**Carl von Ossietzky Universität Oldenburg**

**Institute of Physics**

**Sustainable Renewable Energy Technologies (SuRE)**

**MASTER THESIS**

Title:

# Development Paths for Decentralized Energy Systems in the Context of the Energy Transition – Identification of Interdependencies and Technology Lock-Ins

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| Presented by: | Carlos Eduardo Munoz Robinson |
| First examiner: | Dr. Patrik Schönfeldt |
| Second examiner: | Prof. Dr. Carsten Agert |
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*Dedicated to my family and friends, who always supported me despite challenges that I faced*

# *Abstract*

## Development Paths for Decentralized Energy Systems in the Context of the Energy Transition – Identification of Interdependencies and Technology Lock-Ins

Multiple advantages have been identified when transitioning from a centralized energy system to a decentralized energy system (DES). Nevertheless, in the case of residential DES, there is a research gap on the quantitative analysis of the effect of multiple factors in the decision-making process for the selection of technologies within residential DES. This thesis aimed to investigate the likelihood and viability of different development paths for residential DES in different contexts and frame conditions. A single-family house with an initial gas boiler and other starting conditions was proposed. Boundary conditions related to electricity and gas prices, as well as the status of the gas boiler and incentives for technologies, were also defined. An energy system model that sized the technologies needed to supply the electricity and heat demands from 2022 until 2030 was proposed. The open source framework oemof.solph, which relied on investment optimization, was employed. Four scenarios with combinations of two incentives: heat pump subsidy and PV feed-in were defined. Results shown that the incentives had a strong effect on the penetration of a heat pump, gas boiler and solar rooftop PV system in a single-family house. It was identified, in overall, that: (a) without the incentives, there was a high likelihood that only a gas boiler was present; (b) with only the PV feed-in incentive, there was a high likelihood that a hybrid heating system, i.e., a heat pump together with a gas boiler, was present, followed by a lower likelihood of only heat pump and a lower likelihood of only gas boiler; (c) with only the heat pump subsidy, there was a high likelihood that the heat pump was only present, a lower likelihood that a hybrid system was in place and a lower likelihood that only a gas boiler was present; (d) with a heat pump subsidy and a gas boiler subsidy, it was highly likely that a heat pump was only present, a lower likelihood of the existence of a hybrid system and no likely at all that only a gas boiler was present.

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# Chapter 1

# Introduction

As seen in Figure 1.1, Decentralized/Distributed Energy Systems (DES) bring supply close to demand, which carry multiple benefits compared to traditional long-distance transmission power grids [1]. Some of these benefits are: reduced distribution losses [1], [2], increased resilience [1], and taking significant shares of renewable energy (e.g. solar rooftop PV) needed for achieving a climate neutral supply [3].

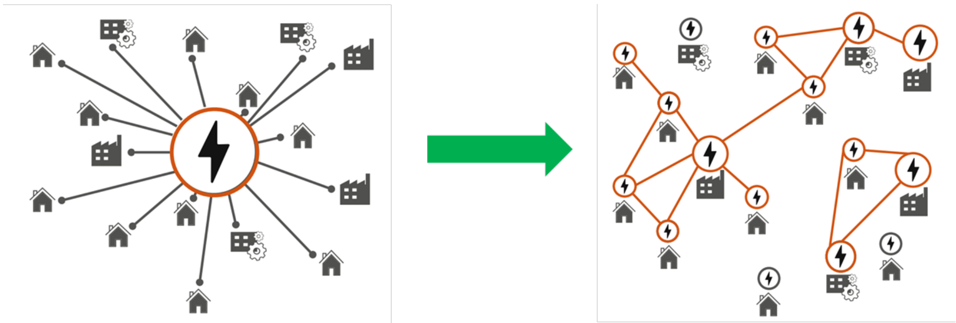


FIGURE 1.1: From a Centralized Energy System to a Decentralized/Distributed Energy System (adapted from [1])

However, for residential DES, the development depends on individual choices made by private users. The factors that may influence the decision making for residential DES are under five main groups: environmental, socio-cultural, institutional, economic and technical [1, p. 38]. This can be seen in Table 1.1. Moreover, once a device or appliance within a residential DES is installed (e.g. a boiler), a technology lock-in condition may appear, i.e., the private users may be unlikely to substitute or migrate to another type of device. Barriers, as for example the substitution of a boiler by another boiler, may also appear.

TABLE 1.1: Factors that influence the decision making for development of residential DES (adapted from [1, p. 38])

| **Factor classification** | **Examples** |
|---|---|
| Technical | Resource availability; technology (design, installation and performance); skill requirement for design and development, manufacturing, installation, operation and maintenance |
| Economic | Cost; market structure; energy pricing; incentives; purchasing power and spending priorities; financial issues; awareness and risk perception |
| Institutional | Policy and regulatory; infrastructure (institutions for research, design and aftersales services); administrative |
| Socio-cultural | Societal structure; norms and value system; awareness and risk perception; behavioural or lifestyle issues |
| Environmental | Resources (land and water); pollution; aesthetics |

The objective of this master thesis is to investigate the likelihood and viability of different development paths for DES in different contexts and frame conditions. The main research question to be addressed is: *what effects do incentives, policies and starting situations for residential users have on the evolution of residential energy demands from 2022 until 2030?*

The following sub-questions are particularly relevant in the context of this master thesis:

- What barriers may hinder the development of DES?
- What is the likelihood of different development paths?
- What technologies lock-ins may appear?

To answer the main research question and sub-questions, a household and its starting conditions were first defined. An initial natural gas boiler, as well as availability of the connection to the natural gas grid and electricity grid, were also assumed. Hourly load profiles for electricity and heat demand were obtained from the demandlib package from the oemof tool, and hourly photovoltaic (PV) potential profiles were obtained by using the Photovoltaic Geographical Information System (PVGIS). Boundary conditions were defined, which included: electricity and heat prices, status of the initial gas boiler, and incentives for installing a heat pump and a PV system. An energy system optimization model was made by using oemof.solph package from oemof. This model analyzed economic feasibility for investments in a heat pump, gas boiler and PV system for each year. As some of the boundary conditions were modeled as a Markov chain, this resulted in the complete model proposed being a Markov chain. In addition, this model was implemented for multiple scenarios which contained different incentives.

The subsequent chapters of this thesis are structured as follows. Theory (Chapter 2) provides a literature review relevant for the research question, as well as the mathematical formulation of a Markov chain, continuous uniform distribution and reliability function of a device. Methodology (Chapter 3) defines all the data required and the steps taken to model the energy system of the household and its future development. Results and Discussion (Chapter 4) presents the findings of the evolution of the household energy system and a discussion based on expectations and literature, as well as the limitations of the model. Conclusion (Chapter 5) provides a summary of the relevant findings that answer the research question, as well as future research.

# Chapter 2

# Theory

## 2.1 Decentralized/Distributed Energy Systems (DES)

A system consisting of one or multiple units that generate energy at a location where it is consumed or nearby it, is called a distributed energy system (DES) as defined in [1, p. 25]. The users of the DES which may be consumers, become also producers, and the units can be either connected through others in a shared grid, or can be isolated [1, p. 25]; moreover, the resource needed for the generation units or technologies can be classified as non-renewable or renewable [1, p. 22]. As an example, the use of a natural gas boiler in a residence is considered a technology that uses a non-renewable resource, while a solar rooftop photovoltaic (PV) system uses energy from the sun which is a renewable resource.

As mentioned in Chapter 1, while there are multiple advantages in the transition from a centralized energy system to a DES, there are also a number of factors that may influence the adoption of DES in residences. The factors that were selected to answer the research question of this thesis can be seen in Table 2.1.

TABLE 2.1: Factors selected in this thesis to study their effect on the decision making for the development of residential DES

| **Category** | **Factors** |
|---|---|
| Technical | Lifetime of the heating infrastructure |
| Socio-economic | 1. Investment and operating cost of gas boiler, heat pump, solar rooftop PV system<br>2. Electricity and gas prices, and their taxation<br>3. Incentives for residential technologies |

Within the scope of this thesis, the technologies that were selected within DES for residences include: electric heat pump, solar rooftop PV system and natural gas boiler. In addition, residential energy demands studied in this thesis were: heat demand and electricity demand.

There are different ownership models of DES: community, utility, hybrid and private ownership [4]. This thesis will be limited to the latter, i.e., the household members are owners of the DES and can take decisions on it.

The following sections of this chapter provide a literature review of relevant facts about households and their Energy Systems in Germany in the context of the scope of this master thesis. A research on the selected factors for residential DES is also presented. Then, the mathematical background of a Markov chain, uniform continuous distribution and reliability function is given.

## 2.2 Relevant Statistics on Households and their Energy Systems in Germany

In 2021, there were around 40,7 million households in Germany [5], and the population was around 83,2 million [6]; this yields an average of 2 members per household. A total of 11,6 million families were reported, with 51% of them having 1 child, 37% having 2 children and 12% having 3 or more children; moreover, 39,8 million family members and an average of 3,4 members per family was recorded [7].

In terms of residential buildings, 66,7% were single-family houses, 16,3% were two-family houses and 17% multi-family houses in 2019 [8]. Regarding households owning their own property, 49,5% of the households owned their own house, with 30,7% of them being single-family houses [9].

### 2.2.1 Energy Demands

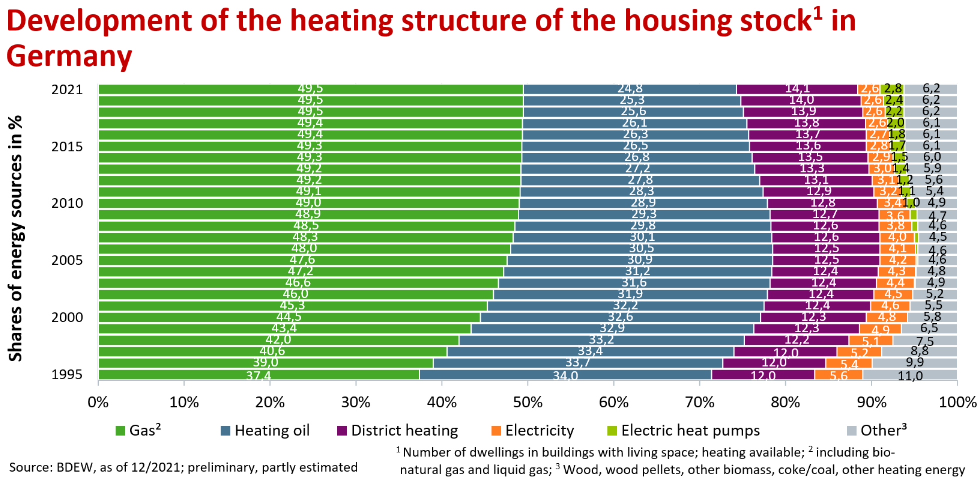
Table 2.2 shows the average energy demands per household depending on the number of members [10]. This is calculated across different household (number of household members) and building sizes (number of housing units in the building) [11, p. 6]. It can be seen that the number of household members play a significant role in the energy demand.

TABLE 2.2: Average heat demand and electricity consumption per number of members in the household [10]

| | Members per household | | |
|---|---|---|---|
| | 1 | 2 | 3 or more |
| **Heat demand (kWh/yr) from which:** | 10457 | 16133 | 21402 |
| Space heating demand (kWh/yr) | 9233 | 13571 | 16560 |
| Water heating demand (kWh/yr) | 1225 | 2562 | 4842 |
| **Electricity consumption per household (kWh/yr)** | 1958 | 3196 | 4919 |

### 2.2.2 Residential Heating Technologies

The development of the share of the energy sources in the heating structure of the current houses in Germany can be seen in Figure 2.1 [12, p. 24]. In 2021, a significant proportion of the residences (49,5%) were heated with gas, while a minority of residences (2,8%) were heated with heat pumps. The share of residences being heated with heat pumps has been slightly increasing over the years. On the other hand, for new residential constructions as seen in Figure 2.2 [12, p. 26], most of them (43,6%) were using heat pumps with this share increasing over the years. The share of new residences that were heated with gas boilers has been decreasing over the years. Since 2020, the share of residences heated with heat pump overtook the share heated with gas boiler.

