Heat Pump Adoption in Germany:

A Model-based Study of the Influences on the Diffusion of Innovation in Space Heating

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Abstract

Heating accounts for two-thirds of the final energy consumption of private homes in Germany, with gas and oil heating dominating the market at a 65% share. Decarbonizing heating is crucial for achieving climate neutrality, with heat pumps being a key solution: They are energy efficient and powered with electricity. Despite gaining momentum, the adoption of heat pumps remains slow. This thesis aims to assess the various factors influencing heat pump adoption, identify strategies and find leverage points to accelerate the exchange of heating systems using a System Dynamics approach. A computational simulation model has been developed that integrates an innovation diffusion model with feedback on costs and capacity development, as well as external factors such as gas prices. Key insights are that the adoption of heat pumps is limited by the low number of heaters exchanged each year due to their long lifespan and high upfront costs. This limits the accumulation of heat pumps which furthermore influences the probability of others adopting them and "locks in" the system in a state where fossil heaters remain the norm. The model-based identified leverage point to accelerate the process is an increase in gas price.

Keywords: heat pumps, space heating, innovation diffusion

Content

Abbreviations

List of abbreviations used in thesis and model:

SD	System Dynamics
STFH	Single- and two-family home
MFH	Multi-family home
HP	Heat pump
FH	Fossil heater
CPI	Consumer price index
BAU	Business as usual

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1. Introduction

Germany has set climate goals to protect the environment and adhere to the international Paris Agreement. This includes a reduction in emissions of 65% compared to the levels of 1990 until the year 2030, and of 88% until 2024 and carbon-neutrality by 2045 (BMWK-Bundesministerium für Wirtschaft und Klimaschutz, n.d.). In 2021 more than two-thirds of the final energy consumption of private homes was used for heating, mainly in the form of gas and oil (Wilke, 2023). This shows the high potential of reducing emissions in this sector, by switching to more sustainable heating methods. Additionally, replacing fossil fuels also reduces dependencies on imports from other countries.

One sustainable alternative to gas and oil heaters are heat pumps. This chapter discusses the characteristics of heat pumps and why I will focus on them. It further includes the reference mode of behaviour, including context for the historic development, and the problem definition. In the next chapter, System Dynamics (SD) is introduced and through a literature review and an expert interview, a Causal Loop Diagram (CLD) and corresponding Stock and Flow Model is developed. In the third chapter, the model is validated and in the fourth chapter, the model and possible policies are analysed. At last, the results are discussed, and limitations are shown.

The thesis is partly based on an earlier report written for the course GEO-SD323 in the Autumn semester 2023 (Siemer, 2023).

1.1. Heat Pump Mechanisms

Heat pumps are devices that can transfer heat from one place to another. They can heat and cool a space by moving thermal energy in opposite directions. In heating mode, a heat pump will extract heat from an outside low-temperature heat source (e.g. the ground or air) and transfer it inside the home. This is possible because even cold air contains heat energy. The heat pump uses a refrigerant to absorb the heat from outside, compresses it, and then releases it inside the home. Usually, the energy required for transfer is provided by electricity. Combined with electricity generated from renewable sources this makes them especially environmentally friendly (Lowe, 2007, p. 418).

In contrast, most other heating methods generate heat directly from a source such as oil or gas, not by transporting heat. In this way, one unit of energy can generate one unit of heat. Since heat pumps transfer heat, they are much more energy efficient and, depending on the outside temperature, they usually have a factor of 3,5 meaning that 3,5 units of heat are transferred into the home for every unit of energy. However, heat pumps usually work with lower temperatures than traditional heating systems. They are more efficient, the smaller the difference between the heat source and heat sink (Born et al., 2017). Therefore, radiators with a bigger surface area or ideally underfloor heating are best to ensure the heat gets transmitted efficiently into the living areas. Additionally, good insulation is recommended.

While energetically, heat pumps save energy compared to other heating methods and can be powered with renewable energy, the financial benefits depend on the price of electricity compared to other sources of energy such as gas and oil. The initial costs for installing heat pumps are usually higher compared to traditional heaters, especially for existing homes that might need to be refitted. This can include the exchange of radiators or improving insulation.

Heat pumps can have a variety of different heat sources, such as air, ground, or (waste-)water, that also lead to different characteristics. For example, ground-source heat pump installations are expensive, since they involve drilling to access the heat source underground. However, they are more efficient compared to air-source heat pumps due to higher and more stable temperatures in the ground (Blum et al., 2011). Depending on the source, a different amount of space is required to place the heat pump device, which can be a challenge in urban areas. Furthermore, noise emissions from heat pumps can be an issue for homeowners and neighbours.

Heat pumps can be installed in single- and two-family homes (STFH) and apartment buildings (MFH). Installing HPs in apartment buildings is more complex and technically challenging compared to STFHs, but there are several possibilities for installing HPs in apartment buildings. The implementation depends on the conditions of the specific building, but options range from fully centralised systems to fully decentralized systems, that include small heat pump units for each apartment (Miara, 2022).

Finally, it is also important to consider alternatives to heat pumps. There are other sustainable heating methods such as biomass, hydrogen heaters, or district heating using waste heat. However, district heating is a rather limited option as it depends on the availability of waste heat. Hydrogen heating might be adopted by very few individuals but is unlikely to become economically viable in the near future (Baldino et al., n.d.). Biomass can be an alternative for some homeowners, but is also limited due to limited (local) available biomass for this purpose (Vávrová et al., 2018). Therefore, heat pumps seem the most prominent candidate to replace gas and oil heaters on a large scale.

1.2. Problem Formulation

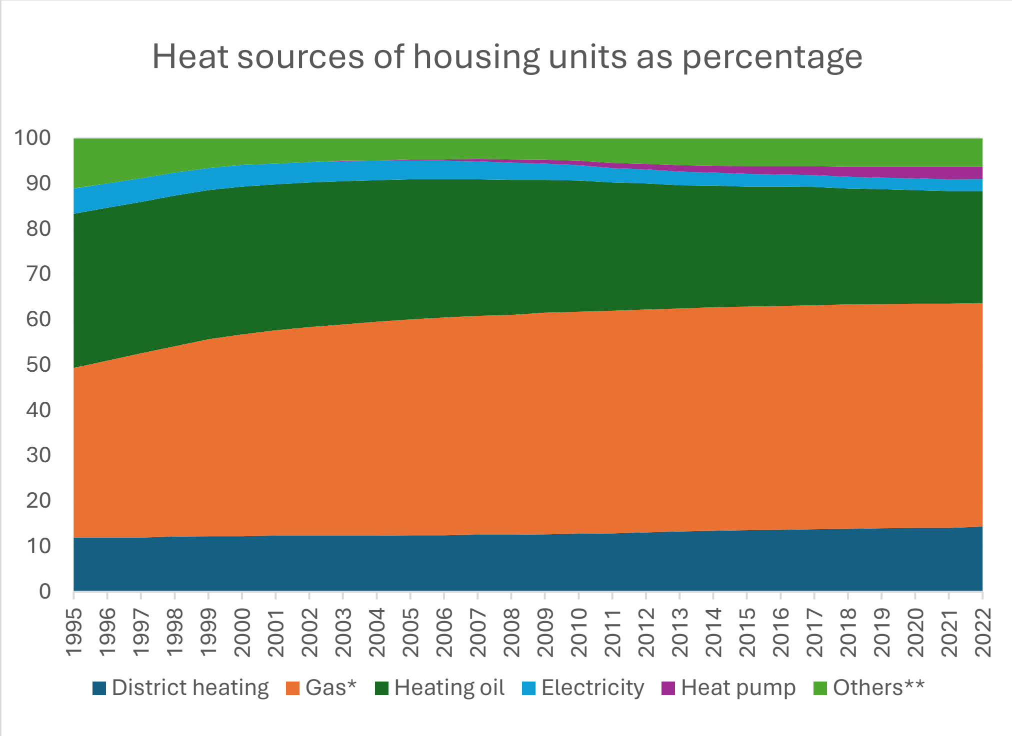

Figure 1 Heat sources of housing units in Germany in per cent. Own depiction based on data from BDEW (2023).[*]

Figure 1 shows the development of heat sources used in Germany. More specifically, it shows the heat sources of housing units, not buildings. Gas and heating oil are the dominating methods with a total of 74% in 2022. District heating is often used for apartment buildings and powers between 12 to 14,4% of housing units in Germany. Electricity is used by a small but declining part of the population (5,6 to 2,7%). Other heating methods include sustainable and non-sustainable methods, inter alia pellet heating, solar thermal energy, and coal. Heat pumps have increased, but still only encompass 2,7% of the heat sources (0,1% in 2003). One of the reasons for the small number is that per heat pump usually only one housing unit is supplied. In 2016 94% of heat pumps in residential buildings were installed in STFHs. Previously the ratio of MFHs heated with HPs has been even lower (Born et al., 2017). Air-source heat pumps started as a minority in Germany but are now by far the most common type (Bundesverband Wärmepumpen e.V., n.d.). Sometimes apartments or buildings are heated using a combination of two or more heat sources, e.g. using solar thermal energy for drinking water and gas for space heating, it is not specified in the source how this is depicted in the data. In the following, I will concentrate on fossil heating (oil and gas) and heat pumps, for simplification and relevancy.

[*] * Gas including renewable natural gas and liquid gas ** inter alia pellet heating, solar thermal energy, and coal

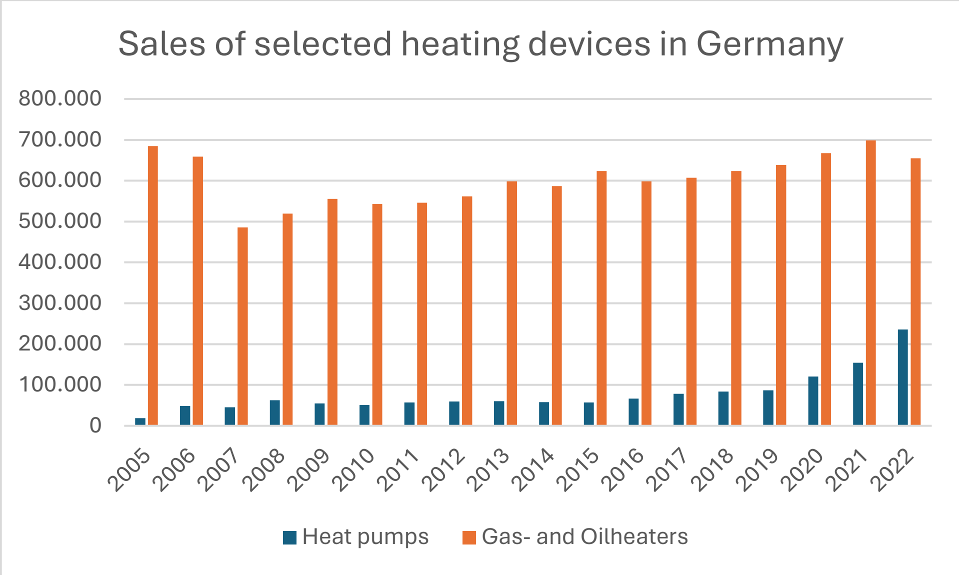

Figure 2 Total sales of selected heating devices in Germany. Own depiction based on data from Deutsche Energie-Agentur (2023).

