\text{a·m}^2}$ $(3 \cdot 23.3)$. If the SFHs in the data set Wohlen, which have installed heat pumps have achieved almost Minergie-Standard, then the $\Delta_{\text{Space+DHW,HP}}$ seems to be plausible.

Nevertheless, the extracted heat demands for space heating and DHW production seems to be too low compared with the reference values from the two independent sources ([14] and [24]). If the output of the method applied on new data is also too low, a possible improvement is the introduction of correction factors.

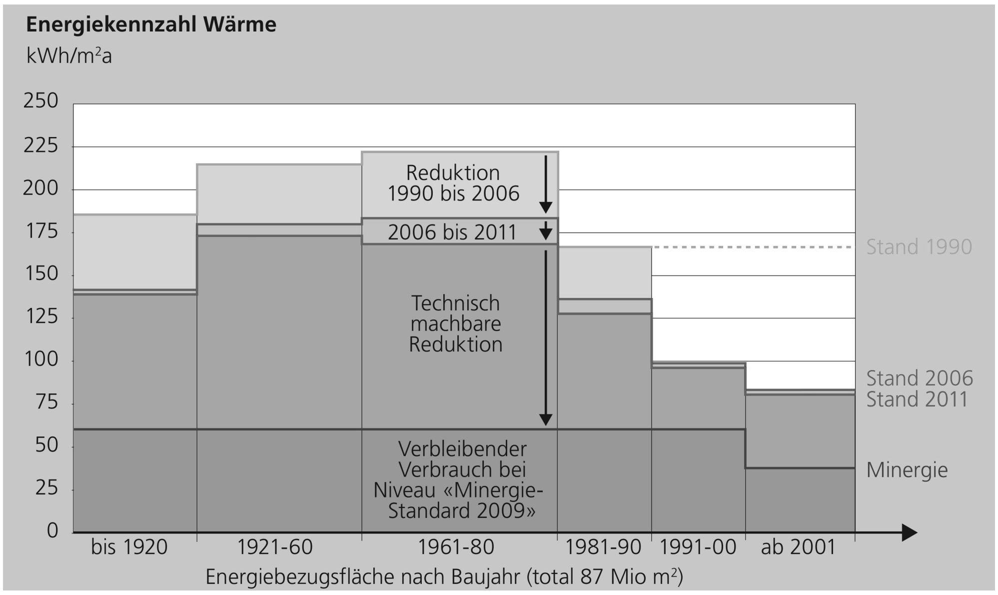

Figure 3.20: Four Year Averaged Mean Energy Index of Residential Buildings in the Canton of Zurich [24]

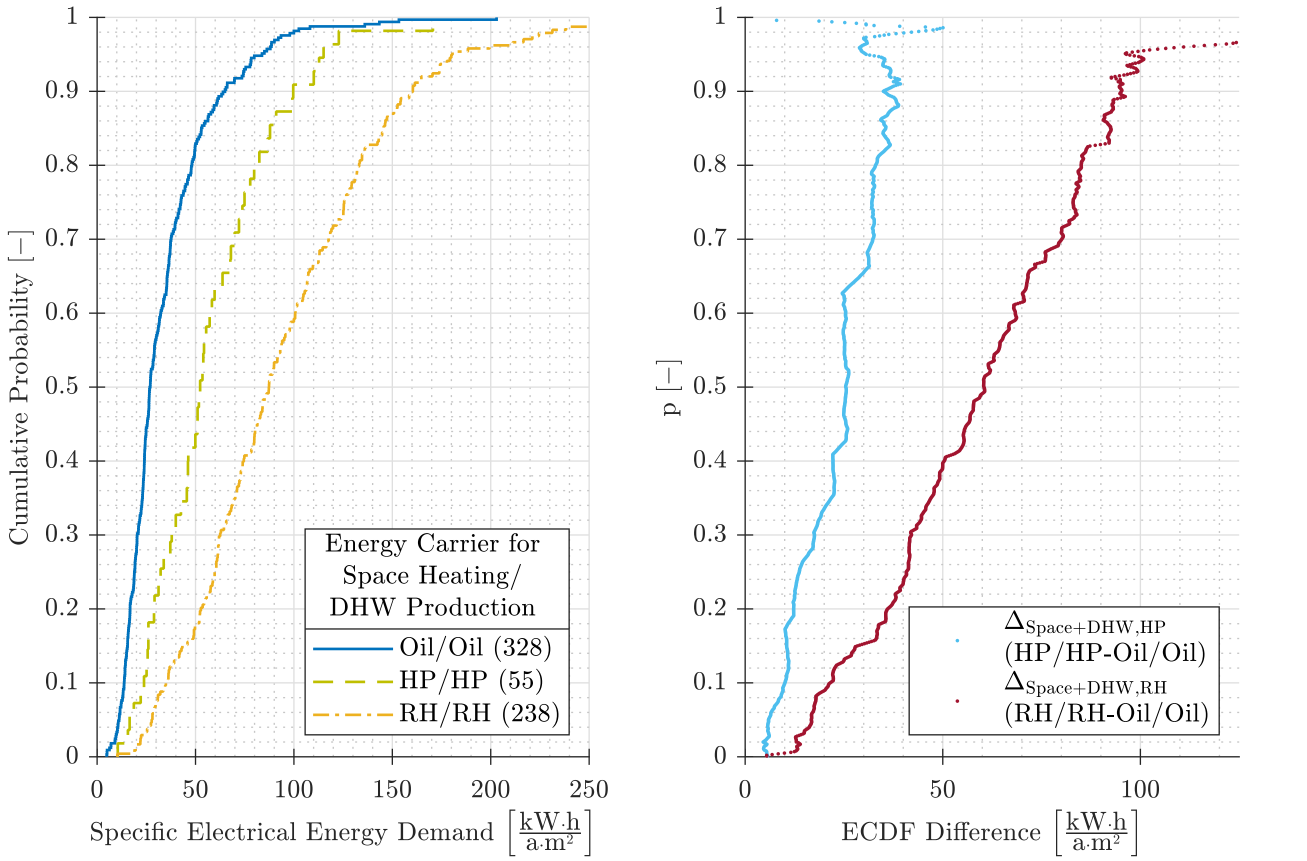

Figure 3.21: Left: ECDFs representing Specific Electrical Energy Demands for Oil/Oil, HP/HP and RH/RH SFHs, Right: The corresponding Differences $\Delta_{\text{Space+DHW,HP}}$ and $\Delta_{\text{Space+DHW,RH}}$, Data set Wohlen[B]

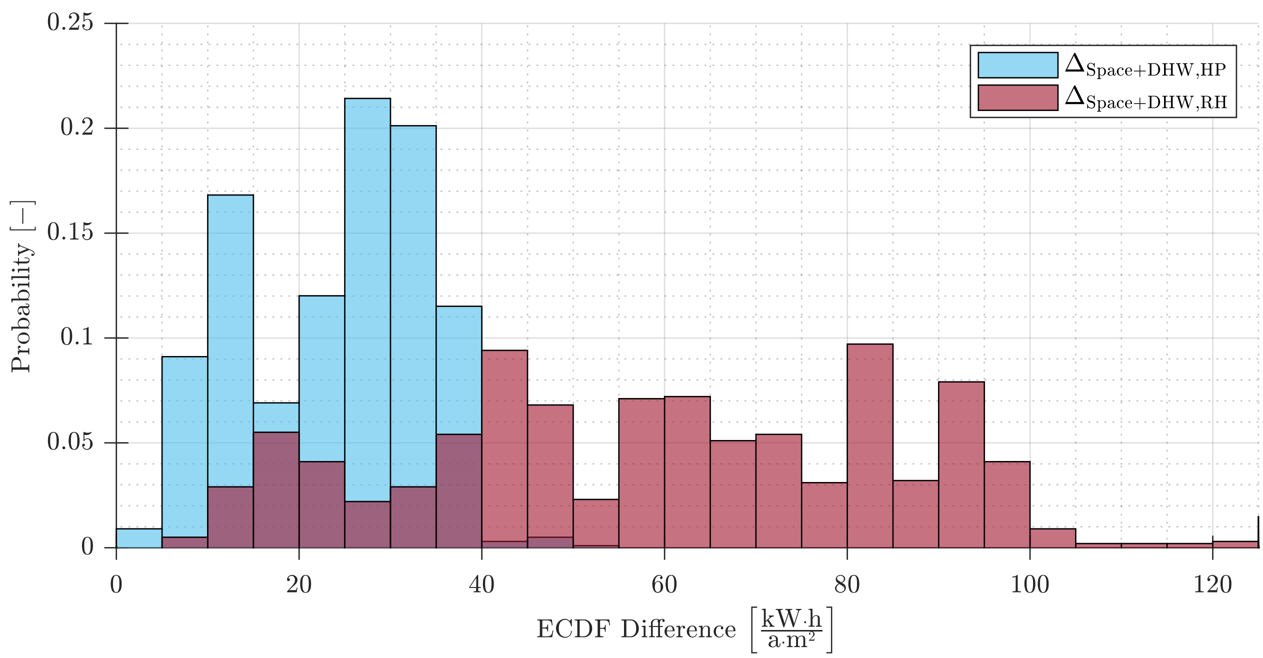

Figure 3.22: Histograms of $\Delta_{\text{Space+DHW,RH}}$ and $\Delta_{\text{Space+DHW,HP}}$[4]

[4]Note that the scale of the vertical axis differs from the histogram in Figure 3.19 since it depends on the bin width.