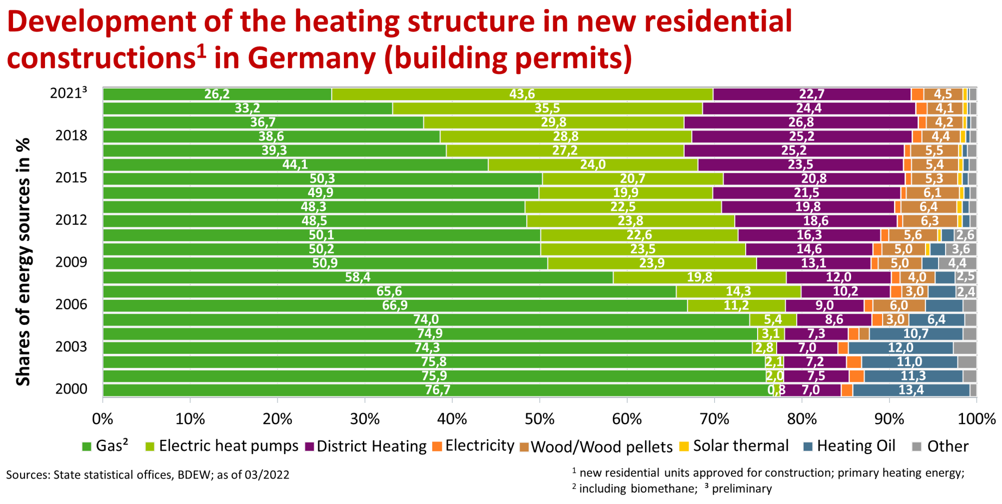


Development of the heating structure of the housing stock[1] in Germany

Source: BDEW, as of 12/2021; preliminary, partly estimated

[1] Number of dwellings in buildings with living space; heating available; [2] including bio-natural gas and liquid gas; [3] Wood, wood pellets, other biomass, coke/coal, other heating energy

FIGURE 2.1: Evolution of the residential heating structure in current houses in Germany (adapted from [12, p. 24])



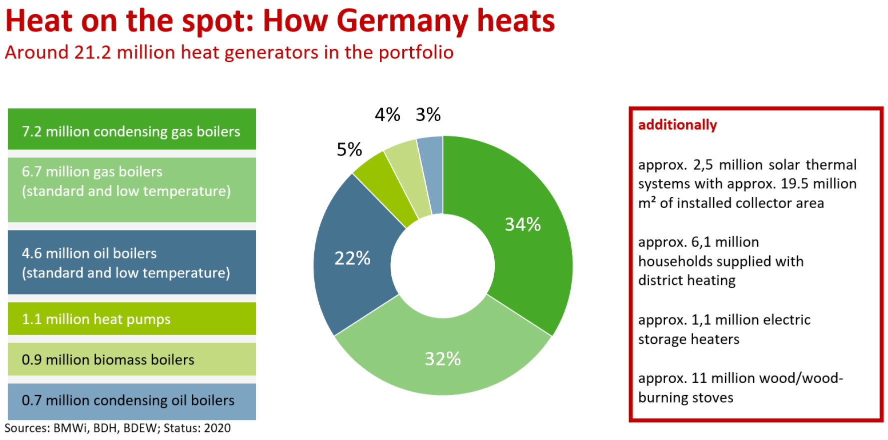
Development of the heating structure in new residential constructions[1] in Germany (building permits)

Sources: State statistical offices, BDEW; as of 03/2022

[1] new residential units approved for construction; primary heating energy; [2] including biomethane; [3] preliminary

FIGURE 2.2: Evolution of the residential heating structure in new houses in Germany (adapted from [12, p. 26])

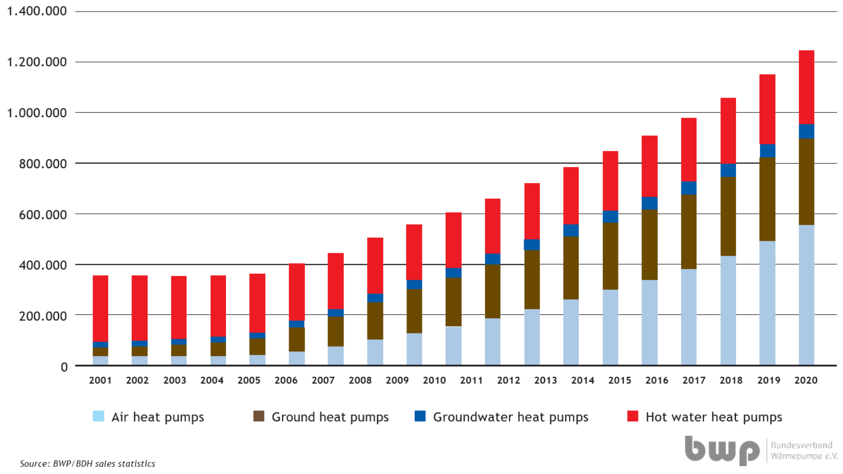
There were around 21,2 million heat generators in Germany in 2020 [12, p. 33], with gas boilers having the highest share (66%), followed by conventional oil boilers (22%), heat pumps (5%), biomass boilers (4%), and condensing oil boilers (3%); this can be seen in Figure 2.3.



Sources: BMWi, BDH, BDEW; Status: 2020

FIGURE 2.3: Heat generators in Germany (adapted from [12, p. 33])

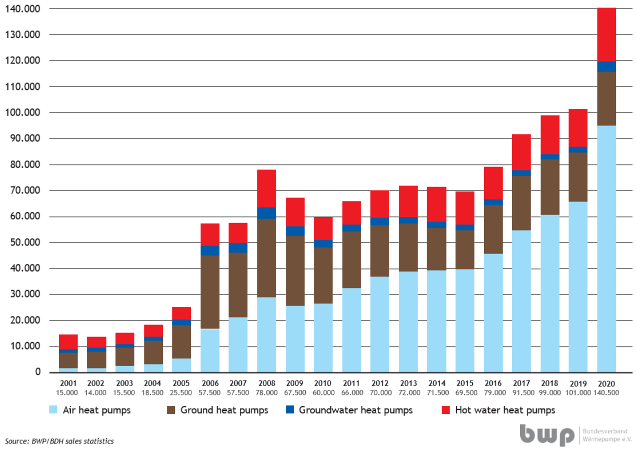
The number of heat pumps installed by type in Germany have been increasing as observed in Figure 2.4 [13, p. 7]. There has been a shift from ground source heat pumps (brown) to air-to-water heat pumps (lightblue), resulting in a total of 600000 air-to-water heat pumps in 2020, which was around 43% share of the total heat pump units. In addition, there were around 140000 heat pump units sold in this year, as seen in Figure 2.5; most of the sales were air-to-water heat pumps (68%) [13, p. 5]. Sales in heat pumps have been increasing.



Source: BWP/BDH sales statistics

FIGURE 2.4: Number of heat pumps installed by type in Germany (adapted from [13, p. 7])

Regarding the prognosis for residential heating technologies, an annual increase of 0,4 million heat pump units per year is expected as part of a series of steps needed for Germany to achieve a 65% reduction in emissions for 2030 [14]. This yields a total of 6



Source: BWP/BDH sales statistics

FIGURE 2.5: Sales of heat pumps by type in Germany (adapted from [13, p. 5])

million heat pumps by this year. Additionally, it is unlikely that oil or natural gas will be energy sources for new heating systems after 2025 [14].

The German government has been discussing in 2022 whether to implement a new regulation for residential buildings to meet the targets needed for Germany to become climate-neutral. If this regulation comes into effect, it states that starting on January 1, 2024, 65% of the sources for all heating systems (existing, renovated or new) in residential buildings must come from renewable energy [15]. An updated policy framework is needed to support the rapid adoption of this target in residential buildings [16]. While solar thermal heating systems replacing conventional boilers are not enough for achieving the target, the installation and operation of heat pumps are a suitable technology for achieving the climate-neutral goals [16].

### 2.2.3 Solar Rooftop Photovoltaic (PV) Systems

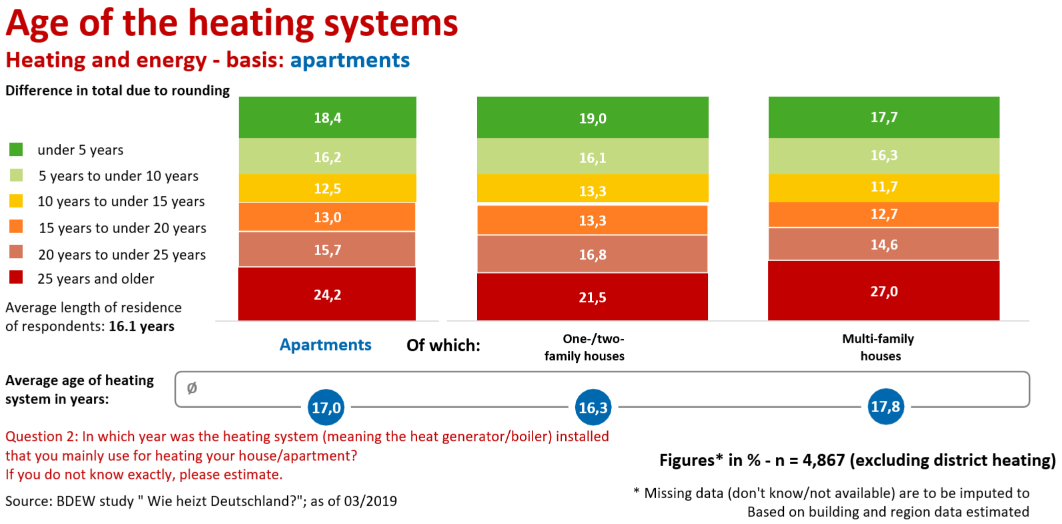
Solar rooftop photovoltaic (PV) systems in houses (low-voltage area) in Germany have an average installed capacity of 6 kWp [17], while solar rooftop PV systems installed by a household who owns its home are commonly below 10 kWp [18]. PV system sizes up to 10 kWp accounted for the 15% of the total PV install capacity in Germany [18].

In 2020, there were approximately 1,3 million houses that installed a solar rooftop PV system. These systems were distributed among single- and two-family houses. In addition, based on suitable roof areas, 11,7 million houses have the potential to install a rooftop PV system. This yields a national level of saturation of around 11%, or in other words, there is a 89% remaining potential for exploiting solar rooftop PV in houses in the country. While the highest saturation levels are in the south of Germany, there exist a significant potential in the east, north and some areas of the west [19]. A total of 500 MW per year of solar rooftop PV is expected to be installed in houses until 2030 [20].

## 2.3 Literature review on the selected factors that affect the decision making for residential DES

### 2.3.1 Lifetime of the heating infrastructure in Germany

The share of the age ranges for heating systems of houses in Germany can be seen in Figure 2.6 [12, p. 62]. It is observed that for single and two-family houses, the highest share of the age ranges is 21,5% which corresponds to heating systems with an age equal or greater than 25. In addition, heating systems for these type of homes are 16 years old in average. Considering that around 14 million (66%) of the heat generators in residences are gas boilers as presented before in Section 2.2.2, this implies that most gas boilers in single and two-family houses in Germany have an average age of 16. Most residential gas boilers that are sold in the market have an useful life of around 15 years [21], so a residential gas boiler that has an age of 16 has an increased likelihood of breaking down.



Question 2: In which year was the heating system (meaning the heat generator/boiler) installed that you mainly use for heating your house/apartment? If you do not know exactly, please estimate.

Source: BDEW study " Wie heizt Deutschland?"; as of 03/2019

Figures* in % - n = 4,867 (excluding district heating)

* Missing data (don't know/not available) are to be imputed to Based on building and region data estimated

FIGURE 2.6: Share of the age ranges for heating systems in houses in Germany (adapted from [12, p. 62])

### 2.3.2 Investment costs for heat pump, gas boiler and solar rooftop PV system

As presented before in Figure 2.5, the most common type of heat pumps in Germany are air-to-water. For an air-to-water heat pump of a size between 8 kW-12 kW, the investment cost is between 10000EUR-12000 EUR [22]. The maximum investment cost from these ranges is around 1500 EUR/kW. This figure is close to the one obtained from a catalog [23] for two models: Buderus WLW196i-4 AR B with 4kW for 5729 EUR, and Viessmann Vitocal 200-A with 4.2 kW for 5909 EUR.

The heating technology in residences with the highest share in Germany is the gas condensing boiler (*Gas-Brennwertkessel*) with 7,2 million units (34% share) in 2020, as shown before in Figure 2.3. Currently, new combi gas boilers that are sold for homes, which provide both domestic hot water and space heating, are also gas condensing boilers. It is also common that gas boilers for single-family homes are combi gas boilers. Typical sizes and investment prices obtained from two combi gas boiler models in a catalog [24] were: Viessmann Vitodens 100-W Brennwert-Kombitherme up to 19kW for a price of 3015 EUR, yielding 159 EUR/kW, and Buderus GB172 K providing up to 23,8 kW for a price of 2369 EUR, which yields 99.6 EUR/kW.

For solar rooftop PV system investment, the total investment cost for solar rooftop in Germany for systems between 10kWp-100kWp was 1036 EUR/kW in 2020 [25].

### 2.3.3 Residential electricity price

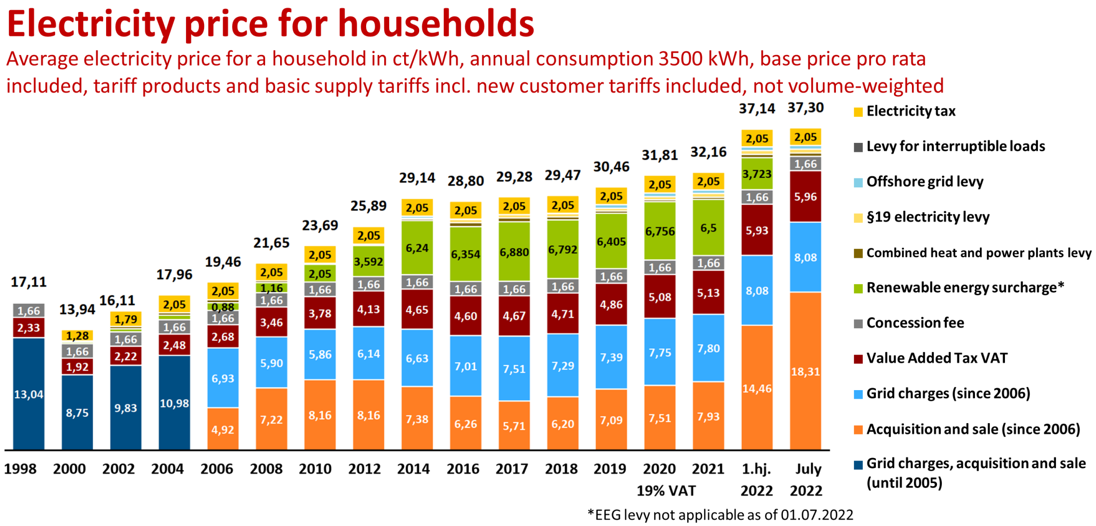
For residential customers, there are three main components of the electricity price in Germany: the acquisition and sale component (*Beschaffung, Vertrieb*), the grid charges, and other charges which includes taxes and levies [26]. The acquisition and sale component represents the cost incurred by the electricity supplier by purchasing power in the wholesale market, as well as its profit [27]. The grid charges(*Netzentgelt*) are defined by the Federal Network Agency (BNetzA) and they represent the fees for using the electricity grid [27].

Other charges which includes taxes and levies (*Steuern, Abgaben und Umlagen)* are:

- Combined heat and power plants levy (*KWKG-Umlage*): starting in 2002 within the Combined Heat an Power Act [28], this component supports the owners of combined heat and power plants. It is calculated by the difference between the price that is secured and the real price they obtain [27].
- §19 electricity levy (*§19 StromNEV-Umlage*): its purpose is to exempt, either partially or totally, customers that consume big amounts of power [27].
- Offshore grid levy (*Offshore-Netzumlage*): introduced in 2013 [28], this is a pass-through charge from grid operators to customers. The responsibility of connecting offshore wind power plants relies on grid operators and if they do not commit in time, this charge is debited [27].
- Levy for interruptible loads (*Umlage für abschaltbare Lasten*): to guarantee the stability of the grid and the system, providers of interruptible loads are needed. The transmission system operators pay the costs related to this service, which is then passed to end customers. This charge started in 2014 [28].