Gas and oil heaters not only dominate the inventory but also the current sales figures (see Figure 2); despite an overall positive development for heat pumps, in 2022 there were still approximately 2.8 times more fossil fuel heaters sold than heat pumps. Heat pump sales cached momentum after 2019 when sales increased from around 86.800 per year (2019) to 236.000 in 2022.

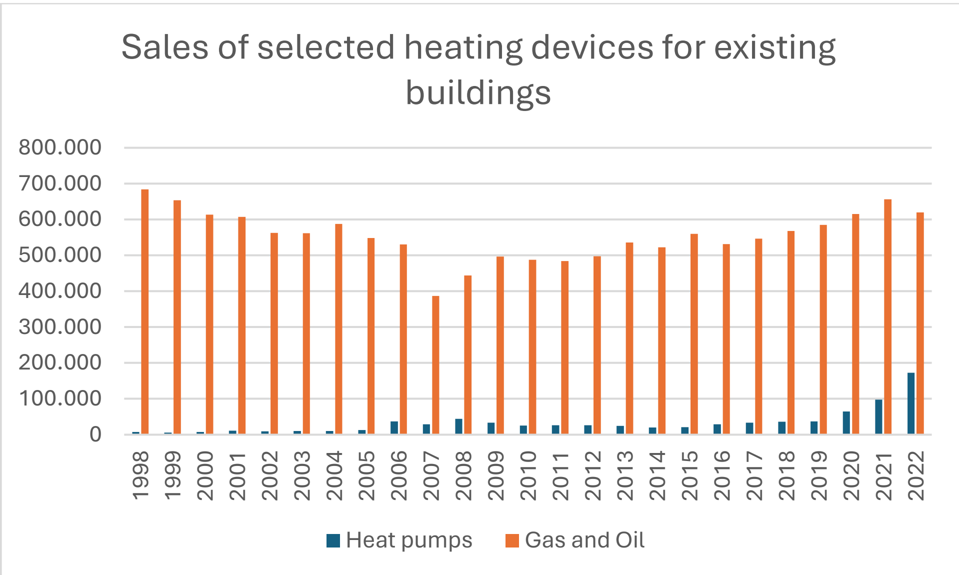

Figure 3 Sales of selected heating methods in existing buildings. Own depictions based on Deutsche Energie-Agentur (2023)

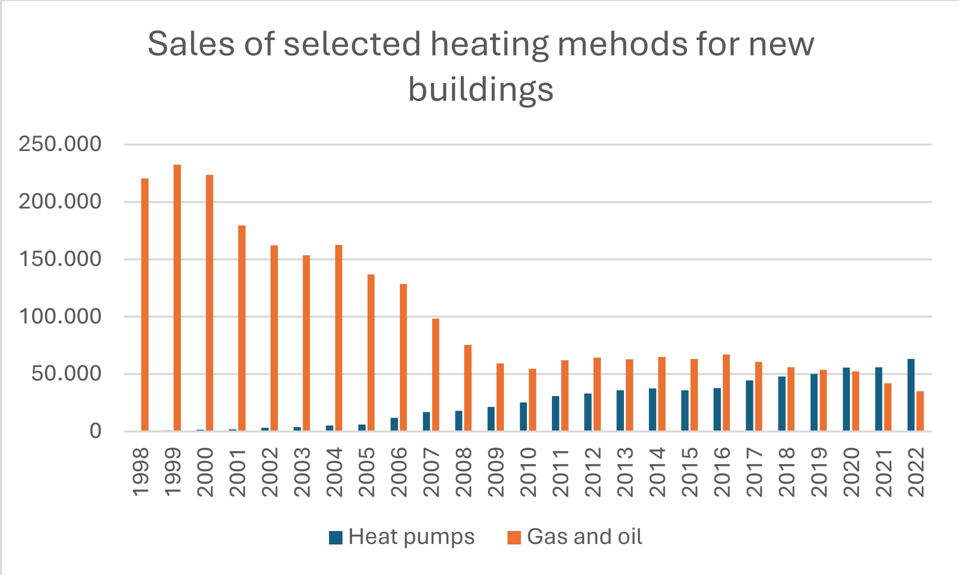

Figure 4 Sales of selected heating methods in new buildings. Own depictions based on Deutsche Energie-Agentur(2023)

Differentiated by installation in new and existing houses, as shown in Figures 3 and 4, two different trends can be seen: Despite the overall decline in heater sales for new buildings, due to a decline in construction, heat pump sales increased approximately linearly from 600 (1998) to 63.300 (2022). In 2020 for the first time, more heat pumps were installed in new buildings than oil and gas heaters together. On the other side, in existing buildings, which encompass the majority of heater demand, oil and gas heater installations are still the majority. The installation of heat pumps has increased overall since 2005, but the increase is much more inconsistent compared to installations in new buildings; this includes sudden increases around 2006 and 2008, a slight drop afterwards and stable, but low installation rates until 2016 and exponential growth afterwards. The Bundesverband für Wärmepumpen (German heat pump association) anticipates stagnation or even decline in 2024 (Bundesverband Wärmepumpen e.V., 2024).

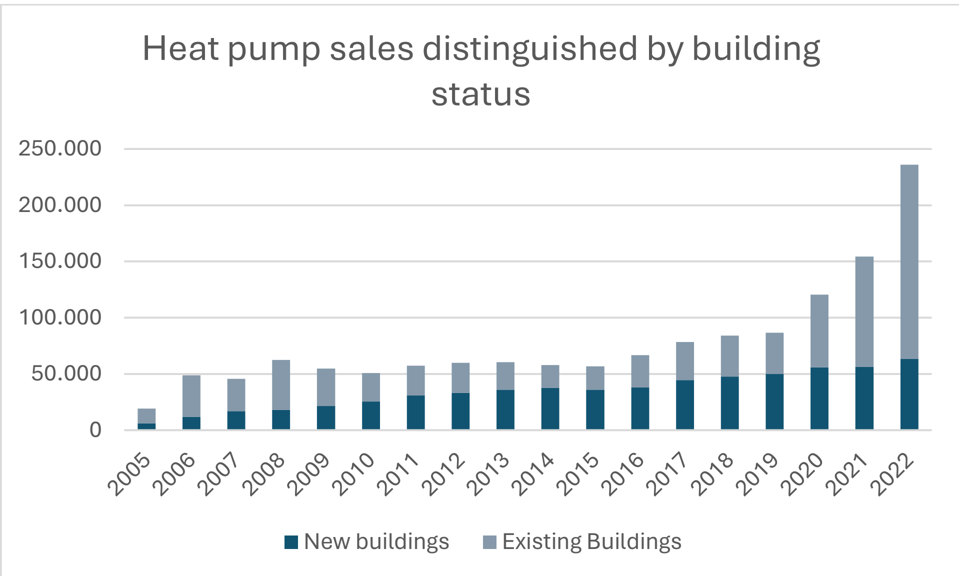

Figure 5 Heat pump sales differentiated by building type. Own depictions based on Deutsche Energie-Agentur(2023)

The steep increase in heat pump demand after 2019, as can be seen in Figure 5, led to a shortage in installation capacity, as well as device availability (Schieritz, 2023), despite the recent increase in workers in the field (Figure 6). Therefore, the uptick has the potential to be even more steep.

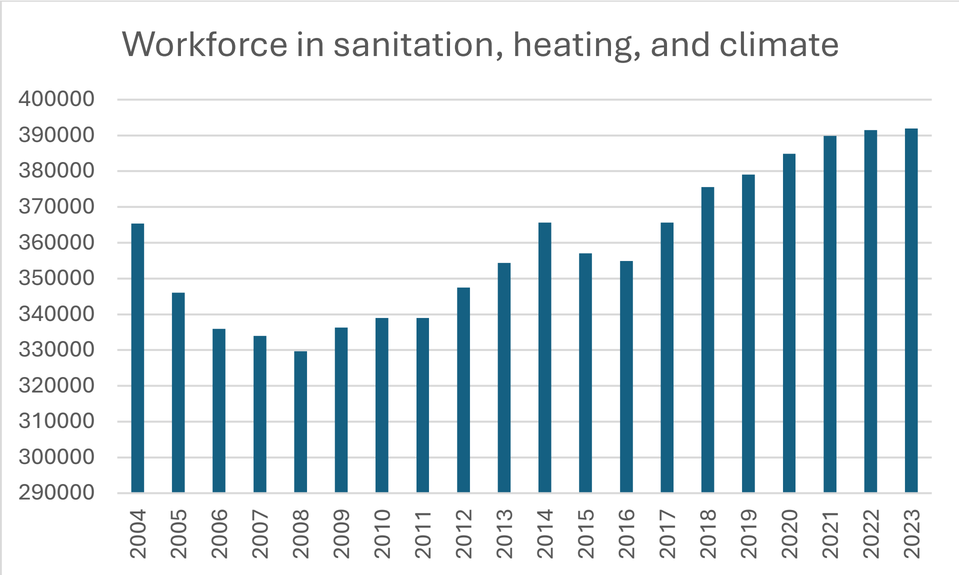

Figure 6 Number of employees in sanitation, heating, and climate. Own depiction based on Scholle (2024).

1.2.1. Context of Historical Development

The huge discrepancy between the apparent success of heat pumps, when looking at yearly sales, and the small fraction of housing units that they heat, can be explained through a combination of factors. While most gas heater producers suggest a lifespan of 20 years (Kunde, 2021), data shows that 13 per cent of heaters in Germany in 2023 are older than 30 years (Erhebung Des Schornsteinfegerverbands 2022, 2022). The discrepancy between the suggested lifespan and real lifespan is partly due to modern heaters having a shorter lifespan and partly due to homeowners preferring reparations over exchange due to initial costs, even if this results in low efficiency and higher utility costs. All in all, this leads to an exchange of less than 5% of existing heaters per year. Apart from heater exchanges in existing buildings, the composition of the heat source inventory is only affected by building demolitions and new buildings. Additionally, heat pumps are mostly only installed in STFH, therefore only one or two housing units are supplied per heat pump.

The inconsistency in the uptake of heat pumps in existing buildings could be partly explained by gas prices and changes in subsidy regulations. The gas price increase and the increase in heat pump sales correlate from 2005 to their peak in 2008. However, the heat pump sales did not decrease in the same manner as the gas price after 2009 but instead stayed stable at a higher level than before.