3.8 SCOP based on Contributions from total Heat Demands for Single-Family Homes

The COP of a heat pump is determined by the ratio of amount of the useful heat generated to the electricity consumed.

Recall that since resistance heaters have a thermal efficiency of 100 percent, it was assumed that the useful heat generated by the heat pumps can be represented as the electric energy demanded to heat space and produce DHW with resistance heaters $\Delta_{\text{Space+DHW,RH}}$. Moreover, the ECDF $\Delta_{\text{Space+DHW,HP}}$ represents the specific electrical energy demand for space heating and DHW production with heat pumps.

The ratio of these ECDF differences, i.e., the ratio of the heat demands to the electrical energy demands for heat pumps, represents the SCOP. Since the ECDF are on a yearly basis, the result corresponds to the distribution of the *Seasonal* COP.

$$\Theta_{\text{SCOP}} = \frac{\Delta_{\text{Space+DHW,RH}}}{\Delta_{\text{Space+DHW,HP}}} \tag{3.4}$$

The distribution of Θ_{SCOP} depends linearly on $\Delta_{\text{Space+DHW,RH}}$ and inverse proportionally on $\Delta_{\text{Space+DHW,HP}}$. The outcome is shown in Figure 3.23. The horizontal axes represents the probability p used to compute the ECDF differences, while the vertical axis represents the values of Θ_{SCOP}.

The points in a range between a probability of 0 and approximately 0.03 and between approximately 0.95 and 1 can be explained by outliers in the SFH subgroups which were used to compute $\Delta_{\text{Space+DHW,RH}}$ and $\Delta_{\text{Space+DHW,HP}}$.

The histogram in Figure 3.24 represents the distribution of the Θ_{SCOP}. The highest probability for Θ_{SCOP} is mainly within a range of approximately 2 and 3.5. In Table 3.10 the means and proportions of the two components from the fitted Gaussian mixture model object are listed.

Table 3.10: Components of Gaussian mixture model fitted to Θ_{SCOP}

	Mean [−]	Mixing proportion [−]
Component 1	2.54	0.965
Component 2	3.65	0.035

To check the plausibility of the two components from the Gaussian mixture model of Θ_{SCOP}, the components were compared with the "reference values" in *Feldanalyse von Wärmepumpenanlagen FAWA 1996-2003 report* [3] The SFOE investigated the performance of heat pumps as part of a long-term project and shared the results within this report.
The report contains the distribution of the cliatmate-standardized annual nJAZ (nJAZ 2, klimanormierte Jahresarbeitszahlen, see also Definitions) of 221 heat pumps installed in Swiss buildings. The values were obtained via measurements. The distributions are graphically represented and organized according to the heat pump source (air- and ground-source).
Recall that the the SCOP is calculated as the ratio of the electricity used for heating with resistance heaters to the electricity used for heating with heat pumps. Hence, it is important to note, that the obtained SCOP distribution considers also the losses in the heat pump system components such as hot water storages which are not installed in resistance heater systems. Thus, it is not critical to compare the distribution of SCOP with the nJAZ 2 distributions which takes thermal losses in the thermal storages as well into account. The corresponding graphs are represented in Figure 3.25. The vertical axes in these graphs represent the frequency, while the horizontal axes represents nJAZ 2.
The averages and standard deviations of the nJAZs 2 distributions of the air/water and brine/water heat pumps analysed within the FAWA report [3] are listed in Table 3.11.

Table 3.11: Descriptive Statistics for Air/Water and Brine/Water Heat Pumps from the FAWA report [3]

	Mean [−]	Standard Deviation [−]
nJAZ 2 Air/Water Heat Pumps	2.6	0.4
nJAZ 2 Sole/Water Heat Pumps	3.4	0.7

The mean of component 1 from the Gaussian mixture model of Θ_{SCOP} is very similar to the mean of air-source heat pump in the FAWA report, while the mean of Component 2 is very similar to the mean of ground-source heat pump in the FAWA report. The mixing proportions indicate that only 4 percent of the heat pumps in HP/HP SFHs contained in the data set Wohlen valorise heat from the ground, while 96 percent valorise the heat from the ambient air. Since the heat sources of heat pumps in the data set Wohlen is missing and other sources of information about the percentage of heat pump types in Wohlen are missing, this outcome could not be compared. However, according to the Fachvereinigung Wärmepumpen Schweiz (FWS), the majority of the number of heat pumps sold between 2010 and 2017 are air-source heat pumps [15].

In Section 3.6, it was stated that, based on a comparison with existing studies, the ECDF difference $\Delta_{\text{Space+DHW,RH}}$ seems to low. Therefore. the Θ_{SCOP} needs to be interpreted with caution. If $\Delta_{\text{Space+DHW,RH}}$ were be bigger, the distribution of the Θ_{SCOP} would be shifted to the right in Figure 3.24. Another note of caution is due here, since the possibility was not considered that SFHs exist which have heat pumps installed which have different heat sources.

However, this finding, while preliminary, confirms the view that the electrical energy demands for heating space and DHW with resistance heaters and heat pumps extracted from the SFHs in the data set Wohlen$^{\text{B}}$ are plausible. That is, the obtained ECDF differences led to a plausible SCOP distribution.