- Concession fee (*Konzessionsabgabe*): municipalities provide rights of way for grid operators, which is paid by the latter and passed to end customers [28].
- Renewable energy surcharge (*EEG-Umlage*): this component is intended to support the expansion of renewable energy power plants by paying a market premium to big producers and feed-in tariffs for electricity [27], [28]. This was set to 0 in July 2022 [29].
- Electricity tax (*Stromsteuer*): this component is intended to promote a rational electricity consumption; moreover, it helps toward to decrease and stabilize pension rates. It was introduced in 1999 [28].
- Value Added Tax VAT (*Mehrwertsteuer*): as electricity is a service provided by businesses, it is subjected to a value-added tax (VAT). It is calculated by adding the acquisition and sale component, the grid charges and the other previous components and applying a 19% charge, which is the VAT rate for electricity [28].

The historic development of the components of the electricity price for residences can be seen in Figure 2.7 [30, p. 8]. It can be seen that as of July 2022, the acquisition and sale component represented 49% of the total electricity price. This was followed by 29% of the taxes and levies components, and 22% of the grid charges component.



*EEG levy not applicable as of 01.07.2022

Source: BDEW; Status: 07/2022

FIGURE 2.7: Historical development of all the components of the electricity price for residences (adapted from [30, p. 8])

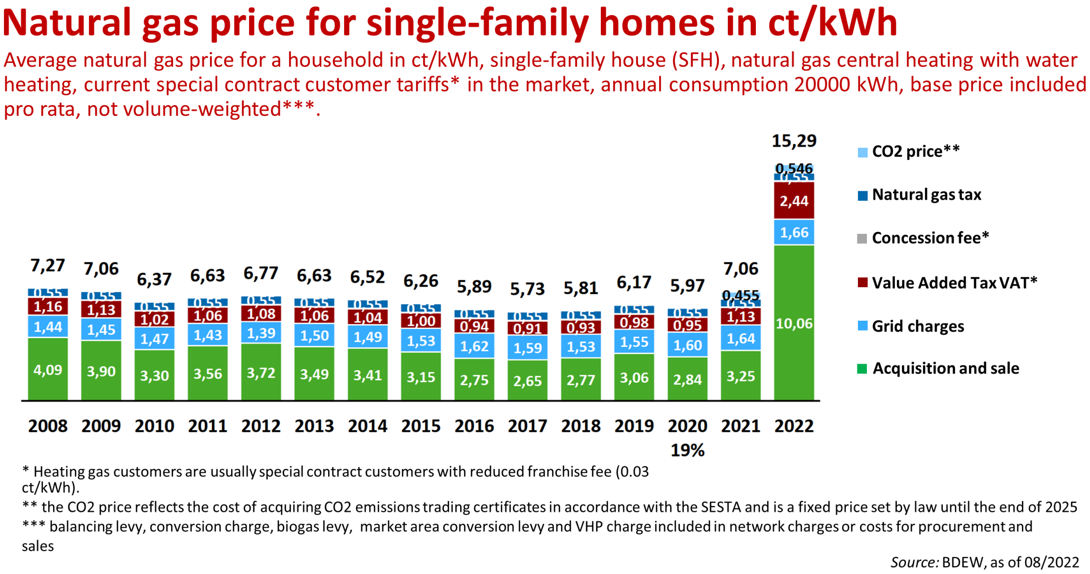
### 2.3.4 Residential gas price

Similar as the electricity price, there are three main components of the gas price for residences in Germany: the acquisition and sale component (*Beschaffung*, *Vertrieb*), the grid charges, and other charges which includes taxes and levies [31]. The acquisition and sale component varies depending on the gas provider and the competition among them [31]. The grid charges (*Netzentgelt*) varies according to the grid area where the end customer is located and the sales in it [31].

Other charges which includes taxes and levies (*Steuern und Abgaben)* are:

- Concession fee (*Konzessionsabgabe*): municipalities provide rights of way for grid operators which are paid by the latter and passed to end customers [32].
- Gas tax (*Erdgassteuer*): this component was originally intended to promote less energy consumption, including gas, by taxing fuel to support policies related to climate [32].
- Value Added Tax VAT (*Mehrwertsteuer*): as gas is a service provided by businesses, it is subjected to a value-added tax (VAT). It is calculated by adding the acquisition and sale component, the grid charges and the other previous components and applying a 19% charge, which is the VAT rate for gas [32].

The historic development of the components of the gas price for residences can be seen in Figure 2.8 [33, p. 5]. As of July 2022, the acquisition and sale component represented the majority (66%) of the total electricity price, followed by the taxes and levies component (23%) and the grid charges component (11%).


**Natural gas price for single-family homes in ct/kWh**

Average natural gas price for a household in ct/kWh, single-family house (SFH), natural gas central heating with water heating, current special contract customer tariffs* in the market, annual consumption 20000 kWh, base price included pro rata, not volume-weighted***.

* Heating gas customers are usually special contract customers with reduced franchise fee (0.03 ct/kWh).
** the CO2 price reflects the cost of acquiring CO2 emissions trading certificates in accordance with the SESTA and is a fixed price set by law until the end of 2025
*** balancing levy, conversion charge, biogas levy, market area conversion levy and VHP charge included in network charges or costs for procurement and sales

*Source:* BDEW, as of 08/2022

FIGURE 2.8: Historical development of all the components of the gas price for residences (adapted from [33, p. 5])

### 2.3.5 Incentives for residential solar rooftop PV and Heat Pumps

The encouragement for the installation and operation of PV systems in Germany was formally presented through the German Renewable Energy Sources Act (*Erneuerbare-Energien-Gesetz, EEG*) which had its first implementation in 2000.

Throughout the years, new versions have been developed. Relevant regulations from the current version in 2021 were [18]:

- PV systems that provide self-consumption will be taxed with 40% of the current renewable energy surcharge if the size of the system is above 30 kW
- A fixed feed-in tariff is offered to PV systems that are up to 100 kW of nominal power
- A feed-in tariff of up to 0,0816 EUR/kWh is offered for small solar rooftop PV systems that are installed and operated until January 2021, for the next twenty years

The historical development of the PV feed-in tariff for small systems (blue) can be observed in Figure 2.9. This tariff has been decreasing by around 80% for small solar rooftop PV systems [18]. In July 7, 2022, a new version of the EEG was approved, which slightly increased the feed-in tariff [34]. A feed-in tariff of 0,0860 EUR/kWh will be offered for PV systems up to 10 kW that provides self-consumption. Moreover, if the PV system provides 100% of its electricity generated to the grid, the feed-in tariff is even greater: 0,134 EUR/kWh [34].

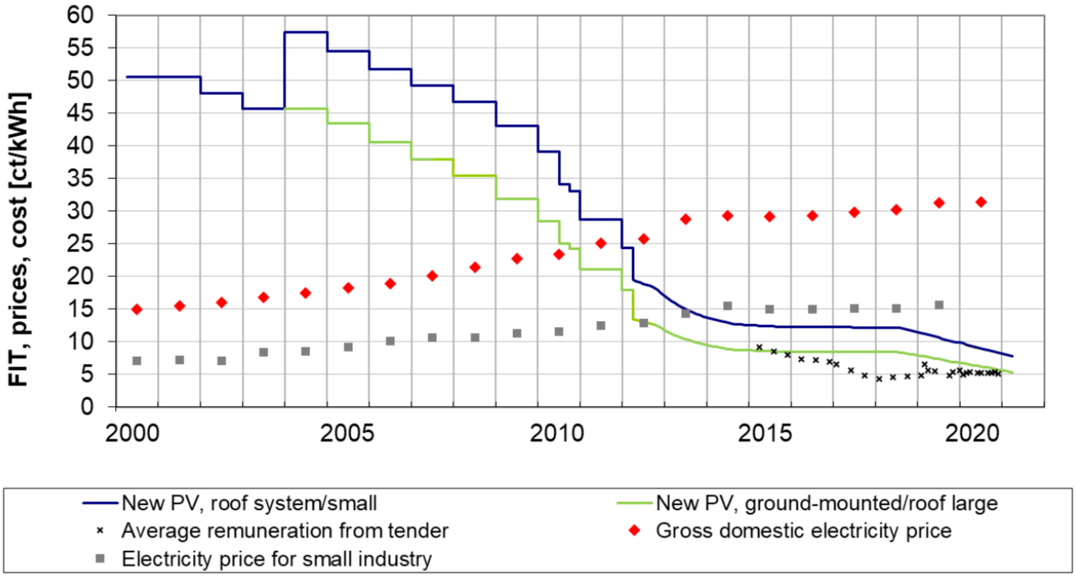


FIGURE 2.9: Historical development of the PV feed-in for new small systems (blue), new large systems (green). The residential electricity price (red) is also shown for comparison [18, p. 11]

Regarding heat pumps, for an air-to-water heat pump there are governmental subsidies to facilitate its adoption for residential customers. If a series of conditions are met (they can be found in [22]), the investment cost for a new air-to-water heat pump can be subsidized up to 35%.

## 2.4 Markov Chain

A Markov chain is a sequence of events where the probability of the next state only depends on the present state [35]. Given a system with multiple states $X = i, j, \ldots$, the probability of the system to go from state $i$ at time $n$ (e.g. time 0) to state $j$ at time $n+1$ (e.g. time 1) depends only on the present state (equation 2.1):

$$P_{ij} = P\left(X_1 = j \ / \ X_0 = i\right) = P\left(X_{n+1} = j \ / \ X_n = i\right) \tag{2.1}$$

All the possible states along with the probabilities to transition from one state to the other, as well as the probabilities to stay in the same state, are contained in a so-called transition diagram. The probabilities to go from one state to the other are called transition probabilities. This can be seen in Figure 2.10 for the example of a 2-state Markov chain. Here, $P_{11}$ is the probability to go from state 1 to state 1, or in other words, to remain in state 1; $P_{12}$ is the probability to go from state 1 to state 2; $P_{21}$ is the probability to go from state 2 to state 1. $P_{22}$ is the probability to remain in state 2.

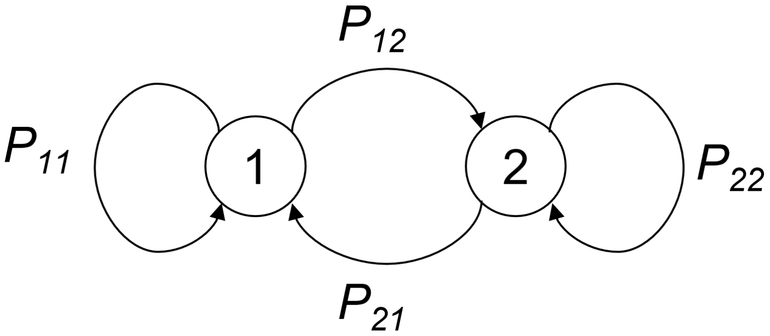


FIGURE 2.10: Transition diagram for a two-state Markov chain (own elaboration)

A Markov chain is defined by its state space, the time interval between each event, and the transition probabilities. The state space refers to all possible states or outcomes. The state space of a Markov chain can be either finite or continuous. The time interval of a Markov chain can be either discrete or continuous. The transition probabilities are usually given in the form of a matrix called a transition probability matrix. If a system has $\beta$ states, the state space $X$ is given by: $(X = 1, 2, 3, \ldots, \beta)$. Then, the transition probability matrix $P$ is given by equation 2.2:

$$P = \begin{matrix} P_{11} & P_{12} & P_{13} & \cdots & P_{1\beta} \\ P_{21} & P_{22} & P_{23} & \cdots & P_{2\beta} \\ P_{31} & P_{32} & P_{33} & \cdots & P_{3\beta} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ P_{\beta 1} & P_{\beta 2} & P_{\beta 3} & \cdots & P_{\beta\beta} \end{matrix} \tag{2.2}$$

Each entry in the transition probability matrix denotes the transition probability from one state to the other. For example, in the first row, $P_{11}$ denotes the probability to remain in state 1; $P_{12}$ is the probability to go from state 1 to state 2; $P_{13}$ is the probability to go from state 1 to state 3, and so on until $P_{1\beta}$ which is the probability from state 1 to the last state $\beta$.

In addition, each row from the matrix in equation 2.2 represents the probability distribution of the transitions from a specific state to the others. According to equation 2.3, as for probability distributions, the sum of all transition probabilities in a row of the transition matrix is 1:

$$\sum_{j=1}^{\beta} P_{ij} = 1 \tag{2.3}$$

Where $i$ is a row $(i = 1, 2, 3, \ldots, \beta)$, $j$ is a column $(j = 1, 2, 3, \ldots, \beta)$ of the transition probability matrix.

## 2.5 Continuous Uniform Distribution

A continuous uniform distribution is a type of probability distribution where all random events within certain bounds have the same probability of occurring. Given a minimum $b$ and a maximum $a$, the probability density function $f(x)$ of a random variable $x$ is uniformly distributed in the range $[a, b]$ according to equation 2.4 [36]:

$$f(x) = \begin{cases} \frac{1}{b-a}, & \text{if } a \leq x \leq b \\ 0, & x < a \text{ or } x > b \end{cases} \tag{2.4}$$

A plot of $f(x)$ for an uniform distribution can be seen in Figure 2.11

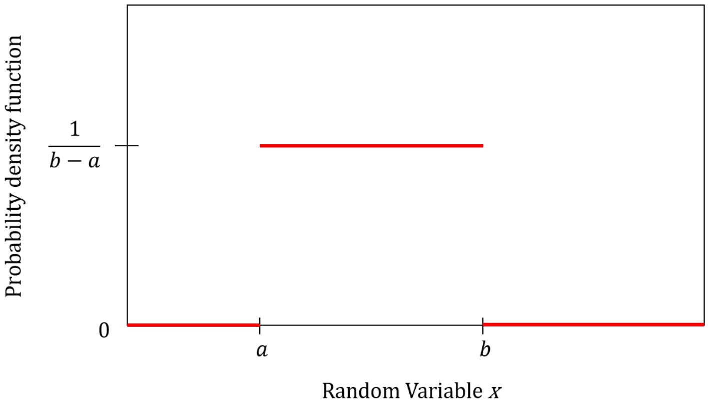


FIGURE 2.11: Probability density function for an uniform continuous distribution (own elaboration)

## 2.6 Reliability Function of a Device

Reliability engineering is a field that focuses on the studies of the estimation, prevention and management of failures [37]. Within this field, there is a specific distribution to model the probability of reliability of a device for a specific year, or in other words, the probability that the device will not fail. This is the Survival Function, $SF$, or Reliability Function, $R(t)$, which describes the probability that an appliance will survive beyond age t.