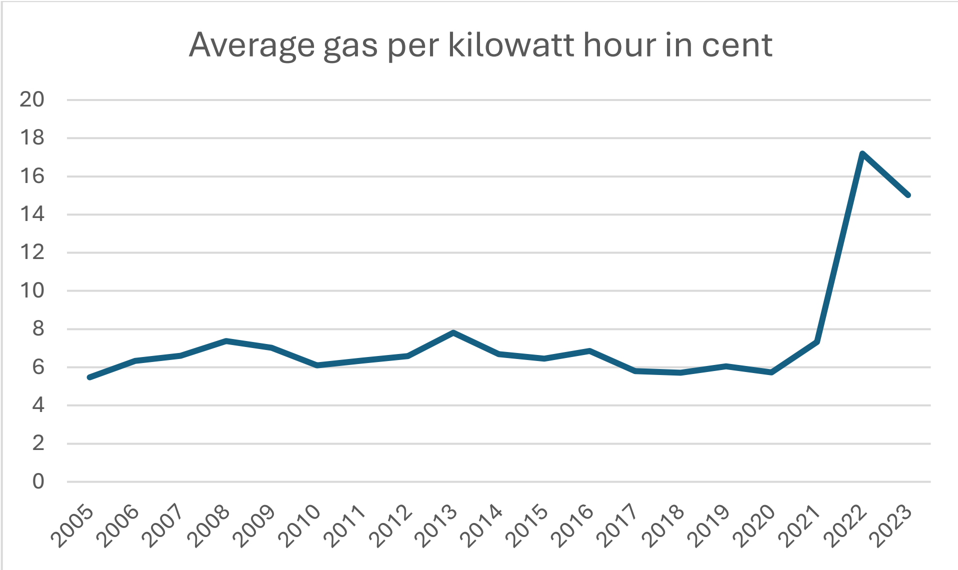

Figure 7 Development of gas price for end consumers. Own depiction based on Verivox (n.d.).

There also is a correlation between the drastic increase in gas prices and heat pump sales in 2022. However, the sales of heat pumps have shot up since 2020 and therefore the high sales in 2022 cannot solely be caused by a higher gas price. This drastic increase could not have been foreseen since it was mainly caused by the Russian invasion of Ukraine. This was unexpected for most people, even many politicians and experts in Germany. Instead, in my opinion, one has to look at the overall political climate in 2020-2021: There was an overall increase of awareness for climate change caused by heatwaves and the Fridays for Future movement. This development could have influenced customers either via an increased desire to live more environmentally friendly or the expectation of increasing gas prices for political reasons such as a carbon tax.

Subsidies and regulations that affect heat pumps play a major role. This includes the following most important incentive programs: Since 2008 the Marktanreizprogramm (MAP, market incentive program), a subsidy programme of the German government, also supports the installation of heat pumps. According to Platt et al. (2010) until 2010 69% of the applications did get support. The support is based on the size of the heated area and consists of up to 15% of the investment costs for existing buildings and up to 10% for new buildings. This could be another influence that led to the increase in 2008. Since 2015 MAP has included financial support for the modernization of the heating system that is necessary when installing a heat pump. The financial support accounts for at least 4.000€ and is based on the size of the living space (Bundesministerium für Energie und Wirtschaft, n.d.)

Homeowners can also apply for specific low-interest credits or credits with repayment bonuses at the Kreditanstalt für Wiederaufbau (KfW, a German state-owned investment and development bank) if renovations improve the energy efficiency of a home to certain standards or a new building is built with a certain standard (Förderprodukte für energieeffiziente Sanierung – Übersicht | KfW, n.d.). These got updated several times during the last few years and do not apply specifically to heat pumps, however, often a renovation is necessary before installing a heat pump. Subsidies not only change demand while they are active but also lead to catch-up effects when homeowners postpone a planned measure to take advantage of announced future subsidies. Vice versa, others might exchange their heaters earlier than necessary to take advantage of subsidies that are about to be discontinued.

1.3. Research Question

The research objective is to gain an understanding of the processes involved in changing towards sustainable heating. This includes identifying the drivers and obstacles of change and exploring basic policy options. However, it does not include extensive policy recommendations, as the thesis excludes political and social trade-offs that need to be discussed before such recommendations are possible and ethical. Instead, it rather aims to show leverage points, and the tools to address these leverage points need to be discussed separately from this thesis.

The following questions will be addressed in this work:

1. *What factors contribute to and slow down the adoption of heat pumps in Germany?*
2. *How do these factors interact with each other and influence the behaviour of the system?*
3. *What policy options can be identified to speed up the adoption of heat pumps?*

The first question aims to increase the understanding of the underlying feedback structure and its positive and negative influences and is answered in Chapter 2. The second question is answered in Chapter 4 and lastly, the final research question is answered in Chapter 5.

2. Methodology

To answer the research questions, a System Dynamics (SD) model has been developed, including different policy scenarios. SD is a computer modelling method in which stock and flows are used to recreate a real-world system. Its strength is the consideration of accumulation and delays and the use of feedback loops to explain behaviour. The creation and analysis of a model help to understand the underlying causes of a problem. SD is a common method to explain the diffusion of consumer goods, starting with the Bass-diffusion model (Bass, 1969) and its various adaptions and extensions (Sultan et al., 1990). The nature of the problem, the accumulation of a now unwanted heating system, is something that can be modelled well using a stock and flow model. The possibility to use a computer model to analyse the different reactions of the system to proposed policies is one of the great strengths of SD and can help to identify policy resistance.

To develop the model, first, a literature review and an interview with an expert on heat pumps in Germany were conducted. The literature review has been conducted as a narrative review due to the broad scope of the research objective. The interview was semi-structured and took place at the beginning of the research to gain an overview of the topic. There was no additional interview to confirm the model structure after the building process. The interview was conducted voluntary, and confidential.

The literature review consisted of SD and non-SD publications, as well as media coverage when no scientific literature was available on the specific topic. This is necessary to identify the key variables and their causal relationships, which are then summarised in a causal loop diagram (CLD), which is the basis for the stock and flow diagram. This process is not linear. A back-and-forth between literature research, modelling and partial model testing and validation is part of the iterative process that is standard for SD model building. This allows to correct mistakes, refine the structure and build confidence in the model gradually (Sterman, 2000, Chapter 3).

2.1. Comprehensive Analysis: Literature and Expert View

For the literature review, I will first touch upon general literature on the diffusion of innovations or "new products" and then go more into depth on heat pumps specifically. Additionally, an interview was conducted with an anonymous expert on heat pumps in Germany.

2.1.1. Innovation Diffusion in System Dynamics

The basis for SD models on innovation diffusion is comparable to modelling infection (SI- or Susceptible-Infected Model): "The spread of rumors and new ideas, the adoption of new technology, and the growth of new products can all be viewed as epidemics spreading by positive feedback as those who have adopted the innovation 'infect' those who have not." (Sterman, 2000, p. 323) This positive feedback loop is described as social contagion or word of mouth. One of the most influential innovation diffusion models is the Bass-Diffusion Model (Bass, 1969), the growth model for the timing of initial purchases of new products assumes that the probability of purchasing a product depends on the number of previous buyers. Bass describes adopting an innovation with an S-shaped curve, where innovators are the first adopters, and adoption then grows exponentially until the growth slows down when market saturation is nearly reached. This curve only applies to first-time buyers and has shown to be a good fit for many products.

While in the bass diffusion model, only potential market size and adopters, are relevant, later researchers added other explanatory variables to their model (Meade & Islam, 2006, p. 525 ff). The potential market size for hat pumps includes most heated buildings, even though some are fitted better than others. For the sake of this thesis, only residential buildings in Germany are included, and therefore the market size depends on the number of STFH and MFH. Whereas heat pumps are suitable for all STFHs, with very few exceptions, it is more complicated for MFHs.

Despite heat pumps being a non-interactive good, meaning they do not need or profit from other adopters (e.g. in the sense that a telephone user does), social contagion is an important factor for their adoption, as further described below. Therefore, the SI-model is a good starting point.

I especially want to emphasize the use of diffusion models for the diffusion of alternative fuel vehicles (e.g. Keith et al., 2020), as they have many common characteristics with heat pumps: long lifetime, high investment costs, and additional operating costs that fluctuate. Both markets are now driving towards electrification, due to a mixture of environmental concerns, technical innovations, rising costs of fossil fuels and favourable government regulations.

2.1.2. Motives for Energy-Efficient Renovation

While there is a wide variety of literature on the motives and decision-making for energy-efficient renovations, most of it focuses on thermal insulation rather than space heating systems (Friege & Chappin, 2014, p. 11). The literature also focuses on single and two-family homes and their owners, while apartments and renters are neglected, despite a high rate of renters in Germany. Despite this neglect, I will differentiate between STFHs and MFHs, as well as between new constructions and heater exchanges in existing buildings. This is necessary due to the different circumstances and especially financial challenges different types of buildings impose on changes in the heating system, see also Chapter 2.1.3.

While some of the motives for general energy-efficient renovations apply to an exchange of the space heating system, the lack of research on this specific topic leads to uncertainty. Additionally, Hofe (2018) describes the available studies on energy-efficient renovations for home-owners as in parts self-contradictory, but identifies three main motives:

1. economic/financial motives, refurbishment as an investment.
2. refurbishment to improve the living environment.
3. refurbishment decisions as a result of social exchange processes of SFH owners.

Social exchange processes have been confirmed to be an influence not only for renovation but heat pump installation as well. The improvement of the living environment, however, is not confirmed to be a driving factor of heat pump installations. On the contrary, many homeowners fear a decline in their living quality caused by lower heating temperatures or noise (*Expert Interview*, personal communication, 16 February 2024). Environmental protection is a benefit for many homeowners but is ranked lower compared to most other economic and non-economic motives (Achtnicht, 2011).

The importance of the social environment is often explained via Structuration Theory (Giddens, 1984), which claims that friends and acquaintances need to draw the connection between available information and everyday life for individuals to change their behaviour. This underpins the idea of word of mouth which is the basis for innovation diffusion models and causes the S-shaped growth. However, there are also other possible explanations for this, such as the heterogeneity of income distribution: assuming the price of an innovation falls and the income distribution is bell-shaped, this also leads to an S curve.

A majority of studies conclude that financial motives are the most important for the decision. On the one side, homeowners hope to save on energy costs, on the other side, the availability of income increases the willingness to invest in energy efficiency (Hofe, 2018). Many theories assume that homeowners act rationally (e.g. Rational-Choice Theory), however, this has been criticised, due to the observed Energy Efficiency Gap. It describes the observation, that investment decisions to increase energy efficiency in the household are only made to an insufficient extent, even though implementation would prove to be cost-effective. Possible causes could be information deficits, risk aversion, imperfect markets and irreversible costs that distort the perception of an investment decision (Hofe, 2018). A lack of financial resources, as well as the unwillingness to raise a loan, are common economic barriers (Friege & Chappin, 2014). However, in their literature review, Friege and Chappin found no prominent papers on decision-making, but rather broad coverage of the topic. Homeowners seem to overemphasis the high additional investment cost and have difficulties thinking long-term. This stands in contrast to developers who are building a new home and usually think more long-term and therefore want state-of-the-art technology (*Expert Interview*, personal communication, 16 February 2024).