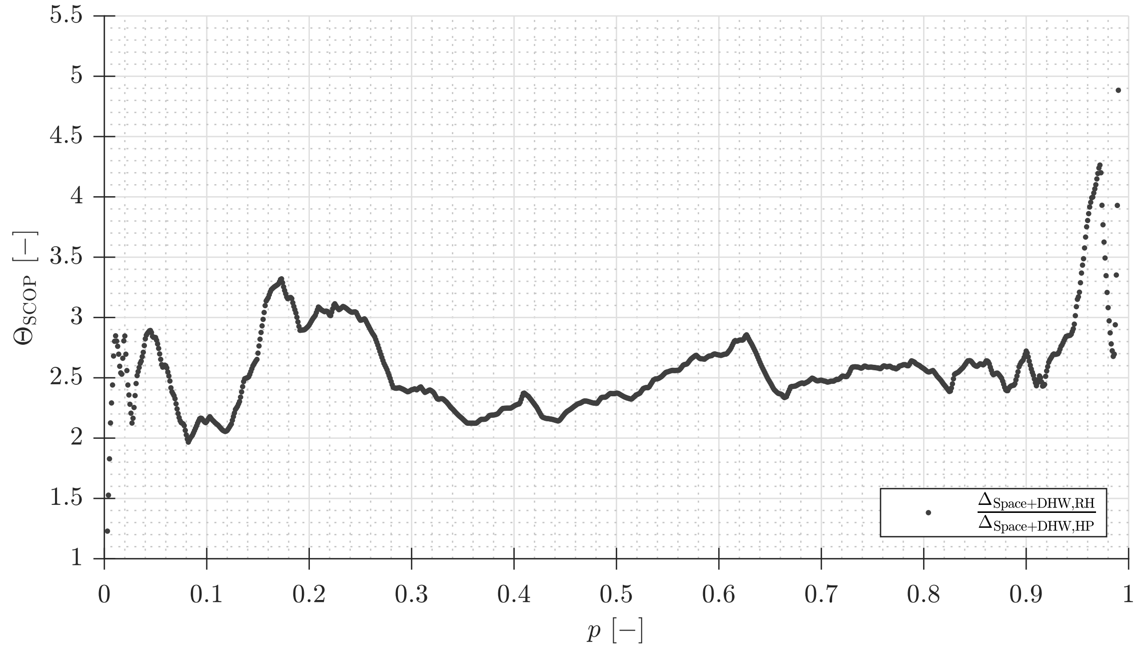

Figure 3.23: Points representing Θ_{SCOP}

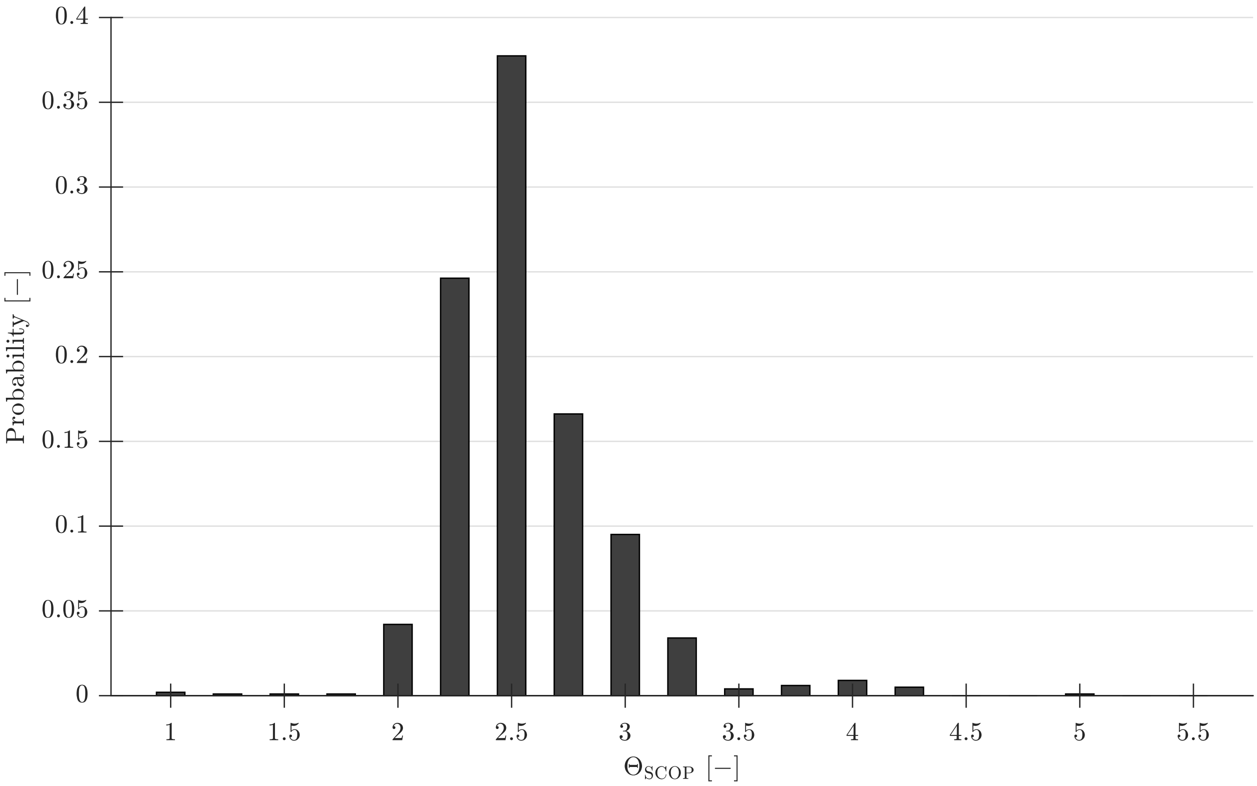

Figure 3.24: Histogram representing the distribution of Θ_{SCOP} [5]

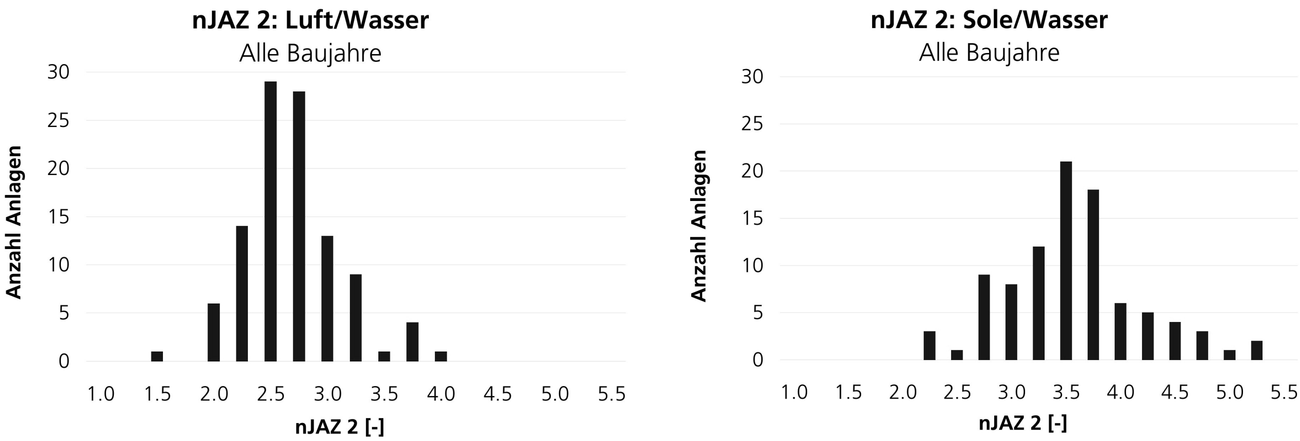

Figure 3.25: Left: Frequencies of nJAZ 2 of Air/Water Heat Pumps analysed. Right: Frequencies of nJAZ 2 of Brine/Water Heat Pumps, both Diagrams are adobted from the FAWA. [3]

[5]Note that the layout and bar width of this histogram were adapted to the layout of the histograms in the FAWA report (Figure 3.25) in order to enable a better comparison.

4 Conclusion

Within this thesis two independent data sets were analysed. A new approach for dividing the distributions of the overall specific electrical energy demands into shares for appliances, space heating and DHW production was developed and validated. The inputs for this method were the specific electrical energy demands for SFHs with different main energy carriers for space heating and DHW production.
Thereby, a metric was defined to calculate the ECDF differences and their ratios. As distributions instead of single buildings were compared, the new approach takes influences, such as user behaviour, into account.

The outcomes of the method were compared with values from existing surveys for the electricity consumption in typical households as well as with standard values for the DHW demand. Furthermore, the distributions of the electrical energy demand and specific electrical energy demand were explained with descriptive statistics such as means, and so forth, and exploitative statistics, such as box plots. Additionally, the age-related segmentation of the buildings in both data sets were analysed and visualized with bar graphs.

The extracted heat demands (ECDF differences) for space heating and DHW production are lower than the standard values. Possible explanations may be the potentially different measurement periods or that the share for appliances in RH/Oil SFHs is slightly lower than the specific electrical energy demand for Oil/Oil SFHs (represents share for appliances). A possible improvement is that the assumption that the specific electrical energy demand of Oil/Oil SFHs is equal to the demand for appliances for other subgroups (e.g., Oil/RH SFHs) should be extended with correction factors.

The ratio of the specific electrical energy demand for space heating and DHW production with resistance heating to the specific electrical energy demand for space heating and DHW production with heat pumps, i.e., the distribution of the SCOP were computed. The outcomes were compared with nJAZ 2 obtained with measurements of the electrical input and thermal output of various heat pumps installed in Swiss buildings. The comparison of the distributions showed promising results.

However, further work is required to develop, based on this work, a comprehensive analytical method. The new approach seems to be promising for computing the shares of the specific electricity demand for large data sets. Applying the method on bigger data sets is necessary in order to obtain more accurate results. For example, a subdivision of the subgroups would enable to analyse the extracted multi-modal distributions within this thesis.

Since big data sets of the yearly electrical energy demands exist, the author recommends a further development of the method as soon as new data sets are available to researchers. Potential future development of the method could include the computation of the specific electrical energy demands with respect to the hull surface (as this is one of the main drivers for space heating demand) or number of inhabitants (as this is one of the main drivers for DHW demand).

A possible challenge is that the distributions of the heat demand for space heating and/or DHW production were calculated by use of the distribution of buildings using resistance heaters for space heating and/or DHW production. The trend was observed that almost no new buildings are built with resistance heaters which can be explained with prospective changes of the legal requirements. Therefore, a computation based on the RH/RH buildings could be challenging in the future.