Different distributions (e.g., exponential, normal, beta) have been employed to model the Survival Function of a device. One widely accepted is the three-parameter Weibull Distribution [38]:

$$R(x) = e^{-(\frac{x-\theta}{\alpha})^{\beta}} \tag{2.5}$$

where $x$ is the appliance age, $R(x)$ is the probability that an appliance will survive (operational) beyond age $x$, $\alpha$ is the scale parameter which corresponds to the decay length in an exponential distribution, $\beta$ is the shape parameter which determines the way the failure rate changes over time, $\theta$ is the delay parameter which provides for a delay before any failures occur.

# Chapter 3

# Methodology

The methodology employed in this investigation is seen in Figure 3.1.

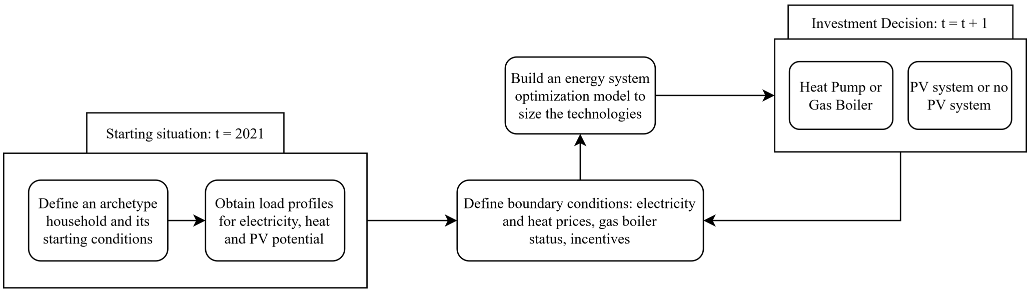


FIGURE 3.1: Flowchart of the methodology employed in this investigation. PV: Photovoltaic

The description of each step is described in detail in the following sections.

## 3.1 Define an archetype household and its starting conditions

A detached single-family household with three members was assumed. The household was connected to the electricity and gas grid to supply its electricity and heat demand. The household had in 2021 a combi gas boiler of 10 kW with an age of 16 years in 2021, while there was no heat pump and no PV system. Battery storage, as well as heat storage, was excluded. The area of the rooftop of the house was enough to accommodate a PV system of a size up to 10 kW, while there was enough space in the house to install a heat pump. There were no budget limitations for investments in these technologies. Regarding the energy system of the household, its members took decisions with a *Homo economicus* thinking, i.e., the members were fully rational and took decisions that minimized their heat and electricity expenses by selecting technologies that are economically feasible. Moreover, there were no time constraints (processing a purchase order, shipping and installation on site) from the moment that a economically feasible technology was chosen until the technology is fully operational at the household. The technologies were assumed to be always available in the market.

## 3.2 Generate load profiles for electricity, heat and PV potential

Figure 3.2 shows the packages employed (demandlib and PV GIS) and the input needed (left of the packages) that generated the profiles (right of the packages). oemof (*Open Energy Modelling Framework*) is an open source toolbox that can be used for energy system modeling and for optimizing an energy system [39]. It contains multiple packages that are used for different purposes.

The demandlib package from oemof [40] was used to generate heat and electricity hourly profiles. For the hourly heat profile generation, test reference year temperatures were provided, which were obtained from the Deutscher Wetterdienst [41] for 2021, and an annual heat demand of 21402 kWh was provided. For the hourly heat electricity profile, an annual electricity demand of 4919 kWh was given. The annual heat and electricity demand are typical for a three-member household as seen before in Table 2.2 [10]. The annual heat and electricity demand, as well as the hourly heat and electricity profiles generated from demandlib for the year 2021, were assumed to remain constant for the household from 2022 until 2030.

For the generation of the hourly PV profile normalized, the Photovoltaic Geographical Information System (PVGIS) [42] was used. It is an online tool from the European Commission that provides hourly solar radiation data and performance information for a given PV system with specific coordinates and characteristics.

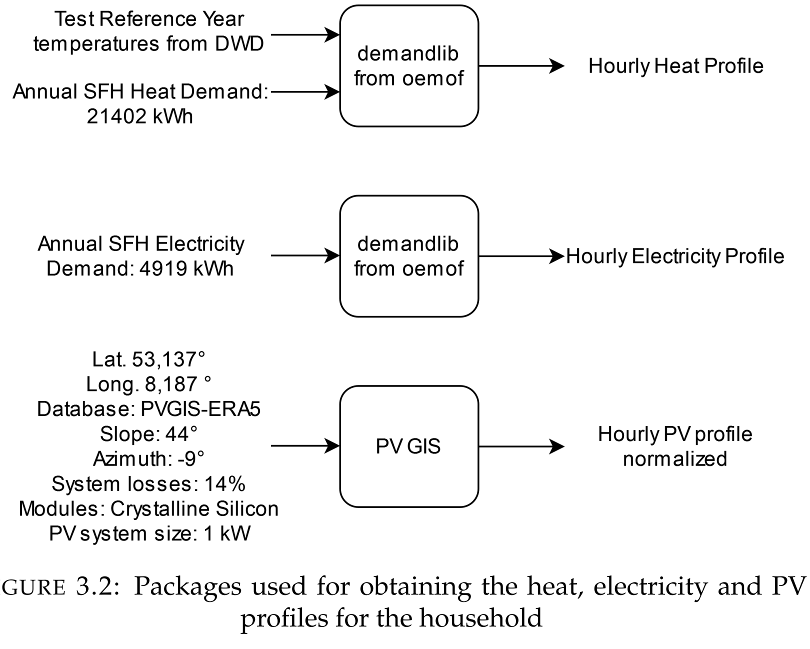


FIGURE 3.2: Packages used for obtaining the heat, electricity and PV profiles for the household

## 3.3 Build an energy system optimization model to size the technologies

The oemof.solph package from oemof [43] was used to model the household energy system and to optimize the sizes of the technologies needed to supply the electricity and heat demands. The components used in oemof.solph can be seen in Figure 3.3. Four main classes where employed: bus, sink, source and transformer. As mentioned before, the household was connected to the electricity grid and gas grid, so this was represented by a source class for each one; moreover, the PV system was also modeled using this class. The transformer class was used to model the gas boiler as well as the heat pump. The heat demand and the electricity demand were modeled using the sink class. A natural gas bus, electricity bus and heat bus were also used, so that there is always a flow between a bus and other component(s), which is a requirement for using the oemof.solph components and buses. So, there is a flow of natural gas from the natural gas import to the natural gas bus, and then the natural gas flows to the gas boiler. Similarly, there is a flow of electricity from the grid electricity and the PV system to the electricity bus, and then a flow going out from this bus to the heat pump. Then, there is a flow of heat from the gas boiler and/or the heat pump to the heat bus, and then a flow of heat from the heat bus to the heat demand sink. In addition, there is a flow of electricity from the electricity bus to the electricity demand sink.

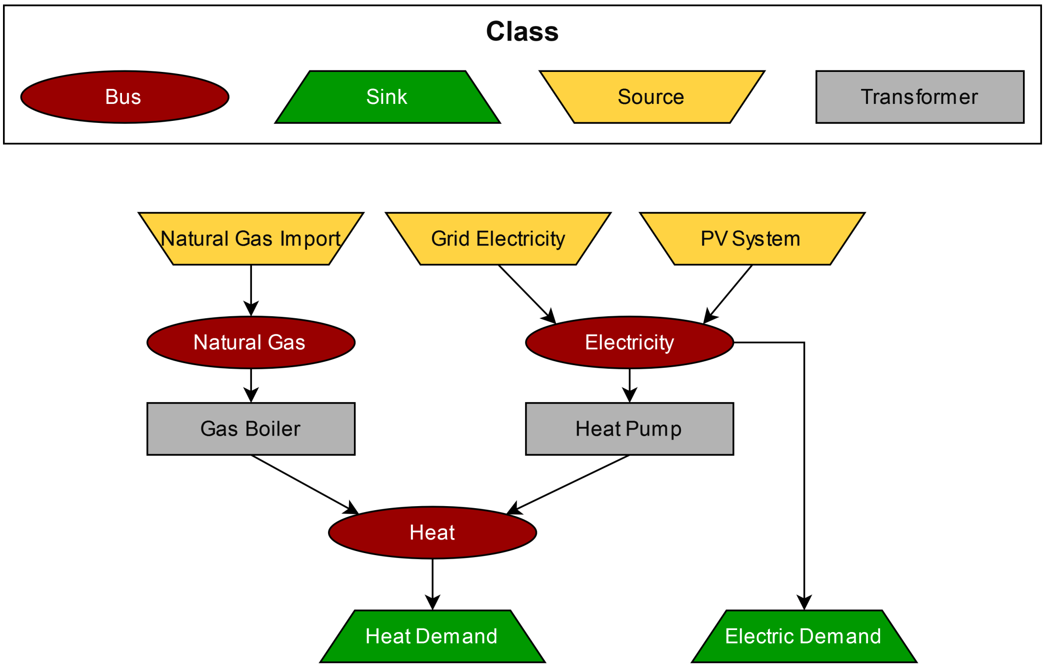


FIGURE 3.3: Components used to model and optimize the household energy system using oemof.solph (own ellaboration using oemof class notation)

## 3.4 Define boundary conditions

Four boundary conditions were defined: electricity price, gas price, gas boiler status, and incentives. The theoretical background was previously described in Section 2.3. The assumptions made in each boundary condition are described as follows.

### 3.4.1 Electricity price forecast

As mention in Chapter 2, the electricity price for the household has three main components: the acquisition and sale component (*Beschaffung, Vertrieb*), the grid charges, and other charges (imposed by the state). A forecast of each component was made as follows.

#### 3.4.1.1 Forecast of the acquisition and sale component

It was assumed that the forecast of this component follows the same forecast as the wholesale electricity price. As described in a study from the University of Köln [44], there are three main factors that may affect significantly the evolution of the wholesale electricity price: the electricity demand, the availability of Russian imports and the expansion of renewable energy. Particularly, given the actual situation in Germany with the uncertainty in the import of natural gas from Russia, this may affect the household electricity and gas prices[45]. In this study from the University of Köln, eight scenarios were developed based on the intensity of these factors, from which two specific scenarios resulted in the highest and the lowest electricity price from all eight scenarios until 2030. The scenario with high electricity demand, no availability of Russian imports and moderate expansion of renewable energy resulted in the highest wholesale electricity price for 2030: 0,135 EUR/kWh. On the other hand, the scenario with moderate electricity demand, low availability of Russian imports and high penetration of renewable energy resulted in the lowest wholesale electricity price for 2030: 0,052 EUR /kWh. Although there is uncertainty in how these three main factors from this study will evolve until 2030, the maximum and minimum wholesale electricity prices expected for 2030 were used as the boundary conditions for this thesis to model the acquisition and sale price component as follows.

Different investigations support the modeling of the development of short and long-term variables, including the electricity price, by employing a Markov chain [46]–[51]. With 2022 as the starting year and assuming that the acquisition and sale price component follows a discrete-time and continuous space state Markov chain (previously explained in Section 2.4), the annual price for the next year is given by the following equation:

$$P_{2023} = P_{2022} \cdot q \tag{3.1}$$

Where $P_{2023}$ is the annual price component in EUR/kWh for 2023, $P_{2022}$ is the annual price component for 2022 (18,31 EUR/kWh for July 2022 as seen in [30]), $q$ is a random factor. $q$ is a random continuous number with a probability density function that follows an uniform continuous distribution as seen previously in Chapter 2 in equation 2.4 and Figure 2.11.

In Section 2.4 it was mentioned that for a Markov chain, each row of the transition probability matrix (equation 2.2) is a probability distribution. Therefore, as an uniform continuous distribution was assumed for the random factor $q$, it can be interpreted that the Markov chain for the acquisition and sale component in equation 3.1 have a transition probability matrix where each row is a probability distribution of the uniform continuous distribution for $q$. In addition, as the acquisition and sale component of the electricity price was modeled as a continuous space state Markov chain, there are an infinite number of states, which also yields in an infinite number of entries in the transition probability matrix. So, it was seen that formulating the transition probability matrix was a difficult task. Instead, the approach followed in equation 3.1 was used, and still a Markov chain was modeled.

In the next year, 2024, the annual sale electricity price component is similarly given as in equation 3.1, by:

$$P_{2024} = P_{2023} \cdot q \tag{3.2}$$

Taking equation 3.1 into equation 3.2, the following equation is obtained:

$$P_{2024} = P_{2022} \cdot q^2 \tag{3.3}$$

By generalizing the previous equations to estimate the electricity price component for any year after 2022, it yields:

$$P_{2022+n} = P_{2022} \cdot q^n \tag{3.4}$$

Where $n$ is the number of years after 2022. For example, for the electricity price component in 2024 as in equation 3.3, $n = 2$. By applying equation 3.4 for 2030, the annual price component for this year can be then estimated as:

$$P_{2030} = P_{2022} \cdot q^8 \tag{3.5}$$

Solving for $q$ and taking only values greater than 0, it yields:

$$q = \sqrt[8]{P_{2030}/P_{2022}} \tag{3.6}$$

Taking the aforementioned boundary conditions of the study of the University of Köln, the highest price $P_{2030,max}$ yields the maximum value of $q$:

$$q_{max} = \sqrt[8]{P_{2030,max} / P_{2022}} \tag{3.7}$$

And the lowest price $P_{2030,min}$ yields the minimum value of $q$:

$$q_{min} = \sqrt[8]{P_{2030,min} / P_{2022}} \tag{3.8}$$

$q_{max}$ and $q_{min}$ obtained were 0.963 and 0.854, respectively. These values were set as the maximum and minimum limits of the range of $q$. Then, $q$ was randomly generated within these limits following the probability density function in equation 2.4, and the value obtained was used in equation 3.4 to obtain the acquisition and sale electricity price component from 2023 until 2030.