2.1.3. Heat Pumps in MFHs

While the use of heat pumps in MFHs is technically feasible, it is not an established method and therefore lacks standardised solutions. As an example, space heating might be possible in a specific MFH with the use of heat pumps, but drinking water requires a higher supply temperature for hygienic reasons and would therefore drive up the running costs. Therefore, a separate solution for drinking water might be necessary which complicates the installation. All in all, this leads to higher costs and makes the decision economically unattractive. Additional challenges are finding space to access the heat source in urban areas, where MFHs are more common, and administrative obstacles, such as ownership. When apartments are owned by the people living in them, decisions on the building often need to be agreed on by all owners, which makes it more difficult due to differences in interests, disposable income and priorities. More decentralized solutions such as small heat pump units in each apartment on the other hand lack social acceptance (*Expert Interview*, personal communication, 16 February 2024; Miara, 2022).

From these challenges and the low number of heat pumps in MFHs it can be concluded, that heat pumps in MFH are still in the early adopters stage. Therefore, information on energy-efficient remodelling or installation of heat pumps in apartment buildings is more difficult to find. Existing literature mostly covers technical and economic feasibility but not the reasoning of owners. Many of the insights about STFH owners cannot be transferred to apartment owners. When landlords rent out apartments, they do not pay utilities themselves and therefore do not have the same financial long-term benefits of switching to heat pumps.

2.1.4. Installation Capacity and Costs

Besides the demand, other obstacles for heat pump installations have been identified mainly in the media and the expert interview. Since the sharp increase in heat pump sales in 2020, it has become apparent that there are also other obstacles to heat pump installations, such as worker shortages and supply bottlenecks.

So far, many installers (Gas-Wasser-Heizungsinstallateure) are not that familiar with heat pumps, through experience and training, the installation speed and therefore capacity can be increased. The shortage of specialists can be avoided by increasing productivity. The economic boom of the last decade led to a lot of construction work which increased the shortage of craftsmen. This might go down now that the economy is in recession. Booms and recessions as well as interest rate development play a role in craftsmen's demand. The interest of young people in jobs like this also plays a role. A former trend of declining apprentices in the field has now been reversed (*Expert Interview*, personal communication, 16 February 2024).

Another limitation was caused by a supply bottleneck for the production of heat pump devices. However, manufacturers invested in increasing capacity, especially after the formation of the “Ampel” coalition, which included ambitious goals for sustainable heating. Additionally, these bottlenecks can be reduced with increased import (*Expert Interview*, personal communication, 16 February 2024).

Another bottleneck can be the capacity of the local electricity grid. At the beginning of 2024 in Oranienburg near Berlin, the regional energy supplier denied new power connections and increased performance needed for wall boxes and heat pumps (Müller-Arnold, 2024). This issue was not caused by too low generated electricity, but the capacity of the grid. On the other hand, local energy suppliers can also enforce the use of heat pumps, if they refuse a gas port. This can happen if maintaining a gas network is not financially viable anymore due to a decline in customers (Kaufmann & Müller-Arnold, 2024).

2.2. Dynamic Hypothesis

Based on the literature review and the interview conducted, as well as including the context of the historic development, the following feedback loops could be identified. The connections are depicted in Figure 8 and described in the following paragraph.

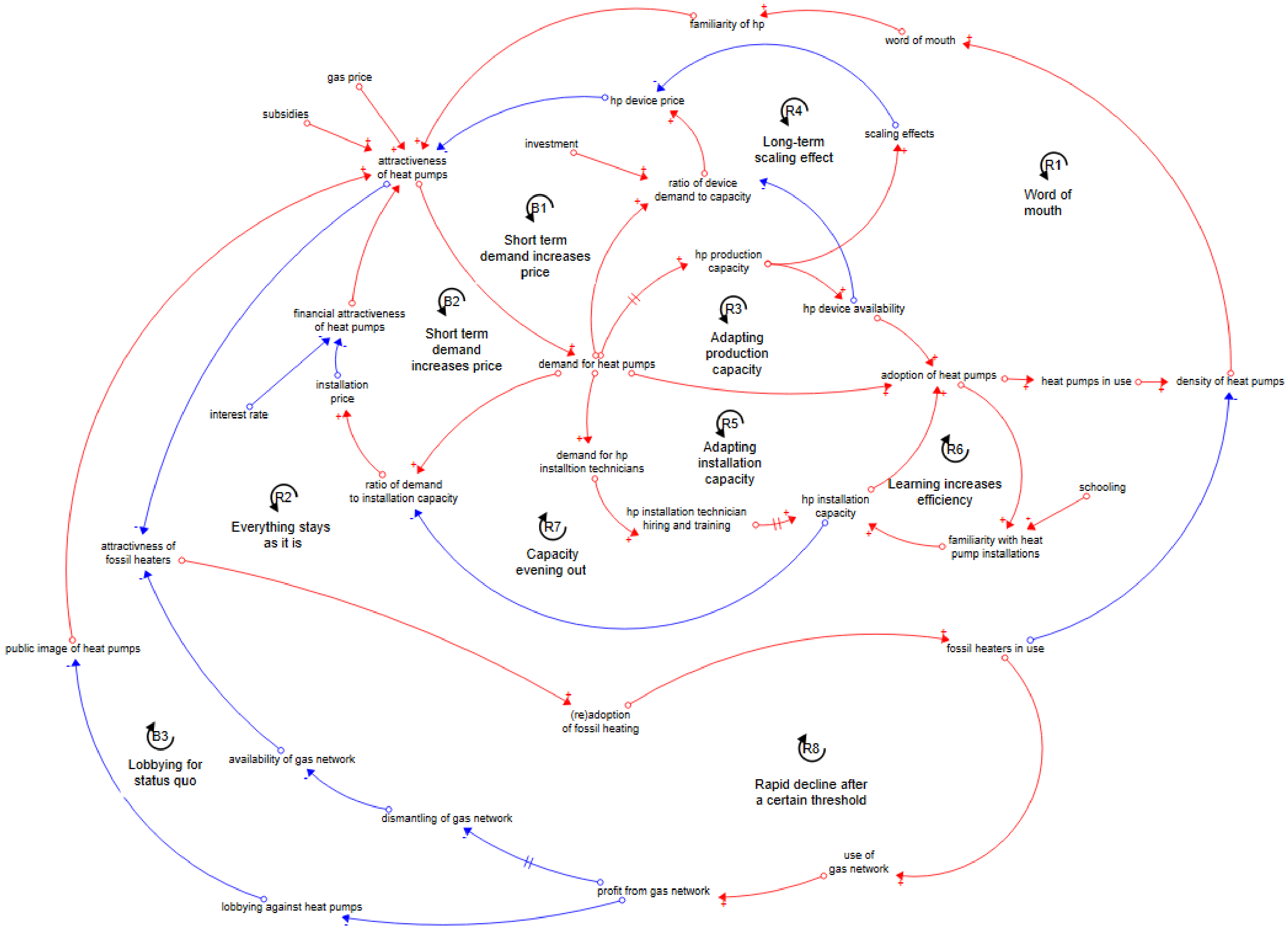

Figure 8 Dynamic Hypothesis

R1 Word of mouth: The more heat pumps, the higher the density of heat pump users. Contact with heat pump users helps to spread the advantages of heat pumps and reduce the fear of adopting a new technology. This leads to an increase in the adoption of heat pumps, which increases the number of heat pumps in use. This relationship is observed for many new technologies.

R2 Everything stays as it is: A high use of fossil heaters, leads to a low density of heat pumps, and a low density reduces word of mouth and therefore familiarity with heat pumps. This lowers the attractiveness of heat pumps, which increases the (re)adoption of gas heaters and therefore the number of fossil heaters. As fossil heaters are the dominant heating method in the beginning, this loop consolidates the status quo.

R3 Adapting production capacity: Increasing demand for heat pumps will lead to manufacturers increasing their production capacity (with a delay), which leads to an increase in the availability of heat-pump devices which can increase the adoption of heat pumps.

An increase in device availability can only directly increase the adoption of heat pumps if the demand is so far higher than the availability. Availability and demand are both limiting factors for heat pump adoption and whatever is smaller, dominates the adoption rate.

R4 Long-term scaling effect: Increasing demand for heat pumps leads to an extension of the production capacity, which leads to scaling effects, reducing the price per device, which increases the attractiveness of heat pumps and therefore the demand.

R5 Adapting installation capacity: An increase in heat pump adoption leads to a higher demand for heat pump installation technicians. This will lead to more people training to become installation technicians, which, with a delay due to the time it takes to train them, increases the capacity to install heat pumps.

Similar to device availability, an increase in installation capacity can only directly increase the adoption of heat pumps if the demand is so far higher than the capacity. Installation capacity, device availability and demand are all limiting factors for heat pump adoption and whatever is smaller, dominates the adoption rate.

R6 Learning increases efficiency: Increased adoption of heat pumps leads to increased familiarity of technicians with heat pump installation, which increases the heat pump installation capacity through increased efficiency. Higher work speed increases the number of heat pumps that can be installed in a limited time. The increased installation capacity can lead to increased adoption of heat pumps, as explained above.

R7 Capacity evening out: An increase in demand for heat pumps leads to increased demand for heat pump installation technicians. This leads to increased hiring and training of technicians and therefore, with a delay, a higher capacity for heat pump installations. This leads to a lower ratio of demand to installation capacity. This leads to lower prices and therefore higher financial attractiveness of heat pumps, which increases the demand for them.

B1 Short-term demand increases price for devices: An increased demand for heat pumps leads to an increased ratio of device demand to availability, which increases the device's price and reduces the attractiveness of heat pumps, leading to decreasing demand.

B2 Short-term demand increases price for installation service: An increased demand for heat pumps leads to an increased ratio of demand to installation capacity, which increases the installation price and reduces the attractiveness of heat pumps, leading to decreasing demand.

B3 Lobbying for status quo: Increased adoption of heat pumps leads to fear of companies depending on selling fossil fuels, this increases campaigning against heat pumps, which damages the public image of heat pumps and therefore reduces their attractiveness.

R8 Rapid decline after a certain threshold: When the attractiveness of fossil heaters drops and therefore the (re-)adoption and use of fossil heaters decline, this leads to a decline in the use of the gas network and therefore reduces the profit made from the gas network. After a delay, this leads to a dismantling of the gas network and therefore reduces its availability, which reduces the attractiveness of gas (or fossil) heaters.

Exogenous influences: The main exogenous influences are gas prices, interest rates and subsidies, which all influence the (financial) attractiveness of heat pumps.