However, possible application fields of a further-developed method are:

- to calculate the shares for different subgroups with the same energy carrier combination, for example grouped by the year built or number of inhabitants, which could enable a comparison of different shares for the same energy carrier combination. This would enable a statement about the energy shares in buildings built in different building periods.
- to analyse the shares between different measuring periods in the same buildings. Doing so would enable to analyse the effect of the measuring period to the shares. Furthermore, this may enable to make statements about the impact to the shares of higher annual temperatures (due to global warming).
- to subdivide the buildings with heat pumps grouped by the source heat or year built/renovation year. This would enable the assessment of different distributions of the SCOP without costly measurements being necessary.
- to analyse the total yearly electrical energy demand shares over several years. This would allow to analyse, for example, the electrical energy demand for DHW production prior and after an electric boiler replacement or prior and after the installation of a heat pump system.

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Finally, I wish to thank my parents for their support and encouragement throughout my studies.

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6 Appendix

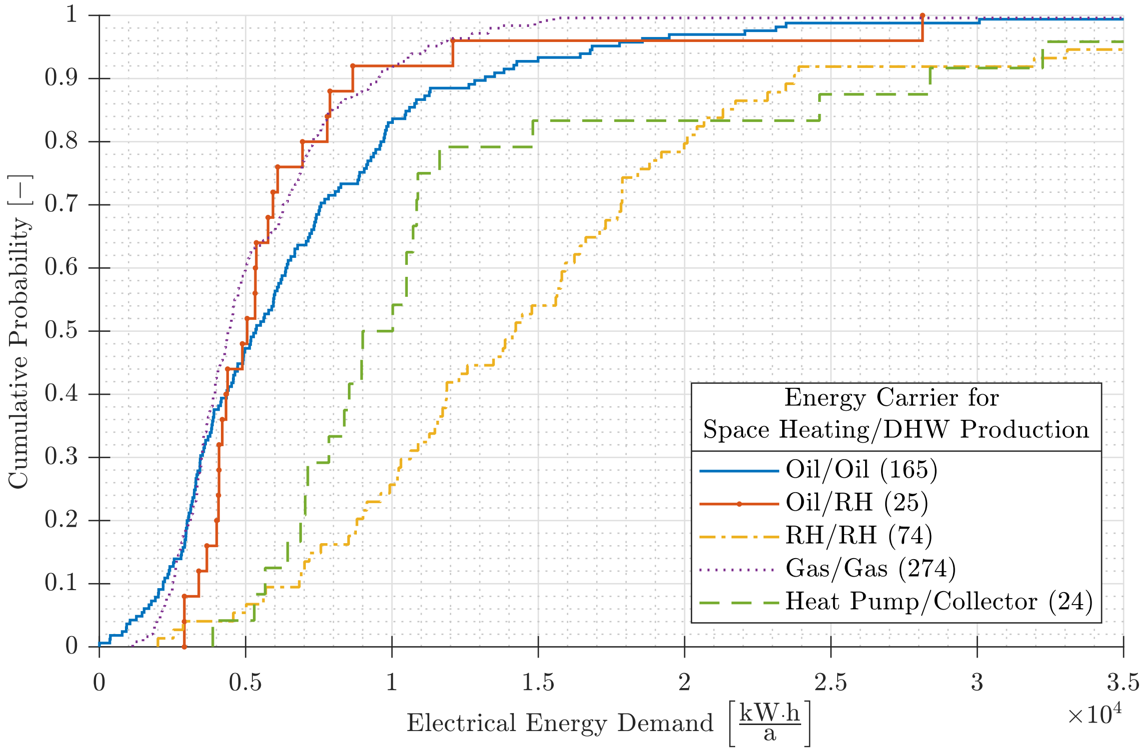

Figure A1: ECDFs representing Electrical Energy Demand for SFHs, Data set Wohlen

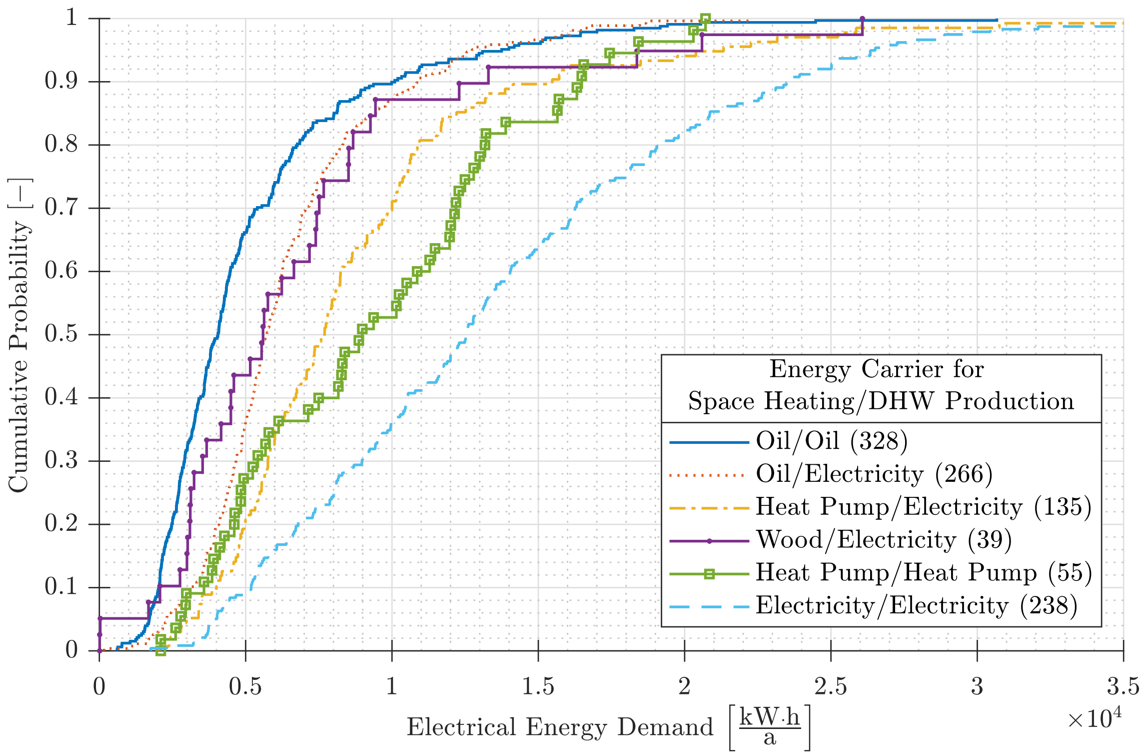

Figure A2: ECDFs representing Electrical Energy Demand for SFHs, Data set Wohlen

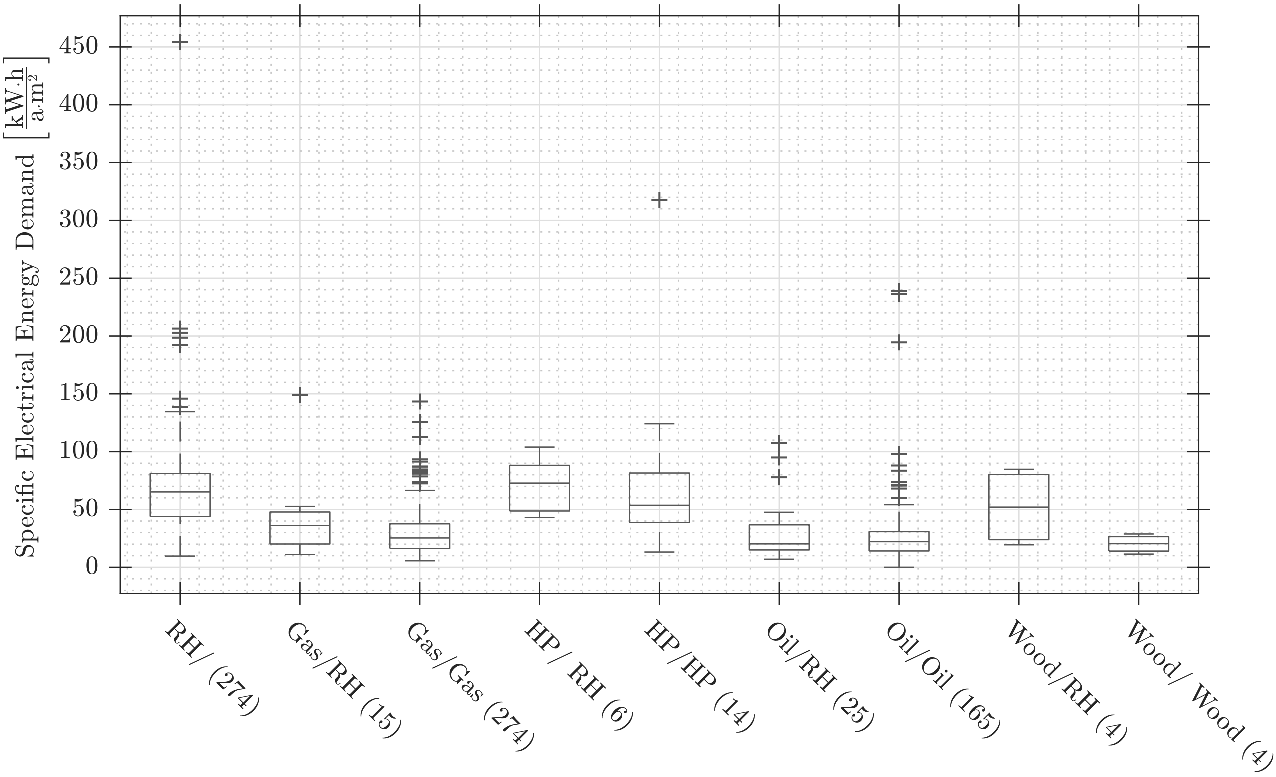

Figure A3: Box plots representing Electrical Energy Demand for SFHs, Data set Rolle

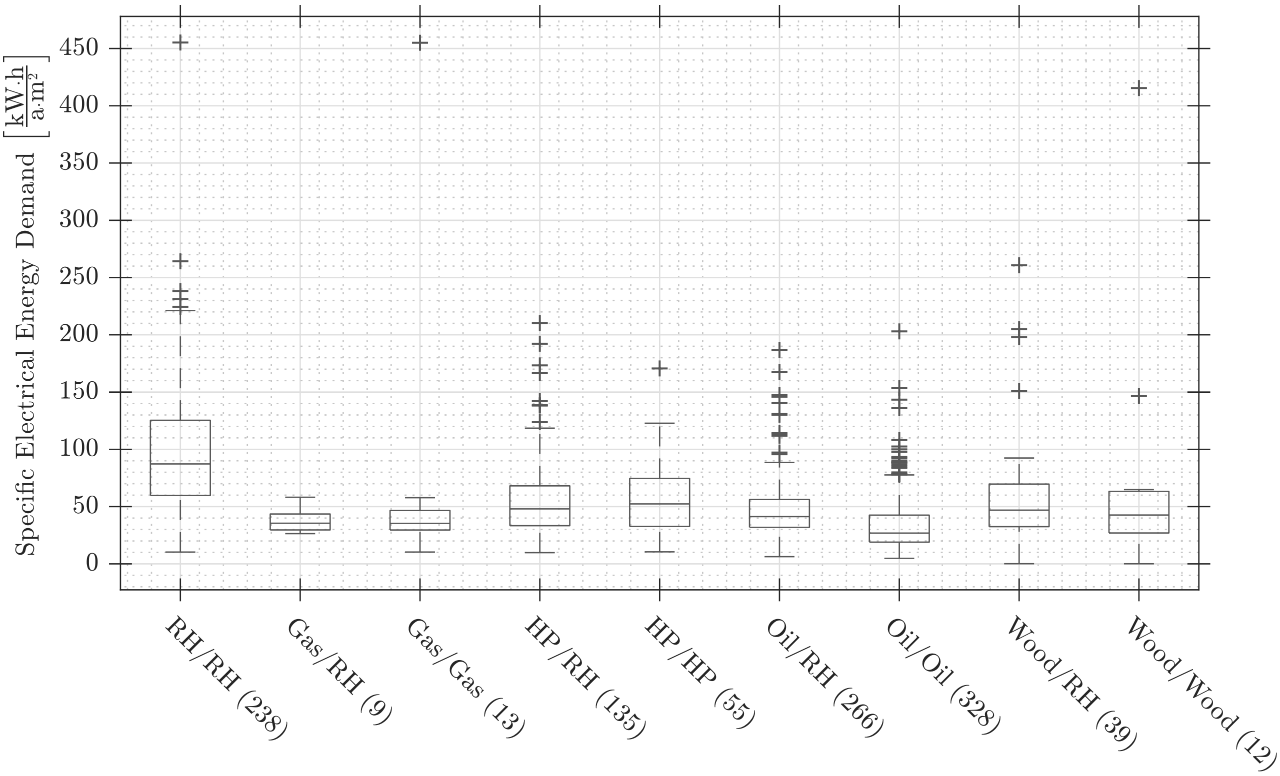

Figure A4: Box plots representing Electrical Energy Demand for SFHs, Data set Wohlen[B]

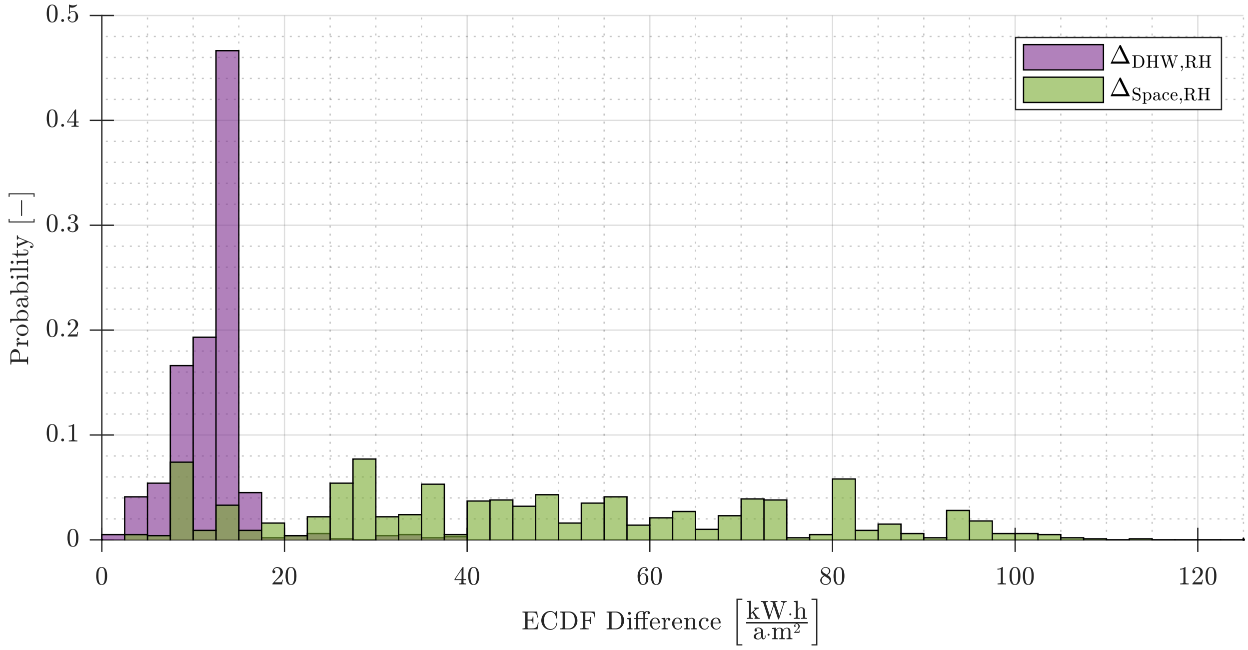

Figure A5: Histograms of $\Delta_{\mathrm{DHW,RH}}$ and $\Delta_{\mathrm{Space,RH}}$ (bind width 2.5 $\frac{\mathrm{kW \cdot h}}{\mathrm{a \cdot m^2}}$)