#### 3.4.1.2 Forecast of grid charges

From the historical data described previously in Figure [30], a linear fit model was applied to forecast the grid charges from 2022 until 2030.

#### 3.4.1.3 Forecast of other charges

The historical development of other charges, as shown previously in Figure 2.7, was employed to forecast them as follows.

Similar as for the grid charges, a linear fit model was employed to forecast the following electricity price charges: combined heat and power plants levy (*KWKG-umlage*), §19 electricity levy (*§19 stromNEV-umlage*), offshore grid levy (*offshore-netzumlage*), levy for interruptible loads (*Umlage für abschaltbare Lasten*).

The concession fee (*Konzessionsabgabe*) has remained fixed historically to a value of 1,66 EUR/kWh [30]. This value was also assumed from 2022 until 2030. The renewable energy surcharge (*EEG-Umlage*) was set to 0 in July 2022 [29], which was also assumed from 2022 until 2030. The electricity tax (*stromsteuer*) has remain fixed to 2,05 which was also assumed from 2022 until 2030.

#### 3.4.1.4 Total electricity price for the household

For each year from 2022 until 2030, the acquisition and sale component, the grid charge and the other components were summed up and a 19% charge for the Value Added Tax VAT (*Mehrwertsteuer*) was applied. The total electricity price can be seen in Figure 3.4.

### 3.4.2 Gas price

Similar to the electricity price, the gas price for the household is composed of the acquisition and sale component, (*Beschaffung, Vertrieb*), the grid charges, and other charges.

#### 3.4.2.1 Forecast of the acquisition and sale component

A study from Agora, Prognos and Consentec [52] estimated the future gas price at the border in Germany (*Grenzübergangspreis*); this forecast was assumed for the acquisition and sale component.

#### 3.4.2.2 Forecast of grid charges

The historical data provided previously in Figure 2.8 [33] was used to generate the forecast for the grid charges from 2022 until 2030

#### 3.4.2.3 Forecast of other charges

By taking the data in Figure 2.8 [33], a linear fit model was applied to forecast the CO2 price from 2022 until 2030.

As seen in Figure 2.8 [33], the concession fee (*Konzessionsabgabe*) has remained historically fixed to a value of 0,03 EUR/kWh. This value was also assumed from 2022 until 2030. The gas tax (*Erdgassteuer*) has remain fixed to 0,55 which was also assumed from 2022 until 2030.

#### 3.4.2.4 Total gas price for the household

For each year from 2022 until 2030, the acquisition and sale component, the grid charge and the other components for the gas price were summed up and a 19% charge for the Value Added Tax VAT (*Mehrwertsteuer*) was applied. The total gas price can be seen in Figure 3.4.

Figure 3.4 shows the evolution of the total electricity and gas prices for households from 2022 until 2030 for 1000 iterations. The electricity price evolution is represented by the box plots. For 2021 and 2022, the electricity price is fixed for each iteration, so the orange median of the box plots is only shown.

The ratio of the electricity to the gas price for each year can be seen in Figure 3.5. Fixed ratios of electricity to gas price in 2021 and 2022 are shown as orange median lines of the box plot.

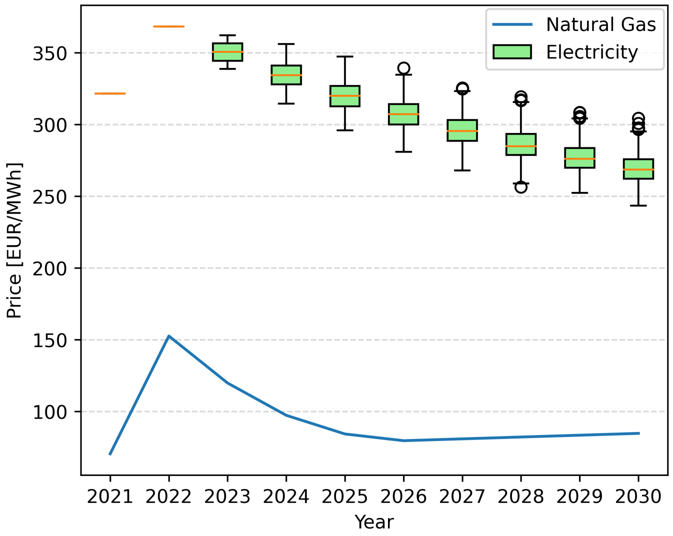


FIGURE 3.4: Forecast of the residential electricity and gas price from 2022-2030

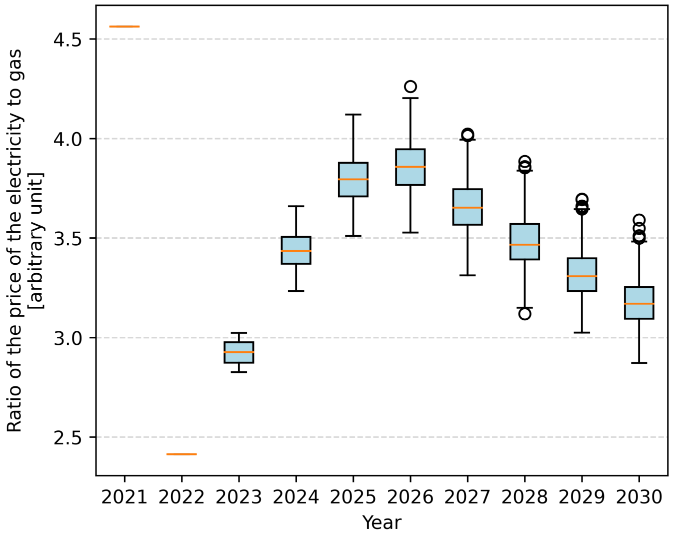


FIGURE 3.5: Ratio of the residential electricity to gas price from 2022-2030

### 3.4.3 Status of the the gas boiler

As mentioned in Section 2.3.1, heating systems for single family households in Germany are 16 years old in average. This was set as the initial age in the year 2021 for the initial gas boiler in the household. Therefore, for 2022, the age was 17, for 2023 it was 18 and so on until 2030. In addition, as the initial gas boiler got older, the probability that it was still operational, i.e., reliable, was modeled using the Survival Function given in Section 2.6 in equation 2.5. The three parameters that were used in the Survival Function for the gas boiler were: $\alpha = 28.5$, $\beta = 2.39$, $\theta = 0$, which were taken from a study of the Survival Function for residential gas boilers [38]. Based on the Survival Function, there were two possible states for the initial gas boiler for each year: operational or broken.

### 3.4.4 Incentives

A feed-in tariff for the PV system, as well as a subsidy for the installation of the heat pump were defined. The maximum and minimum values set for each one will be described later in the section of the scenarios.

## 3.5 Investment Decision Process

An annuity loan for the investment cost, for 20 years and with a 5% interest rate was assumed for the economic feasibility analysis of selecting a heat pump, gas boiler and solar rooftop PV system.

Typical ranges of investment cost for heat pumps, gas boilers and solar rooftop PV systems in residences were mentioned in Section 2.3.2. An air-to-water heat pump was assumed and it was defined to have a fixed investment cost of 1500 EUR/kW. A combi gas boiler was also assumed, which had an investment cost of 160 EUR/kW. For the PV system, an investment cost of 1036 EUR/kW was assumed.

For each year, from 2022 until 2030, the household energy system model (Figure 3.3) executed an investment optimization based on economic feasibility to determine the sizes of the air-to-water heat pump, combi gas boiler and PV system to meet the electricity and heat demands, given the starting conditions of the household in 2021 and the boundary conditions for the next years. Regarding the gas boiler status, it was defined in the model that when the initial gas boiler was operational for a particular year, the household continued to use the same gas boiler. On the other hand, when the initial gas boiler was broken, the model evaluated the economic feasibility between the installation of a new gas boiler and/or a heat pump. In case a new gas boiler was installed, it was assumed that it had a guarantee of 10 years as this is typical for newly purchased gas boilers, which means that it was fully covered and replaced by a new one whenever it broke during 2022-2030, so there was no need to model the Survival Function of a new installed gas boiler, but only for the initial (operational) gas boiler in 2021.

## 3.6 Scenarios

Four scenarios were defined as can be seen in Table 3.1. The PV feed-in and the heat pump subsidy were varied in each scenario, which represents uncertainty of the incentives mainly due to external factors as for example an economic recession or political conflicts that may compromise the governmental budget targeted for these incentives. For all the scenarios except the one with no incentives, the values defined here were up-to-date incentives, as described previously in Section 2.3.5.

The previously defined starting conditions for the household, the boundary conditions and the investment decision process were applied for each scenario. A number of 1000 iterations with random boundary conditions within each iteration were applied to each scenario. This number of iterations was selected on one hand to randomize as much as possible the boundary conditions, but on the other hand this number was not too high so that the results obtained were achievable in the time taken for this thesis.

TABLE 3.1: Four scenarios with combinations of PV feed-in and HP subsidy

| **Scenario** | **PV feed-in [EUR/kWh]** | **HP Subsidy** |
|---|---|---|
| No incentives | 0 | 0 |
| PV feed-in | 0,086 | 0 |
| HP subsidy | 0 | 35% |
| All incentives | 0,086 | 35% |

# Chapter 4

# Results and Discussion

## 4.1 Number of operational and broken gas boiler cases obtained from the breakdown probability model

The results of the operational and the broken gas boiler cases obtained from the gas boiler breakdown probability forecast model of Section 3.4.3 can be seen in Figure 4.1. As the age of the boiler increases throughout the year, the probability of breaking down increases, which can be seen by the decreasing operational cases for 1000 iterations for each year. In addition, as there are decreasing operational cases, there are decreasing broken cases as well throughout the years, which is observed in Figure 4.1.

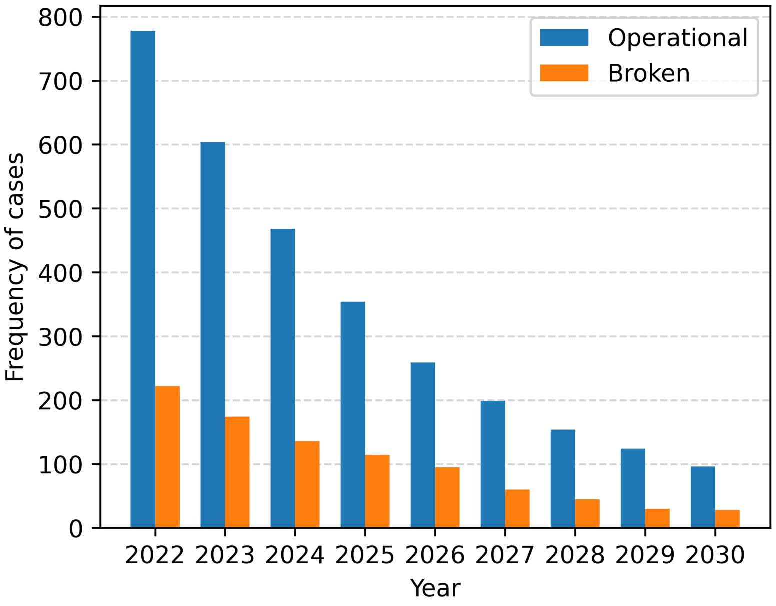


FIGURE 4.1: Number of operational and broken gas boiler cases obtained from the breakdown probability model forecast

## 4.2 Probability distributions from 2022 until 2030

Figure 4.2 and Figure 4.3 show the probability distribution per scenario of the sizing of a heat pump, gas boiler and PV system in the household for each year from 2022 to 2030 for the cases when the initial gas boiler was operational and for the cases when the initial gas boiler was broken, respectively. Detailed plots of the yearly probability distribution for each scenario, as well as the number of operational and broken gas boiler cases, can be found in Appendix A in Figures A.2, A.3, A.4 and A.5. Each scenario involves having/not having a heat pump subsidy and a PV feed-in incentive (as described before in Chapter 3). In all the scenarios, the starting condition is that the household in 2021 have a gas boiler of 10 kW, which is enough to supply the maximum heat demand of the household in a year, i.e., 8,7 kW; moreover, neither a heat pump nor a PV system are present in 2021. The maximum allowed PV system size in the household per year is 10 kW. Figure 4.4 shows the final probability distribution in 2030. The description of the gas boiler cases, as well as the analysis of the final situation in 2030, is described in the following sections.

From Figures 4.2, 4.3 and 4.4, the y-axis represent probabilities for each year, i.e., the best estimate that the sizes of the heat pump, gas boiler and PV are within the ranges seen in the x-axis. These yearly probabilities can also be interpreted as relative frequencies for the total number of counts of this study (i.e., 1000 iterations for each scenario).

### 4.2.1 Operational gas boiler cases

From Figure 4.2, it can be seen that in the "No subsidies" scenario, there is a 100% likelihood that the PV system gets sized to around 2 kW and no further expansion is seen in the next years, while it is not feasible to install a heat pump together with the existing gas boiler.

On the contrary, in the "All subsidies" scenario scenario it is 100% likely that the heat pump can be feasibly added with a size of around 5 kW even though there is an already existing gas boiler which is supplying the maximum demand, and the PV system size from 2022 until 2030 gets fully expanded to 10 kW. This is also observed on the "PV feed-in" scenario when only the PV feed-in exist with no heat pump subsidy.

In addition, in the "HP subsidy" scenario, the heat pump subsidy allows to install a heat pump of around 5 kW as in the last two scenarios with the exception that in this scenario the PV system size is also the same size as the heat pump and not fully exploited, which can explained due to the lacking PV feed-in.