2.3. Boundaries

To make the actual model as simple as possible and as complex as necessary, not all identified feedback loops are included. There is a big similarity in the type of restriction that the loops **R3, R4, and B1 (Adapting production capacity, Long-term scaling effect, Short-term demand increases price for devices)** and the loops **R5, R6 and B2 (Adapting installation capacity, learning increases efficiency, Short-term demand increases price for installation service)** impose on the system. Both “sides” impose a limitation on the system, that is caused by a slow adaption of a subsystem (the production system or the capacity to provide the installation service). Each side has a reinforcing loop **(R3 and R5)** that involves building up capacity to either produce a device or provide a service when the demand is rising; both are delayed due to the time it takes to increase production e.g. by building or extending factories and increase capacity by hiring and training of qualified personnel. Both sides include some type of scaling effect **(R4 and R6)** and both sides react with a price increase when the supply is lower than demand. Therefore, concentrating on one “side” should be efficient in representing the dynamic.

I choose to model the provision of installation services since it has a higher potential to be a limiting factor also in the future. Since manufacturers have already invested in increasing capacity and additionally, HP devices can be imported it does not seem to be relevant. Therefore the loops **B1, R3 and R4** are excluded.

Additionally, there is not yet enough research to quantify the loops **B3 and R8 (Lobbying for status quo and Rapid decline after a certain threshold)**, therefore they are also excluded.

The updated CLD is shown in Figure 9.

When continuing to develop the model from a CLD, into a Stock and Flow diagram and quantifying the relationships between the variables, further simplifications must be made and boundaries need to be set due to the limited time of the project. Table 1 provides an overview.

The model tries to capture the dynamics of installations of ground-source, air-source or water-source heat pumps, capable of heating buildings including warm water and therefore replacing gas heaters fully. From here on they will be referred to as heat pumps without consideration for the type, since it is assumed that the most suitable type for each building will be chosen. Device and installation prices are selected based on air-source heat pumps since they are the most popular type.

The model depicts an exemplary town of 80.000 inhabitants based on average values in Germany or values of towns of a similar size. It does not depict any specific existing town. Different geological conditions can influence the heating demands as well as the possibility and costs of installing heat pumps (Blum et al., 2011). Therefore, choosing to model an example village is a simplification that helps understand the dynamics by avoiding looking at the exceptions. Additionally, regional and local laws can influence the diffusion. Already in 2010 one could observe the co-existence of many different local and regional subsidy and support programs (Platt et al., 2010), that are excluded from this model.

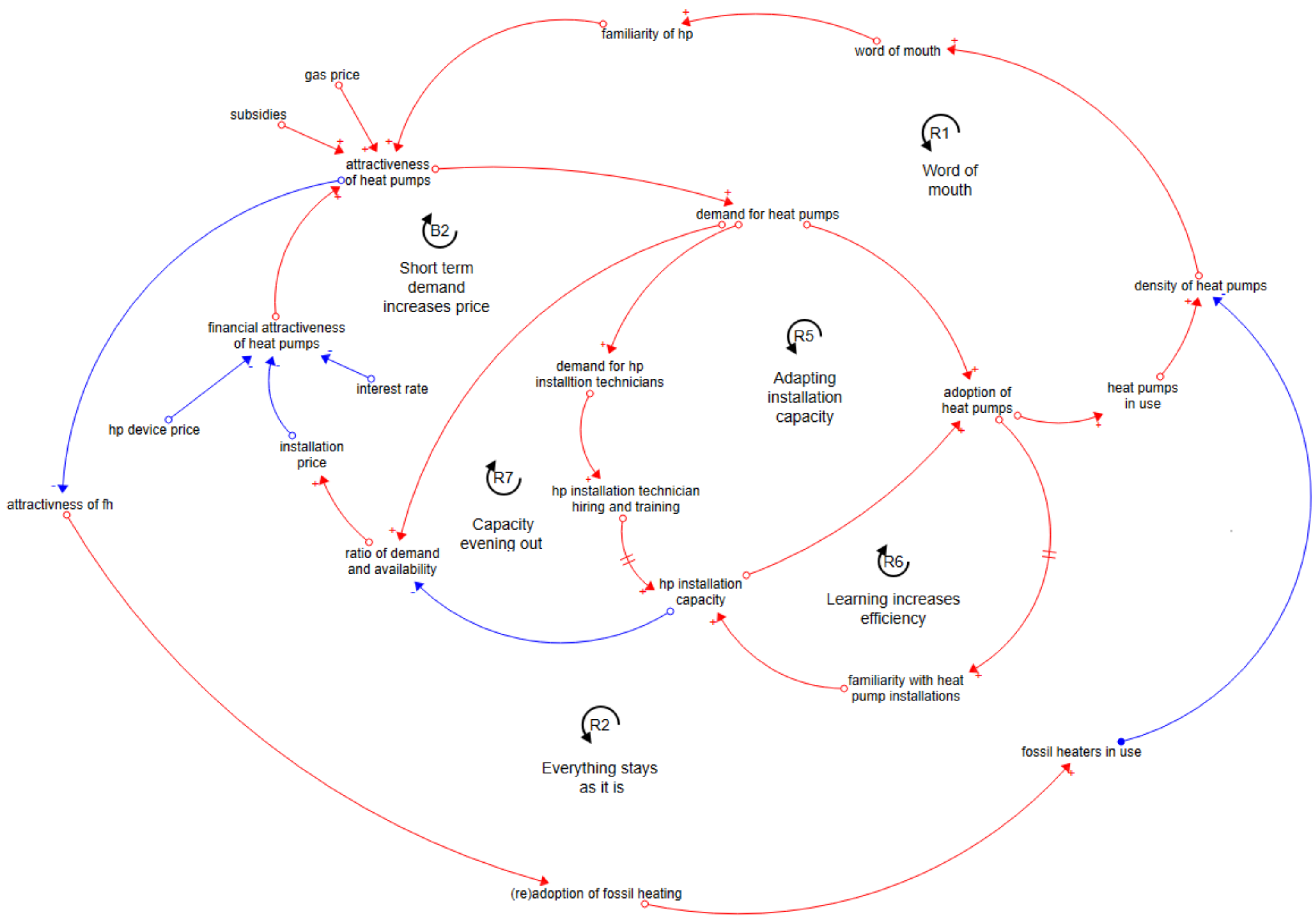

Figure 9 Dynamic Hypothesis after considering model boundaries.

Endogenous	Exogenous	Excluded
• Demand for new heaters • Demand for heat pumps • Number of heat pump and gas heater installations • Heat pump installation capacity and labour costs • Installation technicians with further training for HP installation	• Gas price • Interest • Heat pump device and gas heater price • New buildings • Subsidies through national programmes directly related to heat pump installations • Number of installation technicians • Buildings heated with district heating	• Gas infrastructure availability • Capacity of the electricity grid • Other heating types including oil, pellets, etc. • The possibility to replace gas with hydrogen for heating • Local and regional subsidies • Subsidies through national programmes indirectly related to heat pump installations (renovation or modernisation subsidies) • Electricity price • Media influence • Pressure put on installer by non-heat pump demands • Heat pump device availability • Catch-up effects when subsidy policies change • Influence of subsidies on pricing

Table 1 Overview of endogenous, exogenous and excluded influences.

2.4. Simulation Model - Stock and Flow Structure

This section will describe the simulation model developed using the Software Stella Architect (Version 3.1). The model documentation, which includes each variable, their equation and individual explanation including sources, can be found in Appendix B. The simulation starts in the year 2005 and continues until 2045, the year Germany wants to reach climate neutrality. This goal includes a step-by-step plan to abolish gas- and oil-based heating in Germany. The time step is years.

While the CLD suggests one variable for heat pump adoption and one for heat pump accumulation, this is a simplification. In the model, heat pumps and fossil heaters of STFH and MFH are modelled separately. This includes a separate financial attractiveness and separate weights of each influence on the different HP adoption variables.

The model is divided into 5 sectors. Each is described in this chapter and a Figure is provided to show the structure:

1. STFH and their heating methods
2. MFH and their heating methods
3. Installation capacity
4. Financial attractiveness
5. Exogenous influences

Each sector has its own colour, which makes it obvious where the sectors interact with each other. Variables that are filled with yellow or rose colours were subject to hand calibration and testing due to uncertainties. Variables that are filled in red are Switches that are used to control scenarios or test model boundaries.

Additional sectors are not explicitly described here but are made for accounting, initialization based on historical data and easier analysis or calibration of the model.

2.4.1. STFH and their Heating Methods

To depict the number of buildings that need heating, an ageing chain is included, that is originally fed with an inflow calculated with historical data (after 2023 depending on scenarios) and two outflows for demolishing for different age groups, based on historical demolition ratios. The structure is further used for three purposes: the total number of houses is used to calculate the total number of heaters needed, the number of demolished houses is needed to calculate the number of heaters that are scrapped due to being part of a demolished house and the inflow of new houses is needed to calculate the number of heaters needed in new construction.

Further, one ageing chain depicts the number of heat pumps in use and one the number of fossil heaters (representing both, oil and gas for simplification reasons). The total of both ageing chains represents the total number of heaters in STFH. This number is deducted from the total number of heaters needed in STFH, to calculate the current demand for heaters. Therefore, there are two types of heater demands in the sector, one for new buildings and one for existing buildings, that used to have a heating system, that got scrapped due to age. This differentiation is necessary since there are also two different probability values calculated for heat pumps, determining which type of heater will be installed. Additionally, there is a flow directly from the third stock of the fossil heater ageing chain towards the first stock of the HP ageing chain. This flow depicts early exchanges, where homeowners switch from fossil heaters to heat pumps earlier than necessary.