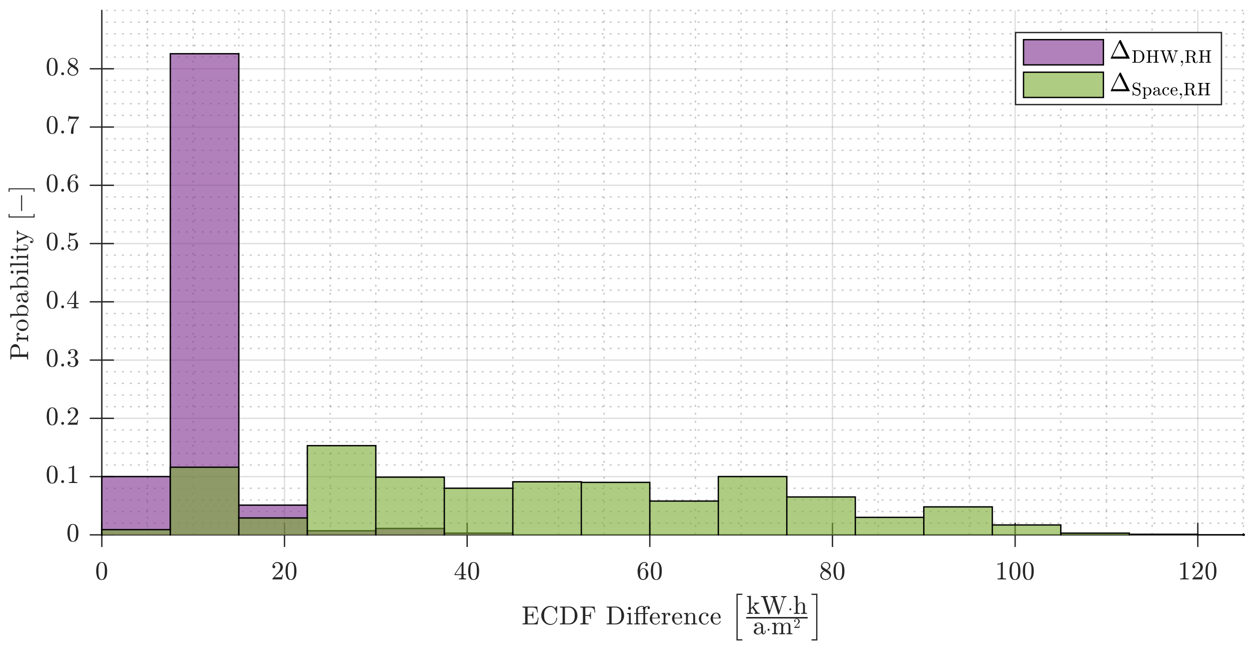

Figure A6: Histograms of $\Delta_{\mathrm{DHW,RH}}$ and $\Delta_{\mathrm{Space,RH}}$ (bind width 7.5 $\frac{\mathrm{kW \cdot h}}{\mathrm{a \cdot m^2}}$)

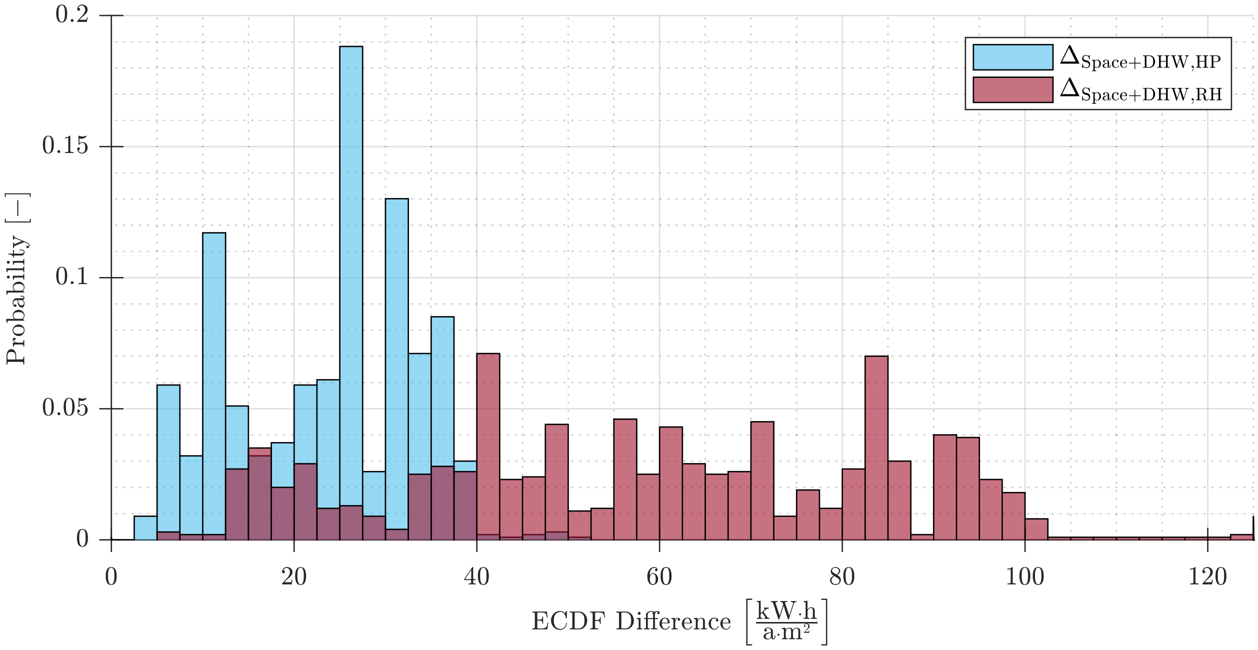

Figure A7: Histograms of $\Delta_{\mathrm{Space+DHW,HP}}$ and $\Delta_{\mathrm{Space+DHW,RH}}$ (bind width 2.5 $\frac{\mathrm{kW \cdot h}}{\mathrm{a \cdot m^2}}$)

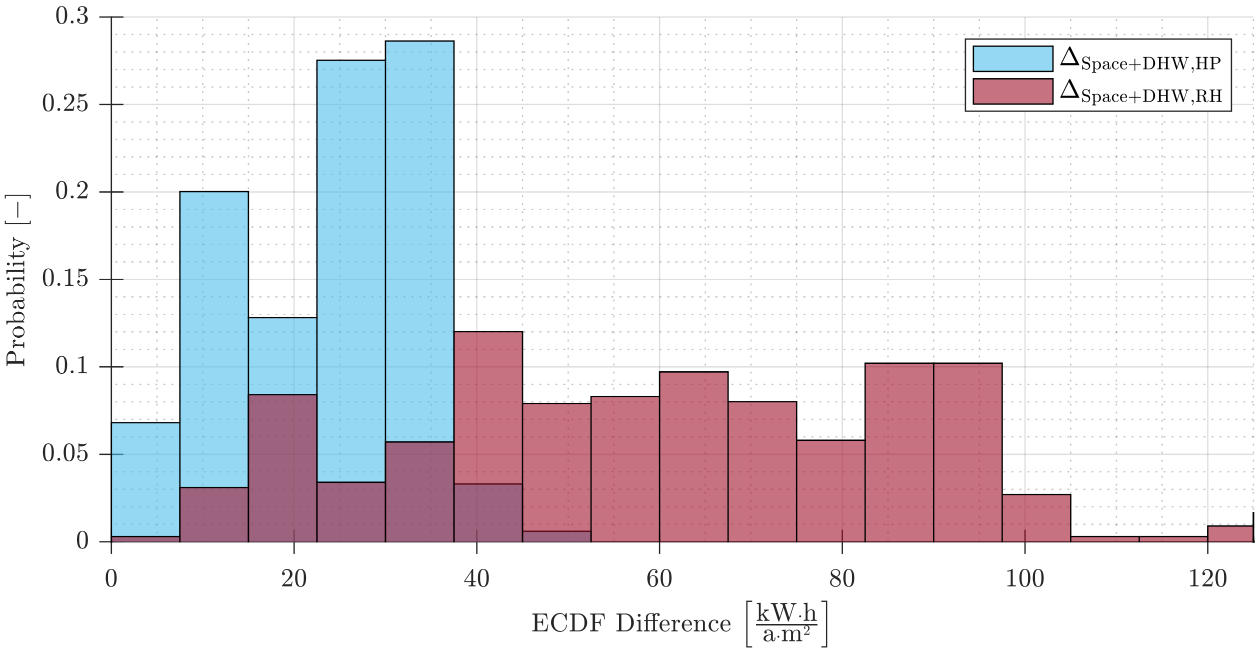

Figure A8: Histograms of $\Delta_{\mathrm{Space+DHW,HP}}$ and $\Delta_{\mathrm{Space+DHW,RH}}$ (bind width 7.5 $\frac{\mathrm{kW \cdot h}}{\mathrm{a \cdot m^2}}$)

Datengerüst

Schritt 1: Werte nach Personenzahl (MFH/EFH, ohne elektrisch Warmwasser, ohne Gaskochen

Die vorab gefilterten Daten wurden, getrennt nach MFH/EFH, jeweils nach Personenzahl analysiert (auch nach Zimmerzahl wurde analysiert, diese ist jedoch für den Elektrizitätsverbrauch weniger relevant als die Personenzahl). Weil die so erhaltenen Auswahlen z.T. nur noch relativ kleine Anzahlen enthalten und diese in einigen Fällen unplausible Abweichungen zeigten, wurden mittels Regression (kleine) Korrekturen bestimmt, um konsistente Werte zu erhalten. Die Figuren 4 und 5 zeigen Beispiele dieses Vorgehensschrittes. Die lineare Regression zeigt unplausible Werte bei 5- und 6+ Personen-Wohnungen bzw. 6+ Personen-EFH. Um diese für das Datengerüst zu korrigieren, wurden die Werte „Fkt." als Modifikation der Regressionsfunktion berechnet.