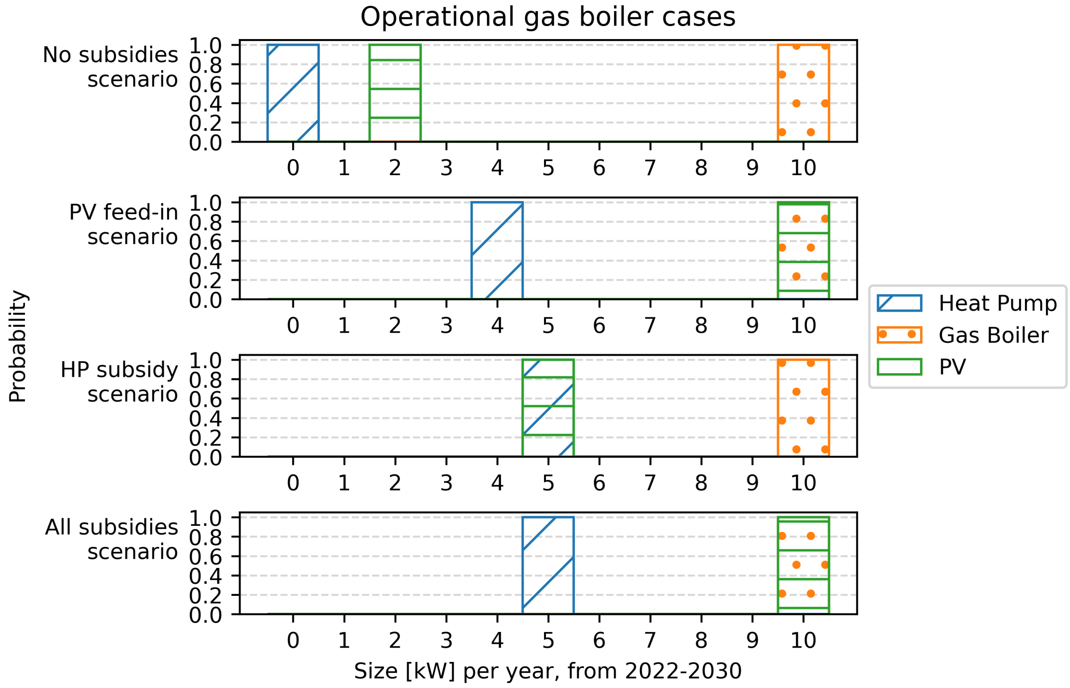


FIGURE 4.2: Probability distribution for the operational gas boiler cases for each scenario. The results for each year from 2022 until 2030 were the same, so instead of repeating the same result for each year, this Figure only shows it once

### 4.2.2 Broken gas boiler cases

Figure 4.3 depicts the probability distribution for the broken gas boiler cases for each scenario. As the probability distribution for some years were the same within each scenario, it was decided to put those same results in clusters containing the respective years, instead of repeating the same result. This is explained as follows. In the "No subsidies" scenario, the probability distribution in 2024 is the same as for the following years until 2030. Similarly, in the "PV feed-in" scenario, the probability distribution of 2023 and 2024 are the same, and similarly from 2027 until 2030. For the "HP subsidy" scenario, the probability distribution from 2022 until 2024 are the same, and same situation from 2029 until 2030. For the "All subsidies" scenario, probability distribution of 2022 until 2024 are the same, as well as the probability distribution from 2028 until 2030.

It is observed that in the "No subsidies" scenario, only in 2022 the choice is always to select a heat pump to supply all the demand rather than a gas boiler and increase the PV size up to 5kW. Then, in 2023 it is 95% likely that the gas boiler is selected over the heat pump together with the existing PV size of 3 kW, while it is only 5% likely that the heat pump is selected over the gas boiler together with a PV size expanded until 5 kW. In the following years (2024-2030), there is a 100% chance that the gas boiler is selected over the heat pump, while the PV size remained the same size as in the operating case (3 kW). This dominance of the choice of a gas boiler over the heat pump can be explained by a cheaper gas price in comparison with the electricity price as seen in Figure 3.4.

On the other hand, in the "All subsidies" scenario, from 2022 until 2024 it is seen that there is 100% chance that the heat pump is selected over the gas boiler and expanded from the 5kW that was present in the operational gas boiler cases until the maximum demand, together with the existing PV size of 10 kW. Then, from 2025 until 2027 a particular situation is reflected: it is 60% likely that the heat pump is being selected and fully expanded while the gas boiler is not, and there is 40% likelihood that the existing heat pump size of 5kW which was previously shown in the operational gas boiler case is selected together with a gas boiler of sizes that ranged between 4 kW and 6 kW so that both technologies supply the demand. In other words, a hybrid heating system is present: gas boiler and heat pump. This situation in 2025 of a hybrid heating system can also be seen occurring in 2026 but with a slightly higher probability (43% in 2026 vs 40% in 2025), while the choice of selecting a heat pump fully expanding it over the gas boiler has a slightly lower likelihood (58%) than in 2025 (60%). In 2027, a hybrid heating system has only a 10% chance of occurring, while selecting a heat pump over a gas boiler is very likely to happen (90% probability). From 2028 onward, the heat pump has a 100% probability of being selected over the gas boiler.

By observing the "PV feed-in" scenario, it is seen that the situation in 2022 is the same as for the "All subsidies" scenario, i.e., the heat pump is selected always over the gas boiler. Then, from 2023 until 2030 it is observed that there is a 100% likelihood that a hybrid heating system is selected together with the fully PV system size. The reason why the hybrid heating system is preferred over selecting only the heat pump can be attributed to the lack of a heat pump subsidy in this scenario, in contrast with the "All subsidies" scenario where the heat pump subsidy resulted in a higher likelihood of selecting a heat pump over the gas boiler and a less probability of mixing overall.

In the "HP subsidy" scenario, from 2022 until 2024 it is seen that there is a 100% likelihood that the heat pump is selected over the gas boiler, together with a PV size of 5 kW instead of full 10 kW which can be explained due to a lacking PV feed-in, as compared with the "All subsidies" scenario where the existence of the PV feed-in fully expands the PV capacity. From 2025 until 2028, there are some situations in which the heat pump is selected over the gas boiler, and others where a hybrid heating system is selected. Although the probabilities of these cases vary throughout these years, it is seen that in 2025 and 2026 it is more likely that the heat pump is selected together with a gas boiler (between 55% and 65%), than the heat pump selected over the gas boiler (between 35% and 45%), while for 2027 and 2028 it is much more likely that the heat pump is selected over the gas boiler (between 80%

and 95%) than selecting a hybrid heating system (between 5% and 20%). For the remaining years (2029 and 2030), it is 100% likely that the heat pump is selected over the gas boiler.

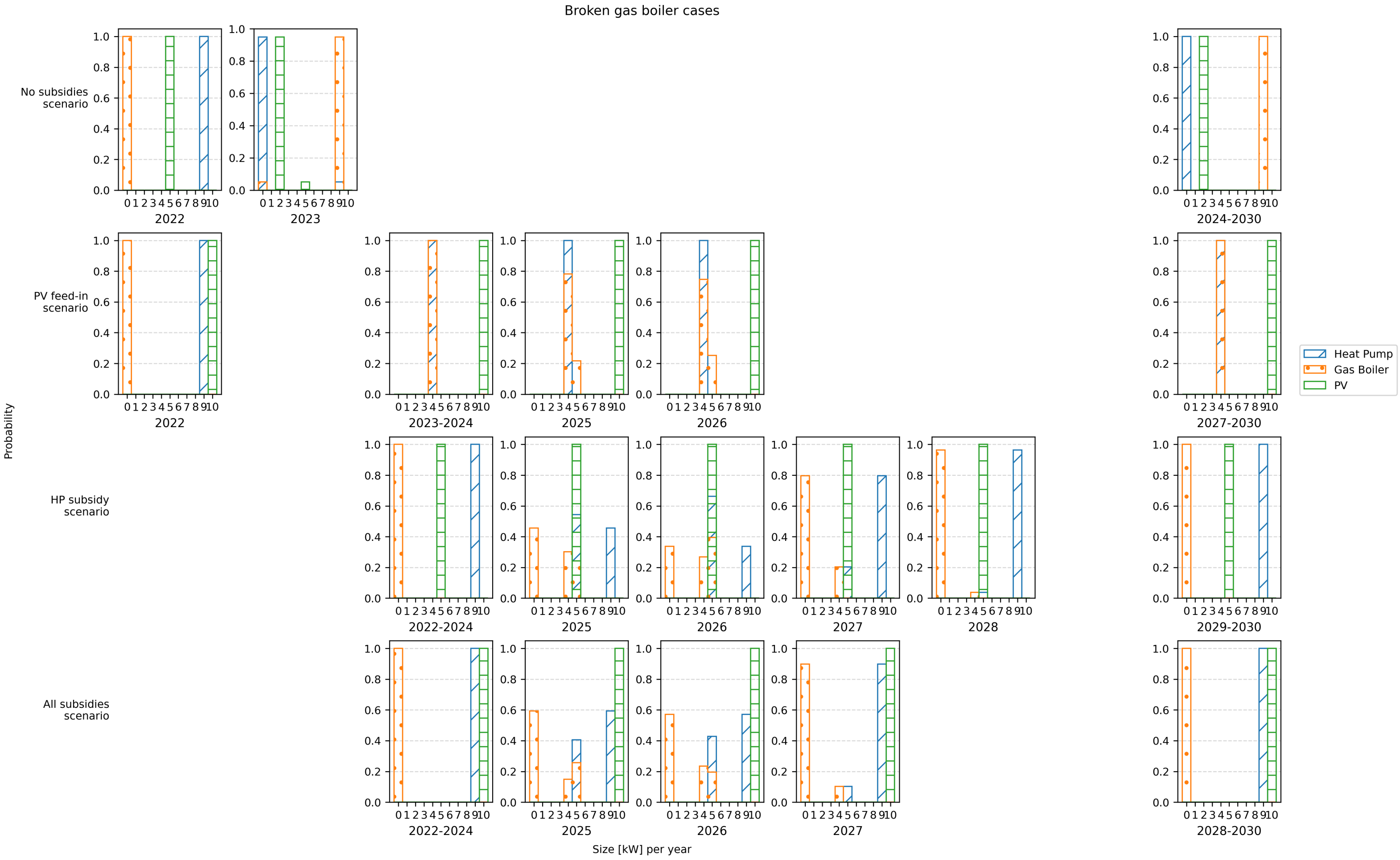


FIGURE 4.3: Probability distribution for the broken gas boiler cases for each scenario

### 4.2.3 Analysis of the final situation in 2030

Looking at 2022 for each scenario within each of the gas boiler cases (operational and broken), by taking the sum of (1) the product of the probability distribution for each technology for the operational gas boiler cases, Figure 4.2, with the number of cases in Figure 4.1, and (2) the product of the probability distribution for each technology for the broken gas boiler cases, Figure 4.3, with the number of cases, also in Figure 4.1) the result represents the total frequency of each technology for 2022 for each scenario. By applying this same operation for the next year, i.e., 2023, until 2030, and then dividing the frequencies by 1000 (as there were 1000 iterations), the result represents the overall probability distribution per technology and per scenario, which can be seen in Figure 4.4 for 2030. An overall yearly probability distribution from 2022 until 2030 can be seen in Figure A.1 from Appendix A. Figure 4.4, which gives the overall probability for 2030, is relevant to answer the research question from an overall perspective, as explained in the next paragraph.

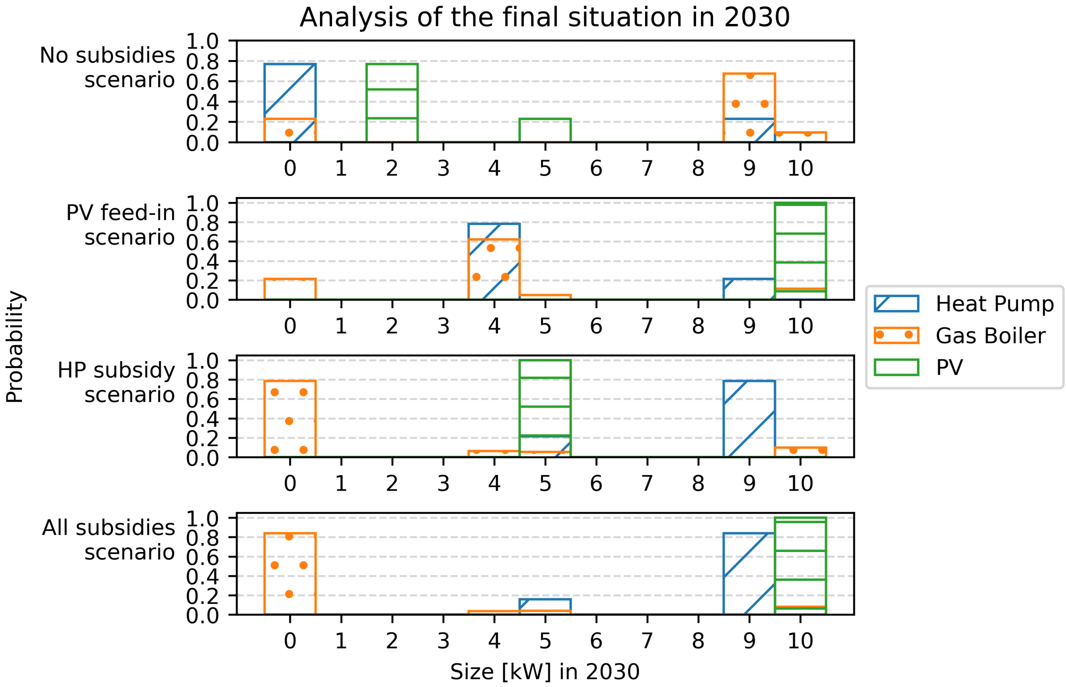


FIGURE 4.4: Probability distribution for all the gas boiler cases (operational and broken) for each scenario up to 2030

So, the research question of this investigation (*what effects do incentives, policies and starting situations for residential users have on the evolution of residential energy demands from 2022 until 2030?*) can be answered, in overall, as follows. Without the heat pump subsidy and the PV feed-in, as well as with the expected forecast of the electricity and gas prices as observed in Figure 3.4 and current investment prices for gas boiler and heat pump, by 2030 there is a 78% likelihood that the household will have a gas boiler over a heat pump to supply the demand, together with a PV system size of up to 3 kW, and a 21% likelihood that a household will have a heat pump over a gas boiler and a PV system size of up to 5 kW. Moreover, it is found that if these incentives exist, the heat pump subsidy is having a stronger effect on gas boilers being replaced (sum of stand-alone and in hybrid system) than the PV feed-in. On one hand, with a heat pump subsidy and no PV feed-in, as seen in the "HP subsidy" scenario, by 2030 it is 77% likely that a heat pump will be present rather than a gas boiler, 10% likely that a household will have a gas boiler rather than a heat pump and 13% likely that a hybrid heating system will be in existence. On the other hand, with no heat pump subsidy and an existing PV feed-in, as seen in the "PV feed-in" scenario, by 2030 it is 21% likely that a household will have a heat pump over a gas boiler, 11% likely that a gas boiler will be present over a heat pump and 68% likely that a hybrid heating system will be in existence. Finally, with both a heat pump subsidy and a PV feed-in, as shown in the "All subsidies" scenario, there is a 83% likelihood that a heat pump is selected over a gas boiler, a 17% likelihood that a hybrid heating system is selected, and no likely at all that only a gas boiler will be present.