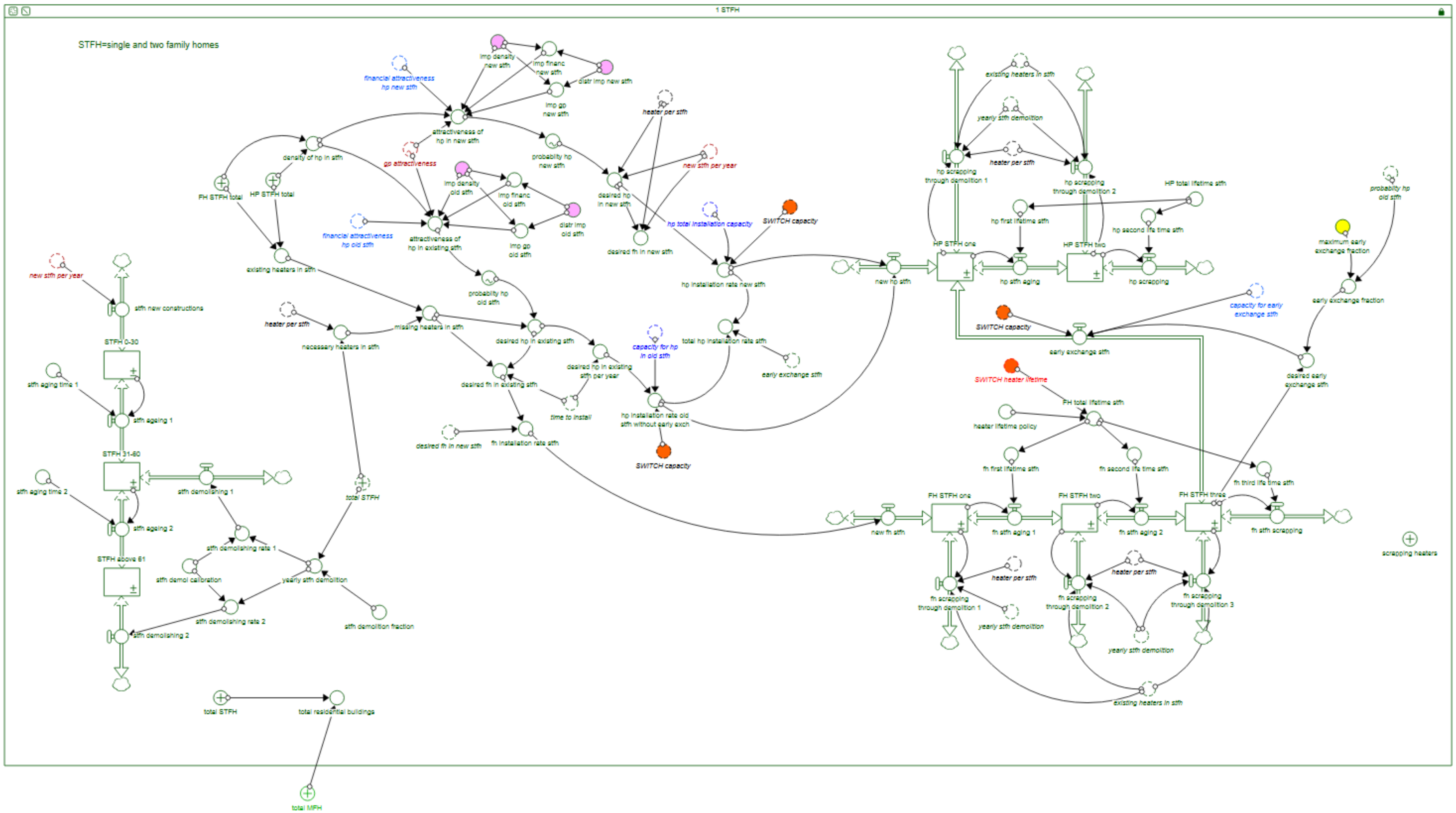

Figure 10 Sector 1: STFH and their heating methods.

The two values depicting the probability of installing HP are fed by two attractiveness values, summarizing different incentives to install heat pumps. The included values are financial attractiveness, gas price attractiveness and density of heat pumps. The density of heat pumps only considers the HP to fossil heater ratio in STFH. Financial attractiveness is calculated differently for new vs. old buildings, as described in sector 4. The attractiveness is calculated with a weighted multiplication and varies between 0 and 1. The weights are separate for the two attractiveness values due to different priorities identified through data and literature analysis. The exact values of the weights are the result of hand calibration. Each attractiveness value is then translated into a probability of choosing heat pumps. The probability of choosing heat pumps is a graphical function depending on the attractiveness. The graphical function is an S-curve and reaches a 100 per cent probability of installing heat pumps already at an attractiveness of 0,8. This is based on the assumption that heat pumps are already the most probable solution even if not all influences support that fully.

The probability of installing HP of each building type is multiplied by the demand for heaters in new or old buildings to determine the desired heat pumps and fossil heaters in each category. The early exchange fraction is calculated via the probability of choosing heat pumps for old STFH and the maximum early exchange fraction, which represents the maximum fraction of fossil heater owners in the last third of their heater's lifetime, that are willing to exchange their heater earlier than normal.

The actual installation rate for heat pumps in each building type is calculated using a MIN function considering the demand and the capacity of the installers. A MIN function chooses the smaller value of two provided inputs. The capacity limit is calculated in sector 3 for each category of HP installation separately. There is no capacity limit for fossil heater installations since it is an established technology.

Both installation rates of heat pumps are added to the inflow of the heat pump ageing chain, and the fossil heater installation rates for new and old buildings are added to the respective fossil fuel ageing chain where they accumulate until they are scrapped.

2.4.2. MFH and their Heating Methods

The MFH sector is very similar to the STFH sector: It includes an ageing chain for the buildings, one for their respective heat pumps and one for fossil heaters, as well as a calculation for density of hp and attractiveness and probability to choose hp separated for new and existing buildings.

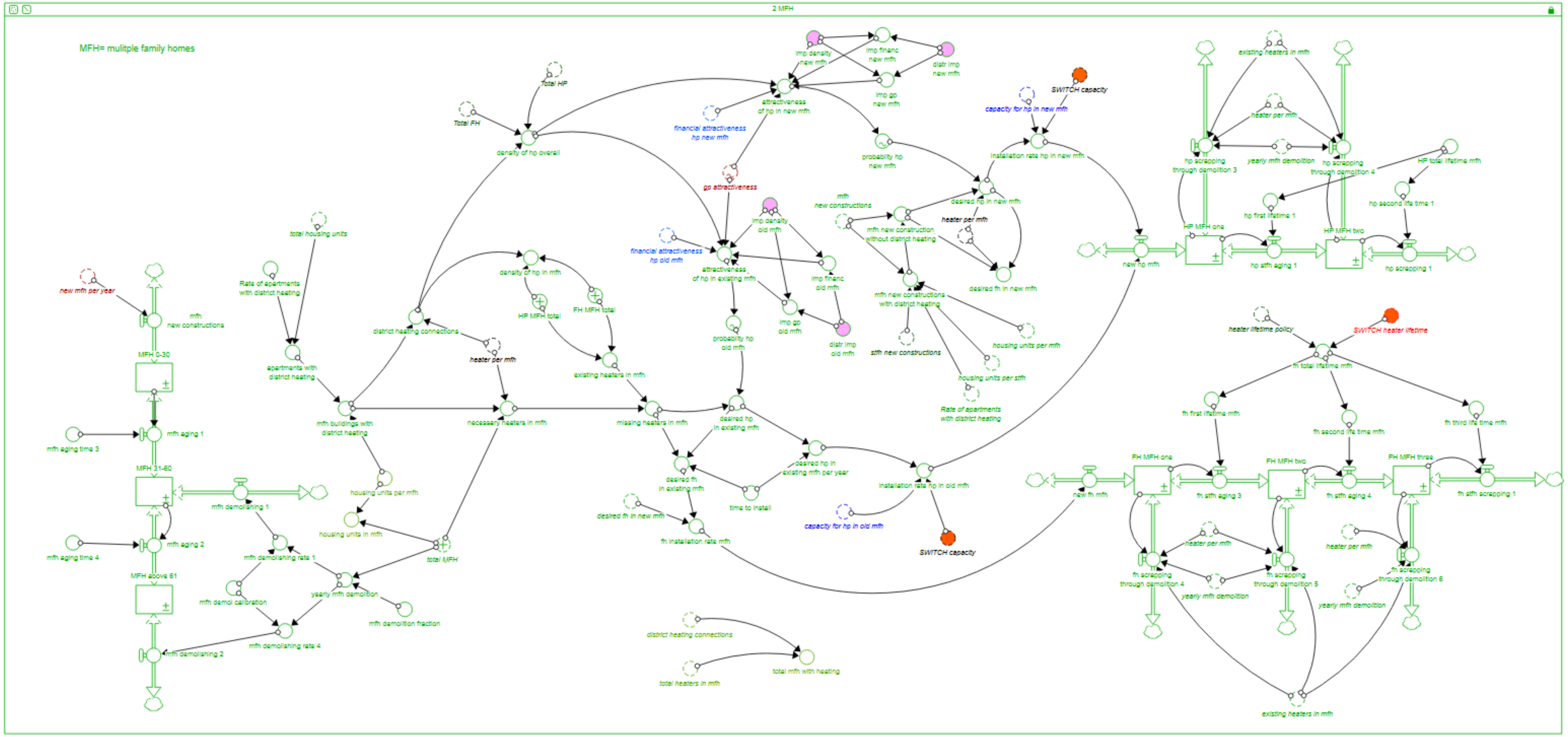

Figure 11 Sector 2: MFH and their heating methods.

The two main differences between the two sectors are the inclusion of district heating for MFHs and a change in the calculation of the density of heat pumps. About 13% of housing units in Germany are heated with district heating, a value that only changed slightly over the past years, therefore as a simplification a stable 13% of housing units in the model are heated with district heating, all in multi-family homes. By using the average amount of housing units per MFH the number of buildings with district heating can be calculated. These buildings do not need any additional heaters and therefore are not part of the calculation for the number of necessary heaters anymore.

While the density of HP in the STFH sector is calculated only using heat pumps and fossil heaters in STFHs, the density in the MFH sector is calculated using heat pumps and fossil heaters in STFH and MFH. This assumes, that STFH-homeowners are not influenced by the decisions made by investors who usually own MFHs, but only by peers. Investors on the other hand are more influenced by the overall situation since a higher density also comes with other benefits of a more established technology.

The probability of installing HP is again modelled using a graphical function depending on the attractiveness. The S-shaped curve for the probability of new MFH installing HP is the same as for new and old STFH. The s-shaped curve for old MFH only starts increasing after an attractiveness of at least 0,15 is reached. This is added as a result of calibration and also fits the early adopter stage HP in apartment buildings, especially existing, are in.

2.4.3. Installation Technician and Installation Capacity

The installation technician sector contains one main ageing chain, depicting the heating installers from the start of their apprenticeship till their retirement after 45 years. The installer stock contains people who work in craft workshops related to heating engineering and installation and electrotechnology. This includes unskilled labourers and non-craft-related employees (e.g. administration) of these workshops. It has two inflows, one for people starting the apprenticeship and one for hiring unskilled labourers, the hiring of unskilled labourers is limited to 15% of the people starting the apprenticeship. The number of apprentices starting each year is exogenous. The decision to include unskilled labourers is made due to the historical data availability which shows the number of people working in specific workshops, but not the number of people with a specific apprenticeship (Zentralverband des deutschen Handwerks, 2023).