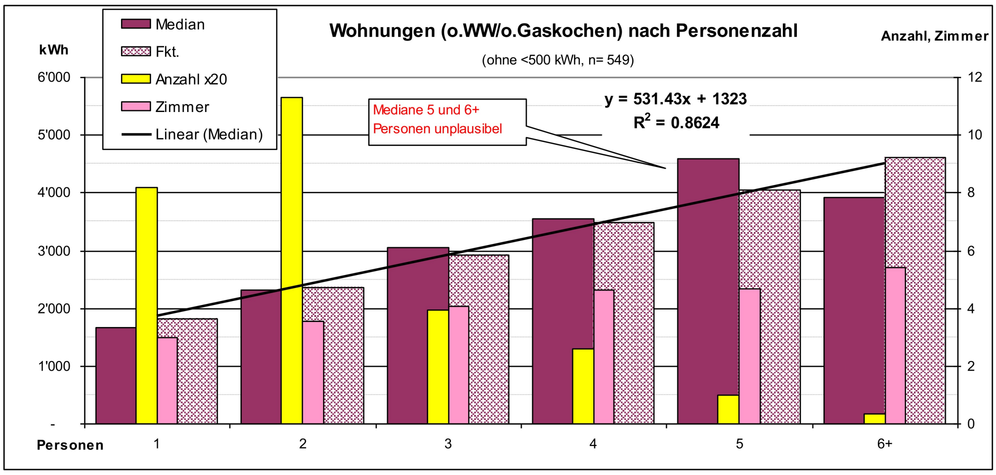

Fig. 4 Elektrizitätsverbrauch von MFH-Wohnungen (ohne elektrisch Warmwasser, ohne Gaskochen), Medianwerte nach Personenzahl aus VSE-Erhebungsdaten. „Fkt." zeigt die mit Hilfe der Regression korrigierten Werte. „Anzahl" (gelb) ist die Anzahl Objekte pro Klasse.

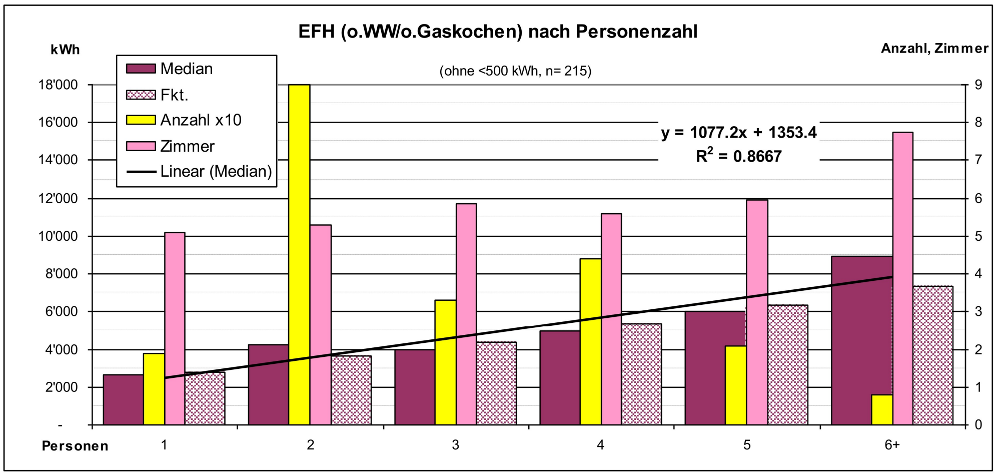

Fig. 5 Elektrizitätsverbrauch von EFH (ohne elektrisch Warmwasser, ohne Gaskochen), Medianwerte nach Personenzahl aus VSE-Erhebungsdaten. „Fkt." zeigt die mit Hilfe der Regression korrigierten Werte. „Anzahl" (gelb) ist die Anzahl Objekte pro Klasse.

Die Ergebnisse dieser Auswertungen und Korrekturen sind in Fig. 10 und Tabelle 2 im Ergebnisteil

Figure A9: Extract from Page of from *Typischer Haushalt-Stromverbrauch* report [11]

In der detaillierten Darstellung der Aufteilung nach Anwendungen (Tabelle 4) wird – anders als in der stark vereinfachten Darstellung von 2007 – berücksichtigt, dass der Stromverbrauch von Geräten und Einrichtungen nicht linear von der Personenzahl abhängt, sondern dass der Typ des Haushalts, insbesondere auch ob MFH-Wohnung oder EFH, ebenfalls eine Rolle spielt. Bei den meisten Anwendungen ist auch zu beachten, dass es einen „Sockelverbrauch“ gibt und dann der Mehrverbrauch für die zweite, dritte usw. Person viel kleiner als der Sockel ist. Bei einigen Anwendungen sind die Unterschiede nicht eigentlich personenabhängig, sondern durch grössere Geräte beim grösseren Haushalt bedingt (Kühl- und Gefriergeräte). Die Werte wurden z.T. auch gerundet und etwas angepasst, um das Zahlengerüst mit der Personen-Abstufung möglichst konsistent zu machen.

	Wohnung in MFH			Einfamilienhaus		
Gerätekategorie	2 Personen	pro zusätzliche Person	4 Personen	2 Personen	pro zusätzliche Person	4 Personen
Kochen/Backen inkl. Spezialgeräte, z.B. Kaffeemaschine	300	80	460	300	80	460
Geschirrspüler	250	25	300	250	25	300
Kühlschrank mit oder ohne Gefrierteil	275	40	355	325	60	445
Separates Gefriergerät	275	25	325	350	25	400
Beleuchtung	350	90	530	450	125	700
Unterhaltungselektronik (TV, Video, HiFi, div. Player etc.)	250	60	370	275	80	435
Heimbüro (PC, Drucker, Modem, Komforttelefon etc.)	200	60	320	200	80	360
Div. Pflege- und Kleingeräte inkl. Luftbefeuchter	250	45	340	325	60	445
Waschmaschine	225	65	355	250	78	405
Wäschetrocknen (ca. 2/3 der Wäsche mit Tumbler)	250	85	420	275	88	450
Allgemein (Haustechnik)	400			900	150 *	1200 *
Total	3025	575	3775	3900	850	5600
Total ohne sep. Gefriergerät	**2750**	**550**	**3450**	**3550**	**825**	**5200**

Tab. 4 Typischer Haushaltstromverbrauch nach Anwendungen, in kWh/Jahr
Bei den blau hervorgehobenen Anwendungen kein Unterschied MFH/EFH
* Mehrverbrauch Gebäudetechnik EFH 3 und 4 Personen: grösseres Haus angenommen.

Korrekturen nach Besonderheiten des Haushalts

Wer einen genaueren Vergleich machen möchte, vor allem wenn der Haushalt deutlich von der Standard-Geräteausstattung oder bezüglich Zimmerzahl oder Fläche abweicht, kann mit den folgenden Korrekturansätzen die Abweichungen erklären bzw. es kann ein angepasster Vergleichswert berechnet werden.

Elektrische Wassererwärmung
Die typischen Verbrauchswerte von Elektroboilern bleiben gegenüber der Studie 2007 unverändert (aber der Basiswert für 1 Person ist angegeben); sie werden jedoch differenziert nach MFH/EFH und um Werte für die Wassererwärmung mit Wärmepumpenboiler (nur im EFH einsetzbar) ergänzt. Weil im EFH die Wassererwärmung i.d.R. im Keller ist, ergeben sich grössere Verluste und damit etwas höhere Verbrauchswerte für den Elektroboiler. Auch Haushalte mit Wärmepumpenboiler konnten ausgewertet werden. Die Werte von Tabelle 5 werden von den Erhebungsdaten 2011 gestützt.