## 4.3 Interdependencies and technology lock-ins

The interdependencies and technology lock-ins that the household experienced were identified as follows:

### 4.3.1 Interdependencies

1. When the gas boiler was operational, Figure 4.2, the existence of at least one of the incentives (heat pump subsidy or PV feed-in) promoted a strong interdependence between a heat pump and a PV system. In other words, the subsidy(s) allowed the installation of a PV system size that promoted also the installation of a heat pump, which was not seen possible when there were no subsidies because in this latter scenario even though a PV system installation was allowed, a heat pump installation was not.

2. The previous interdependence between the heat pump and the PV when there were subsidies was also observed when the gas boiler broke as seen in Figure 4.3. Moreover, the existence of either one or both of the subsidies allowed situations in which a heat pump was selected together with a gas boiler so that the sum of the heat generation of each one equaled the heat demand, resulting in an interdependence between them.

### 4.3.2 Technology lock-ins

1. When the gas boiler broke, it was replaced by a new gas boiler instead of a heat pump when there were no subsidies, as seen in Figure 4.3.
2. As long as there was an operational gas boiler and it did not break, the household continued to use it to supply the heating demand, which is observed in Figure 4.2. Even though one of the subsidies or both of them, i.e., PV feed-in and/or HP subsidy, resulted in allowing a heat pump and a PV system with sizes greater than the ones in the scenario of no subsidies, the operational gas boiler still provided part of the heating demand needed for the household.

In addition, as mentioned in Section 2.2.2 a new regulation may be implemented, stating that at least 65% of the source of heating in residences must come from renewable energy, starting in 2024. If this regulation is approved, this should support the penetration of heat pumps in households by promoting strong incentives with the purpose of avoiding technology lock-ins, as the one observed with the gas boiler as identified previously when there were no incentives.

## 4.4 Limitations of the household energy system model

The results shown depend on the assumptions, thesis scope and boundary conditions presented before in Chapters 2 and 3. So, a change in these three latter aspects to represent more real-life behavior may influence the results. These will be discussed as follows.

- An annuity loan for 20 years was assumed for the economic feasibility analysis of selecting a heat pump, gas boiler and solar rooftop PV system. In reality, the single-family home may not opt for an annuity loan, but instead for a one-time investment payment. In this latter situation, there may be a yearly investment limit which depends on the income and expenses from the members of the household, which may lead to a constraint for the decision making of installing a heat pump, gas boiler or PV system.
- The members of the household were assumed to be under a *Homo economicus* thinking every year, but in reality it has been proved that humans are not fully rational when taking decisions [53]. This may lead in reality to not taking the decision-making process with a frequency of a year as was assumed in this thesis, but rather randomly (e.g. every four years, only once from 2022 until 2030, etc) or even some cases of not having a conscious decision-making process at all during the following years.
- Specific technologies for heating were chosen: air-to-water heat pump and combi gas boiler. However, as presented before in Chapter 2, there are also

other types of heat pump technologies (air-to-air, ground source, water source) and other gas boiler types (low temperature and high temperature) in German households. Considering these other types may modify the results not only due to a different investment cost, but also due to new components added to the energy system, as for example the addition of a hot water storage tank. In addition, there may be technical limitations, as for example space limitations for installation and availability of manpower. To add, home renovation might be needed before installing a new technology, but this was out of the scope of this thesis.

- A fixed household gas price was assumed through each iteration, in contrast with the electricity price which due to the property of being a Markov chain it varied throughout each iteration. Assuming a Markov chain for the gas price and giving limits for its minimum and maximum expected gas prices for the following years may influence the results
- A private ownership model for DES was assumed. As presented in Section 2.2, however, around 50,5% of households lived in residences not owned by them, so in reality considering this fact may influence the decision-making process of installing new residential technologies, as the household may not have full control in the process and may request a discussion with the landlord.
- Two different weather datasets were employed for the generation of the heat profile and the PV profile, as mentioned before in Section 3.2. On one hand, the hourly heat profile was generated from test reference year (TRY) temperatures for the reference period 1995-2012 from the Deutscher Wetterdienst. TRY data describes average hourly data that is common for a year and is useful for adequately sizing heating systems [41]. On the other hand, the hourly PV profile was generated through the online platform PV GIS with ERA5 radiation data for 2020. ERA5 is a dataset from the European Centre for Medium-Range Weather Forecasts (ECMWF) which considers both sensors on earth and satellite data to produce long term data [54].
- A constant investment price [EUR/kW] was assumed for a heat pump, gas boiler and solar rooftop PV. A price experience curve which considers situations such as a decrease of the investment price may be investigated further

# Chapter 5

# Conclusion

The aim of this master thesis was to investigate the likelihood and viability of different development paths for DES in different contexts and frame conditions. The research question to be answered was: *what effects do incentives, policies and starting situations for residential users have on the evolution of residential energy demands in Germany from 2022 until 2030?*

It was found that in a scenario where there were no incentives for the installation of heat pumps and solar rooftop PV systems, there was a 78% probability that the household had only a gas boiler and a 21% probability that a heat pump was only selected. This high likelihood in having a gas boiler rather than a heat pump can be attributed to the fact that the electricity price was higher than the gas price for the following years, and the investment cost for a heat pump is higher than the one for a gas boiler. The absence of subsidies yielded in overall a significant gas boiler penetration over heat pump. Then, in a scenario with only PV feed-in incentive, there was a 68% probability that a hybrid heating system was present, a 21% probability that the heat pump was in place and a 11% likelihood that the gas boiler was present. In the scenario with only a heat pump subsidy, there was a 77% probability that a heat pump was present, a 13% probability that a hybrid heating system was present and a 10% likelihood that a gas boiler was present. Finally, in a scenario where both a PV feed-in incentive and a heat pump subsidy existed, there was a 83% probability that a heat pump existed, a 17% likelihood for the existence of a hybrid heating system and 0% likelihood of the existence of only a gas boiler.

Further research can be focused on quantifying the effect of the following considerations: budget of a household, selecting other heat pump and gas boiler types as well as hot storage or water storage, stochastic behavior of the gas price, other ownership model for DES such as community-owned and utility-owned, hybrid heating system incentives, home renovation, price experience curves for heat pump, gas boiler and solar rooftop PV.

## Appendix A

# Yearly probability distributions for each scenario

The overall probabilities for each year for the sizes of the gas boiler, heat pump and PV for all the cases combined, i.e., operational and broken, can be seen in Figure A.1.

Figures A.2, A.3, A.4 and A.5 show the probability distribution of the sizing of the heat pump, gas boiler and PV system in the household for each year from 2022 to 2030 for each scenario. In each Figure, there are three cases shown with respect to the status of the initial gas boiler: operational gas boiler cases, broken gas boiler cases and other cases. This latter refers to the cases when the initial gas boiler broke before the year in question. For example, by looking at other cases in year 2030, the probability distribution shown refers to all the cases when the initial gas boiler broke in 2029 or before. This excludes 2022, because in 2021 there is always an operating gas boiler, so there is no plot for the year 2022 for other cases. The number of operational, broken and other cases for the initial gas boiler can be found at the top of each plot. For each year, the sum of the operational, broken and other cases for the initial gas boiler is equal to 1000, as there were 1000 iterations.