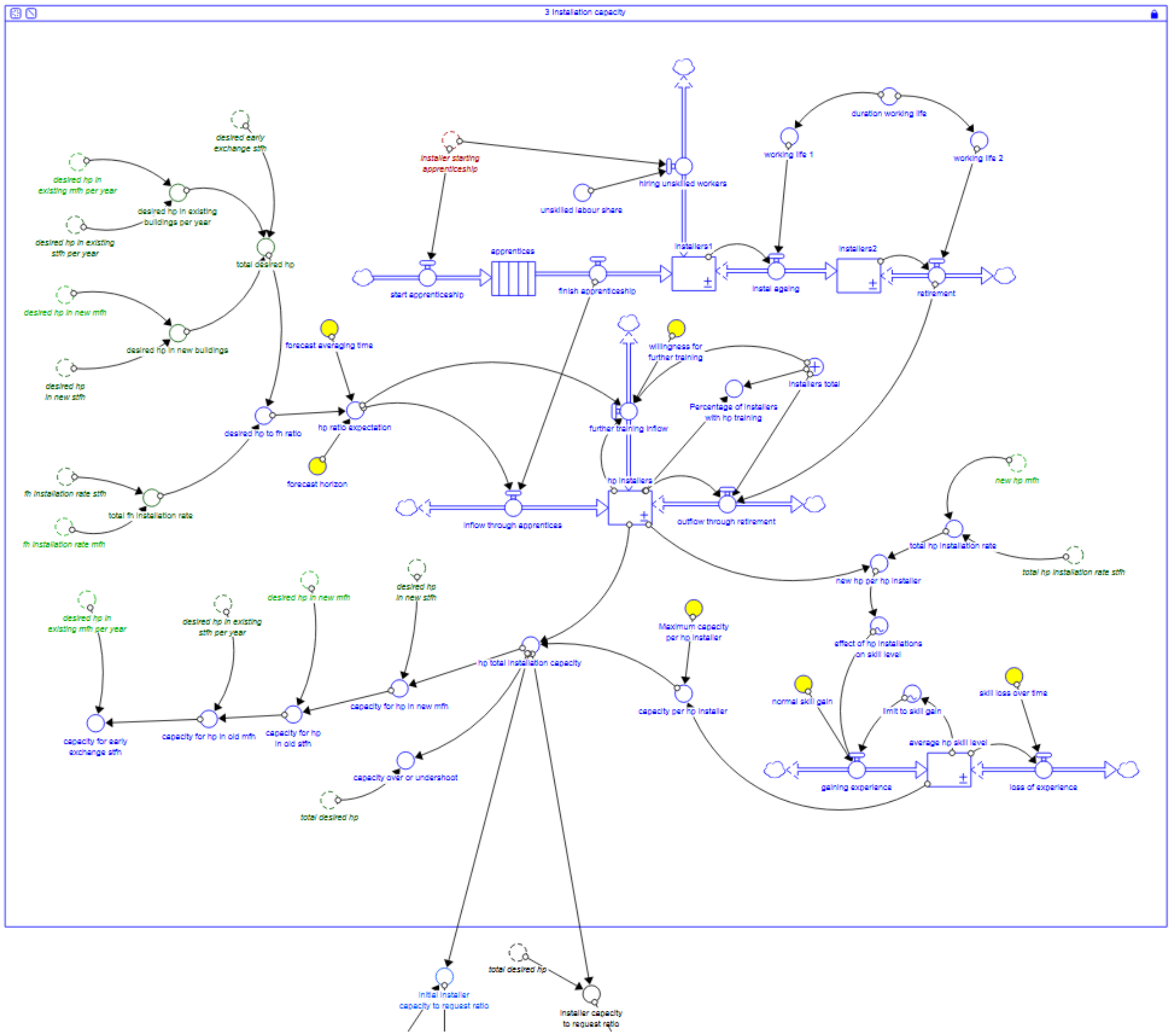

Figure 12 Sector 3: Installers and Installation capacity

Since not all heating installers are also trained to install heat pumps, a stock with hp installers is added, that is fed and drained via co-flows of apprentices and requirements of the installer ageing chain. The number of inflows through apprentices is based on the actual apprentices and the hp ratio forecast, this assumes that the more HP installations are expected the more likely an apprentice is to learn about them. A forecast is used rather than the actual demand since some planning ahead is assumed. Additionally, an inflow is based on already trained installers who take additional training to become hp installers. This inflow is also based on the forecast and a ratio of installers per year, who have not yet had additional training but are willing to consider it.

The capacity for heat pump installations is calculated using the number of hp installers and the capacity per hp installer per year. The capacity per HP installer depends on the average skill level of installing HPs, which is modelled as a stock with the inflow depending on the HPs installed per installer (experience) and drained with time. This means in the model the installers are only affected by HP installation orders and therefore endogenous. No other, exogenous tasks, such as fossil heater installation, solar thermal or photovoltaic installation, or other renovation or new construction that requires installers is influencing the variable. This is a limitation of the model, that reduces the explanatory value of capacity of installers and its influence on the costs of installation (see description of next sector). However, as explained previously this boundary is necessary due to data and time constraints.

To determine the capacity for each type of hp installation, the desired hp for new stfh is subtracted from the total capacity, to get the capacity for hp in new MFH and so on with the priority being new stfh, new mfh, old stfh, old mfh and early exchanges at the bottom. These capacities are then used in the respective sectors.

2.4.4. *Calculation of Financial Attractiveness*

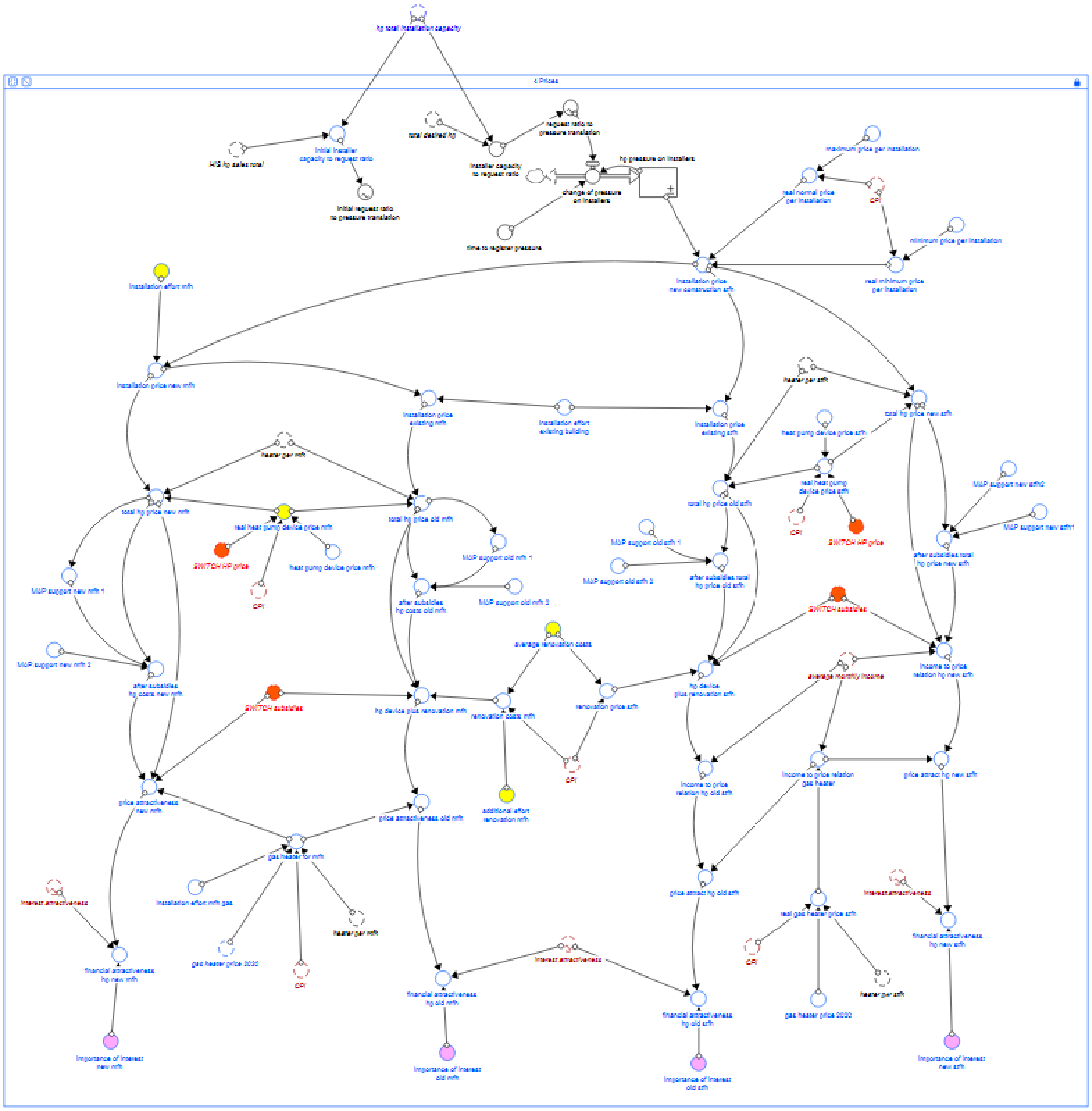

Figure 13 Sector 4 Price and financial attractiveness.

The starting point for calculating the financial attractiveness of HP in the four different building types is the HP installer capacity. The ratio of capacity to demand puts pressure on the installers and the higher the pressure the more money they can demand per HP installation. The calculated price applies to installation prices in new STFH. Then depending on the building type, the installation price is multiplied because of the higher effort necessary in MFHs compared to STFHs and in old buildings compared to new buildings. While the result for new and old STFHs can be partially backed up by data, the result for MFHs is more speculative due to a lack of data.

Furthermore, the price of the device is added, and possible subsidies are subtracted. For existing buildings renovation costs are added.

Installation costs are additional to its other influences dependent on the consumer price index (CPI). Renovation costs and gas heater prices are also multiplied by CPI. Therefore, they all automatically become more expensive throughout the simulation. This is important to correct for inflation, especially considering that the average monthly income is also an indirect influence on financial attractiveness. The heat pump device price however stays stable at 12.000€ due to different data points that suggest this stable price. Sources from 2010 (Platt et al., 2010) as well as data from 2024 (Bruderus, n.d.; Vaillant, n.d.) both show a price of around 12.500€. However, prices fluctuate depending on the source (Statista, 2023). Innovations tend to become cheaper when they are produced on a larger scale and original development costs are paid off. In this case, the innovation has a stable price, but everything else becomes more expensive.

The prices for a new heat pump in MFHs are than compared to the price of gas heaters. The resulting ratio as well as the interest attractiveness (calculated in sector 5) is added to the overall financial attractiveness of new MFH and old MFH as a weighted total.

For STFH the prices of heat pump installation and gas heater installation are first set in relation to income and then to each other. This is due to STFHs more often being owned by the people living in them. As above the resulting ratio as well as the interest attractiveness is added to the overall financial attractiveness of new MFH and old MFH as a weighted total.

The resulting attractiveness for old MFH, new MFH, new STFH and old STFH then feed into the Sector 1 and 2 for the calculation of the overall attractiveness.

2.4.5. Exogenous Influences

The gas price and interest rate are both important exogenous influences, as well as subject to scenario building. Before they are fed into the model, they become translated into influences on the financial attractiveness and the general attractiveness of heat pumps.

For the gas price, the influence is based on the perceived change. An increasing price leads to an increasing attractiveness of heat pumps, due to the price increase of using gas heaters. Since gas heaters are the most common fossil heating method and gas and oil prices often correlate, the gas price is representative of the costs of heating with fossil fuels.

For the interest rate, the influence is calculated based on a guide value. A lower interest rate makes it more attractive to take out loans, which can be necessary to install a new heat pump, especially in old buildings that need extensive renovation or MFHs.