Figure A10: Extract from Page 17 of *Typischer Haushalt-Stromverbrauch* report [11]

	MFH-Wohnung, **1 Person**	EFH, 1 Person	Pro zusätzliche Person (MFH & EFH)
Elektroboiler (Elektro-Wassererwärmer)	1200	1400	800
Wärmepumpenboiler (EFH)	-	450	260

Tab. 5 Zusätzlicher Stromverbrauch mit elektrischer Wassererwärmung (kWh/Jahr)

Zimmerzahl
Wenn die effektive Zimmerzahl deutlich, d.h. mehr als 1, vom Bereich der „typischen Zimmerzahl" gemäss Tabelle 2 abweicht, oder wenn die Räume ungewöhnlich gross (oder klein) sind, kann die folgende Korrektur zu einem besseren Vergleichswert führen. Mehr- bzw. Minderverbrauch ergeben sich vor allem bei Beleuchtung und Unterhaltungselektronik (Standby!) sowie im EFH durch die Gebäudetechnik.

- Weniger Zimmer und/oder kleine Flächen: Basiswert um 5 bis 10% reduzieren
- Mehr Zimmer und/oder grosse Flächen: Basiswert um 5 bis 10% erhöhen.

Kochen und Backen

- Wenn besonders intensiv gekocht und oft gebacken wird und wenig auswärts warm gegessen wird, kann dies den Basiswert um 50 bis 100 kWh pro Person erhöhen.
- Umgekehrt ist bei wenig intensivem Gebrauch von Kochherd und Backofen und häufigem Auswärts-Essen eine Reduktion des Basiswerts um 50 bis 75 kWh pro Person möglich.

Effiziente Lampen
Die Basiswerte gelten für einen Anteil an effizienten Lampen von etwa 40 bis 50% (Stromsparlampen, LED, Leuchtstoffröhren). Achtung: Halogen- oder „Eco-Halogen"-Lampen sind nicht effizient!

	Korrektur MFH-Wohnung 2 Personen	Korrektur EFH 2 Personen	Pro zusätzliche Person (MFH, EFH)
Mehr als 80% effiziente Lampen	- 200	- 275	- 55
Weniger als 20% effiziente Lampen	+ 200	+ 275	+ 55

Tab. 6 Abweichungen/Korrekturen für effiziente Beleuchtung (kWh/Jahr, bezüglich Basiswerten)

Wäschetrocknen an der Sonne oder mit Wärmepumpentrocknern
Wenn kein Wäschetrockner benutzt wird, gilt als Vergleichswert ein reduzierter Basiswert. Da der **Energieverbrauch** fürs Wäschetrocknen gut die Hälfte des Verbrauch „Waschen + Trocknen" ausmacht, ist die Hälfte des Werts „ggf. ohne Waschen + Trocknen" von Tabelle 2 vom Basiswert abzuziehen.
Beispiel MFH-Wohnung, 2 Personen: 2750 – (475/2) = 2512,5 kWh
Wenn ein neuer Tumbler der Effizienzklasse A (mit Wärmepumpe) oder ein Raumluft-Wäschetrocknerbenutzt wird (Stromverbrauch ca. 50% von B/C-Tumblern), ist die Hälfte dieser Korrektur einzusetzen.
Beispiel MFH-Wohnung, 2 Personen: 2750 –(475/4) = 2631 kWh

Waschmaschine und/oder Geschirrspüler an Warmwasser angeschlossen
Da der grösste Teil der Energie für das Waschen wie auch für Geschirrspüler zum Aufheizen des Wasch-/Spülwassers verwendet wird, bedeutet der Warmwasseranschluss eine wesentliche Stromeinsparung. Dementsprechend ist der Vergleichswert gegenüber dem Basiswert zu reduzieren.
Waschmaschine mit Warmwasseranschluss (spezielle Modelle, vgl. Topten.ch):
Ein Viertel des Werts „ggf. ohne Waschen + Trocknen" von Tabelle 2 ist vom Basiswert abzuziehen.
Beispiel MFH-Wohnung, 2 Personen: 2750 – (475/4) = 2631 kWh
Geschirrspüler an Warmwasser angeschlossen:
Die Hälfte des Werts „ggf. ohne Geschirrspüler" von Tabelle 2 ist vom Basiswert abzuziehen.
Beispiel MFH-Wohnung, 2 Personen: 2750 – (250/2) = 2655 kWh

Figure A11: Extract from Page 18 of *Typischer Haushalt-Stromverbrauch* report [11] verkaufter Wasserkraft nicht enthalten ist. Durch den Abzug der in der Schweiz produzierten zertifizierten Wasserkraft kommt es vor allem zu einer Erhöhung der Anteile von Strom aus schweizerischen Kernkraftwerken (29.6 %) und von Stromimporten (36.0 %).

In Tab-Z. 1 ist eine Übersicht der Umweltkennwerte der Schweizer Strommixe für das Jahr 2014 präsentiert.

Tab-Z. 1 Umweltkennwerte der Schweizer Strommixe 2014

Indikator	**Einheit**	**Produktions-Strommix**	**Lieferanten-Strommix**	**Stromprodukt aus erneuerbaren Energien**	**Verbraucher-Strommix**
Treibhausgas-Emissionen	g CO_2-eq/kWh	29.8	149.4	13.0	181.5
Primärenergiebedarf, nicht erneuerbar	MJ/kWh	6.1	6.8	0.1	8.4
Primärenergiebedarf, erneuerbar	MJ/kWh	2.4	2.3	4.2	1.9
Gesamtumweltbelastung	UBP/kWh	214	299	46	359

Die Treibhausgasemissionen des Stroms betragen 13.0 g CO_2-eq/kWh (9.0 g CO_2/kWh) für das durchschnittliche Schweizer Stromprodukt aus erneuerbaren Energien und 29.8 g CO_2-eq/kWh (23.6 g CO_2/kWh) für den Schweizer Produktions-Strommix. Die Treibhausgasemissionen des Schweizer Lieferanten- und des Verbraucher-Strommixes sind mit 149.4 g CO_2-eq/kWh (138.5 g CO_2/kWh) und 181.5 g CO_2 - eq/kWh (169.0 g CO_2/kWh) deutlich höher. Die erhöhten Treibhausgasemissionen stammen hauptsächlich aus dem Import von Strom unbekannter Herkunft über den Stromhandel, zu einem geringen Teil auch aus dem bekannten Import von Strom aus fossil-thermischen Kraftwerken. Da der Anteil von Strom unbekannter Herkunft gegenüber 2011 deutlich zugenommen hat und zudem dieser Strom neu mit dem der Realität deutlich besser entsprechenden europäischen Residualmix modelliert wird, sind die spezifischen Treibhausgasemissionen des Lieferanten- und des Verbraucher-Strommixes 2014 gegenüber denjenigen der Strommixe 2011 um 63 % beziehungsweise über 79 % höher.

Der nicht erneuerbare Primärenergiebedarf des Produktions-, Lieferanten- und des Verbraucher-Strommixes liegt bei 6.1, 6.8 und 8.4 MJ/kWh. Das durchschnittliche Schweizer Stromprodukt aus erneuerbaren Energien weist einen deutlich tieferen nicht erneuerbaren Primärenergiebedarf von 0.1 MJ/kWh auf. Der nicht erneuerbare Primärenergiebedarf des Produktions-, Lieferanten- und Verbraucher-Strommixes ist vor allem auf den Strom aus Kernkraftwerken zurückzuführen. Auch die Stromimporte aus nicht überprüfbaren Energieträgern tragen zum erhöhten nicht erneuerbaren Primärenergiebedarf des Lieferanten- und des Verbraucher-Strommixes bei. Der tiefe nicht erneuerbare Primärenergiebedarf des durchschnittlichen Schweizer Stromprodukts aus erneuerbaren Energien ist mehrheitlich im geringen spezifischen nicht erneuerbaren Primärenergiebedarf von Strom aus Wasserkraft und anderen erneuerbaren Energien begründet.

Der erneuerbare Primärenergiebedarf des durchschnittlichen Schweizer Stromprodukts aus erneuerbaren Energien ist mit 4.2 MJ/kWh knapp doppelt so hoch wie der

Figure A12: Extract from *Umweltbilanz Strommix Schweiz 2014* report [23]