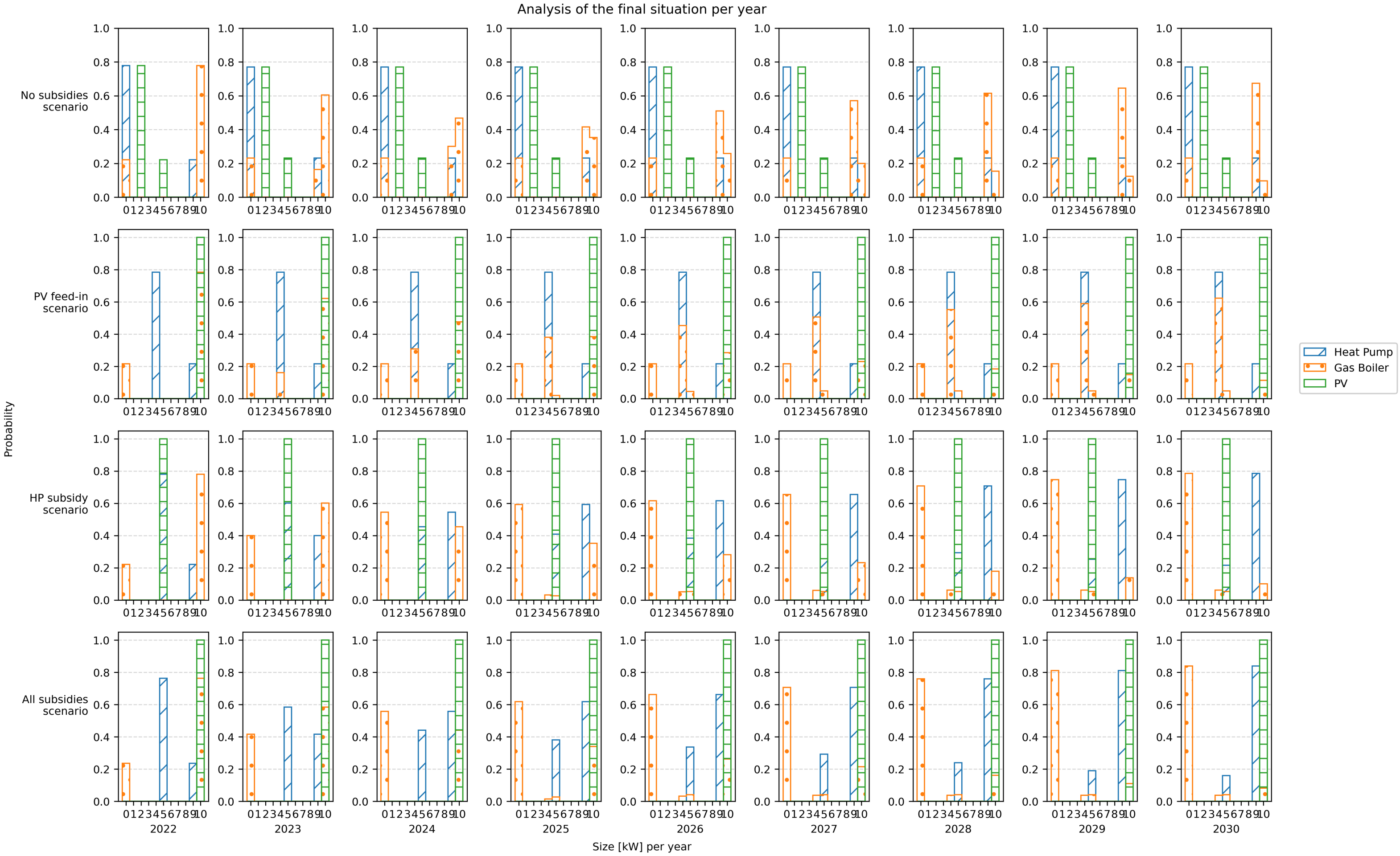


FIGURE A.1: Analysis of the final situation per year, from 2022 until 2030

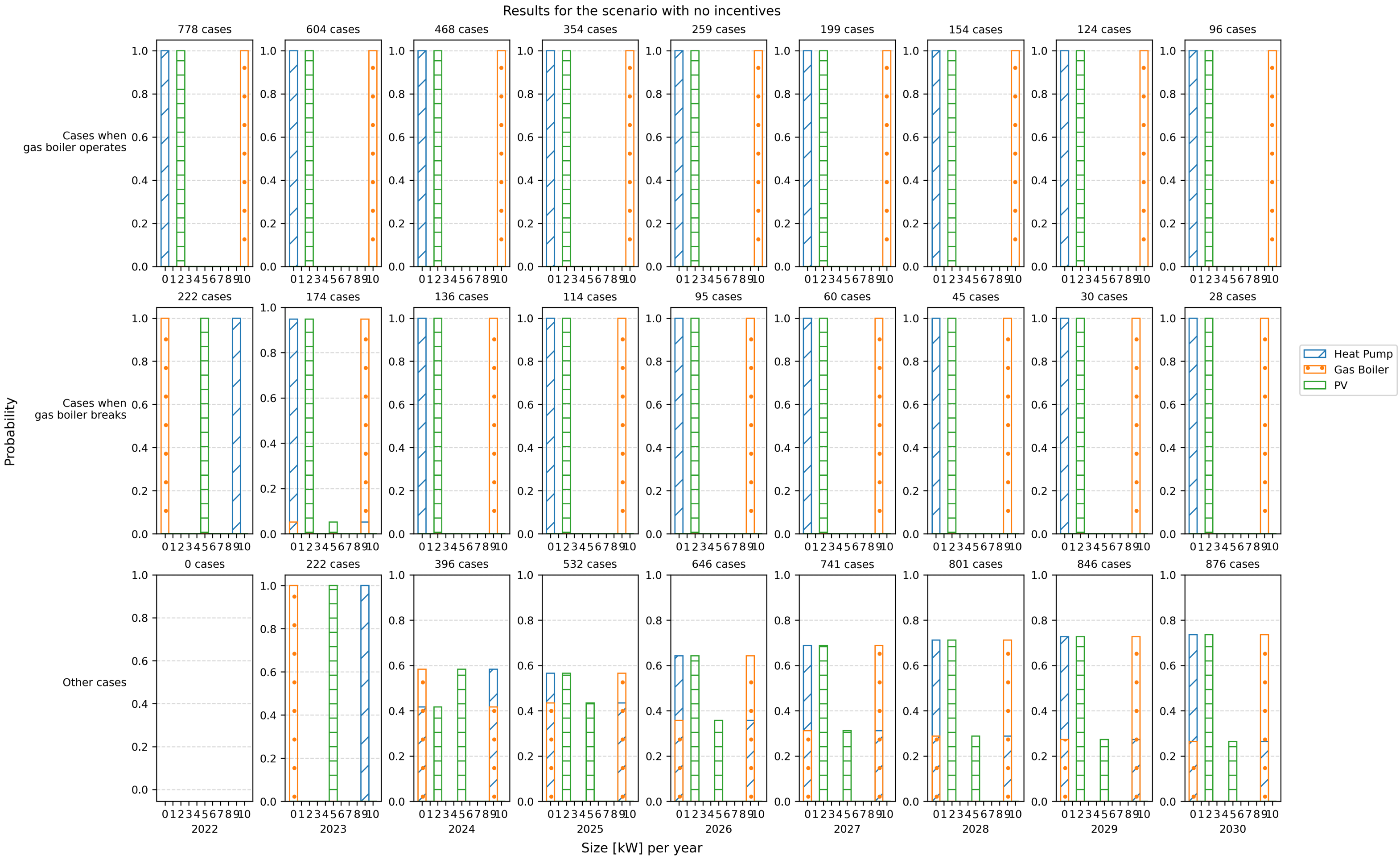


FIGURE A.2: Results for the scenario with no incentives

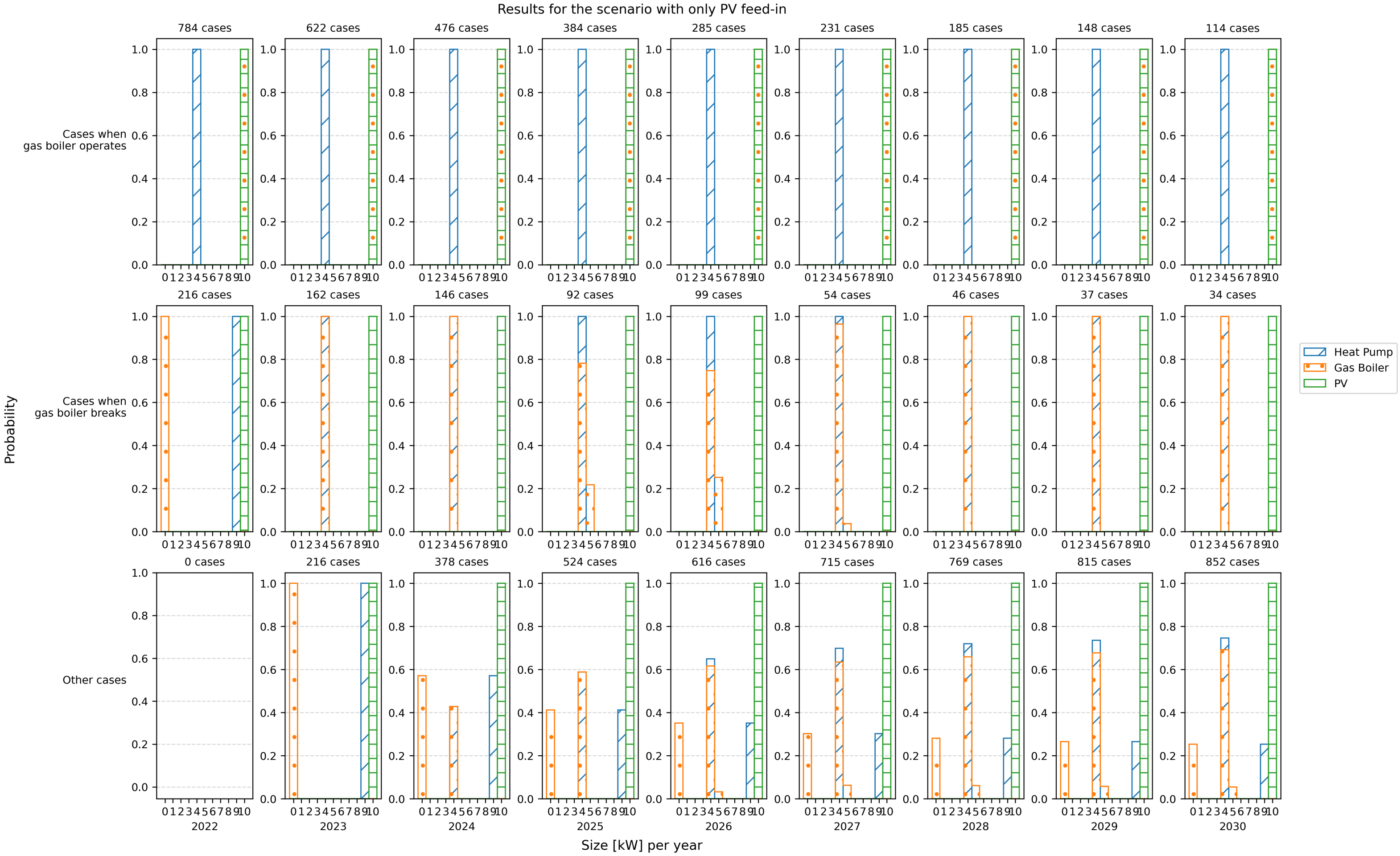


FIGURE A.3: Results for the scenario with only PV feed-in

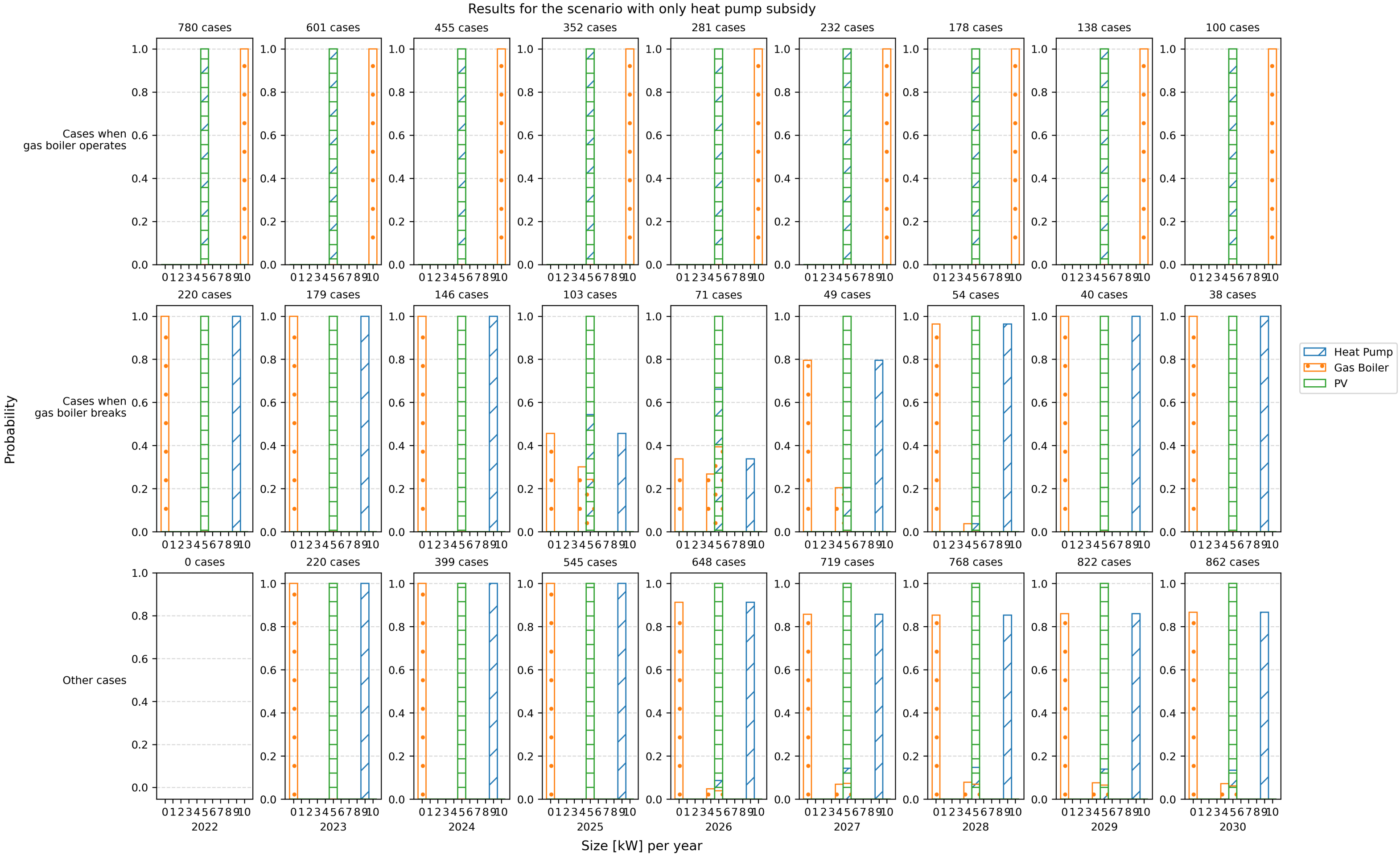


FIGURE A.4: Results for the scenario with only heat pump subsidy

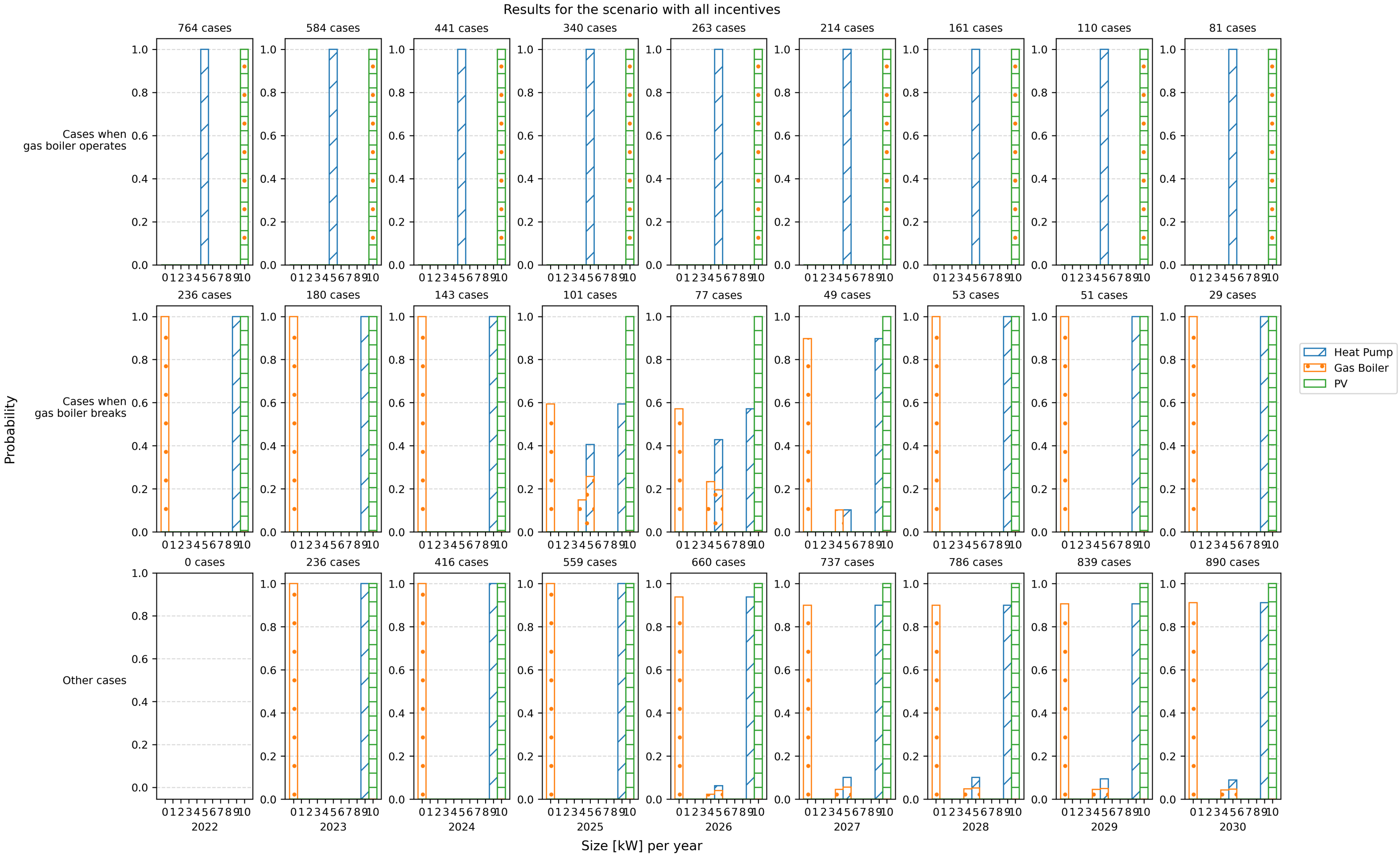


FIGURE A.5: Results for the scenario with all incentives

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# Declaration of Authorship

I, Carlos Eduardo Munoz Robinson, hereby declare in lieu of an oath that I have written this work independently and that I have not used any other sources and aids other than those indicated. Furthermore, I confirm that I have complied with the general principles of scientific work and publication, as laid down in the guidelines of good scientific practice ("Leitlinien guter wissenschaftlicher Praxis") of the Carl von Ossietzky University of Oldenburg.

Signature: ______________________________