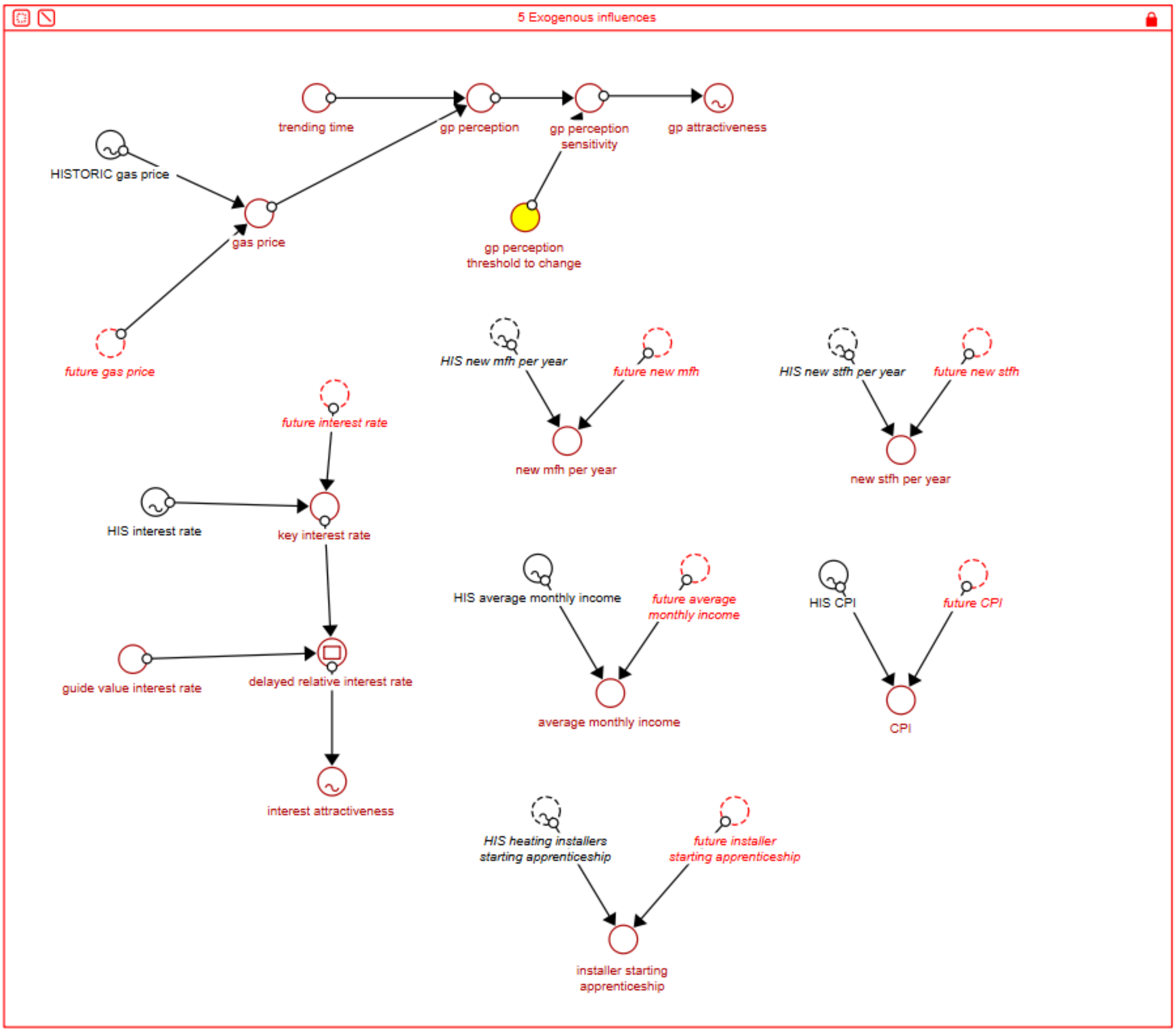

Figure 14 Sector 5: Exogenous influences.

3. Model Validation

The goal of model validation is to build confidence in the usefulness of the model, not to “verify” the model, as this is impossible, since fundamentally all models are wrong, as they are limited and simplified representations of the real world (Sterman, 2000, Chapter 21). Model testing helps uncover flaws and limitations and find and possibly fix mistakes.

In addition to standard SD model testing, I want to show the adherence to the following criteria that must be fulfilled for good practice when applying growth curves to forecast market development (Meade, 1984), as done in this model: For model validity, the product needs to be adoptable rather than consumable and therefore has an obvious bound to the saturation level. For statistical validity, model parameters need to be tested for significance and the forecast should be accompanied by a measure of uncertainty. Heat pumps meet the first condition due to their characteristics. In the model, this characteristic manifests in two structures: 1. Heat pumps are modelled using an ageing chain and have a long lifespan of on average 18 years. 2. The obvious saturation bond is explicit through the maximum number of heaters needed that depends on the number of houses in the model and the variables heater per MFH and heater per STFH. The second condition is met by standards of SD model testing, as provided in the sensitivity analysis and through the development of various scenarios (Chapter 4.2.)

Most important for model validation is the structural validity, and of secondary importance is the historical fit. Therefore, the following tests have been conducted: Structure confirmation, parameter confirmation, dimensional consistency, and direct extreme condition test. Afterwards, the sensitivity analysis and the reference mode replication were conducted.

3.1. Direct Structure Tests

Structure-Confirmation

For the structure-confirmation test, the model structure is compared to its real-world counterparts by using literature to ensure the structure is consistent with existing knowledge. This happens continuously during the iterative modelling process and is documented in Chapter 2 of this thesis, as well as the model documentation. When assumptions had to be made or model boundaries led to simplification, this is stated in the model documentation and is considered during sensitivity analysis.

Parameter Confirmation

The parameter confirmation has been validated in the model documentation, available in Appendix B. All variables have real-world counterparts, however, in some cases, assumptions had to be made due to a lack of data availability or averages had to be estimated based on a range of values available. This has been made visible in the model documentation.

Dimensional Consistency

The dimensional consistency has been tested using the modelling software: Stella Architect did not find any inconsistencies or missing units. Additionally, all units have real-world counterparts and no dummy variables have been used to force dimensional consistency.

Direct-Extreme Conditions

During the modelling process, partial model testing was conducted to ensure the robustness of formulations. To prevent variables from taking on unreasonable values as well as computational error, MIN and MAX functions were used where necessary. No computational errors or unreasonable values were detected after these were placed.

3.2. Structure-Oriented Behaviour Tests

3.2.1. Integration Error test

Euler and Runge Kutta 4 integration and smaller and higher time steps have been tested. A DT of 0,015625 and RK4 has shown to be sufficient and therefore chosen.

3.2.2. Behaviour Sensitivity

I further conducted a sensitivity analysis for all relevant parameters in the model. For the analysis, each parameter was varied over 50 sensitivity runs, using Sobol Sequence sampling and a uniform distribution random draw. The results are reported in Table 2, more detailed results can be found in Appendix A. The model is appropriately sensitive to all parameters.

Model sector	Parameter	Range	Sensitivity
STFH	Imp density new stfh & distr imp new stfh*	0-1 (both)	Numerical
	Imp density old stfh & distr imp old stfh*	0-1 (both)	Behavioural**
	HP total lifetime stfh	10-30	Numerical (low)
	FH total lifetime stfh	10-50	Behavioural**
	Maximum early exchange fraction	0-1	Numerical (strong)
MFH	Imp density new mfh & distr imp new mfh*	0-1 (both)	Numerical (low)
	Imp density old mfh & distr imp old mfh*	0-1 (both)	Numerical (low)
	HP total lifetime mfh	10-30	Numerical (low)
	FH total lifetime stfh	10-50	Numerical (low)
Installers	Forecast averaging time & Forecast horizon*	1-10 (both)	Numerical (low)
	Willingness for further training	0-1	Behavioural**
	unskilled labour share	0,05-0,3	Numerical (low)
	duration working life	35-50	Numerical (low)
	Maximum capacity per hp installer	1-20	Behavioural**
	normal skill gain	0,01-0,1	Behavioural **
	skill loss over time	1-5	Behavioural**
Financial attractiveness	time to register pressure	1-5	Numerical (low)
	maximum price per installation	3.000-10.000	Numerical (low)
	minimum price per installation	500-3.000	Numerical (low)
	gas heater price 2020	5.000-20.000	Numerical
	installation effort existing buildings	1-3	Numerical (low)
	average renovation costs	5.000-50.000	Numerical
	heat pump device price for mfh	10.000-100.000	Numerical (low)
	additional effort renovation mfh	1,5-10	Numerical (low)
	installation effort mfh gas	1-6	Numerical (low)
	importance of interest new stfh	0-1	Behavioural**
	importance of interest old stfh	0-1	Numerical
	importance of interest new mfh	0-1	Numerical (low)
	importance of interest old mfh	0-1	Numerical (low)
Exogenous influences	gp perception threshold to change	0,05-3	Numerical
	guide value interest rate	0,5-5	Numerical (low)
Initialisation	heater per stfh	1-2	Behavioural**
	heater per mfh	1-7	Numerical
	Initial hp installer ratio	0-1	Numerical
	Initial hp stfh	0-2000	Numerical

*analysed together
**see Appendix A

Table 2 Summary of behaviour sensitivity analysis.

Due to their theoretically justified importance, a higher sensitivity was expected for the combined testing of the variables ‘Imp density’ (short for the importance of density) and ‘distr imp’ (short for distribution of importance) for the different building types. The variables mitigate the strength of the different influences on the attractiveness of heat pumps for each building type and therefore are important for the loop dominance. ‘Imp density’ is responsible for the weight of the influence of the density of heat pumps (“word of mouth”), while ‘distr imp’ mitigates the importance of the gas price (gp) influence and the financial attractiveness influence, after accounting for the importance of density. Further model testing showed that the lower-than-expected sensitivity is likely caused by all three influences behaving similarly: While there are quantitative and behavioural differences the development of density, gas price and financial attractiveness is overall positive for a further installation of heat pumps.

The model was the most sensitive towards changes in the installers sector. This was to be expected since it is a limiting factor in the model. If the capacity of installers is negatively affected, the installation rates are affected in the same manner, no matter how attractive heat pumps are otherwise. Furthermore, even an initial low capacity that grows afterwards would stunt the growth of heat pumps since they are widely affected by the density of existing HPs and therefore HPs installed prior.

The model is generally more sensitive towards changes in the STFH sector. A higher sensitivity was expected since heaters in STFH outnumber heaters in MFH and therefore dominate the behaviour. Most heat pumps are installed in STFHs, especially in existing STFHs, since they are the most common building type. Therefore, changes that influence the installation of heat pumps in STFH also influence the attractiveness of heat pumps in other building types through the density of installed heat pumps **(Loop R1).**

3.3. Reference Mode Replication

The simulation results for the years 2005 to 2022 have been tested against historical data for the following KPIs: yearly HP sales for new houses, yearly fossil heater sales in new houses, yearly HP sales for old houses, yearly fossil heater sales for old houses and percentage of housing units heated with HP. The behaviour replication showed to be very good for heat pumps and fossil heaters in new houses (Figure 15), while there are moderate deviations for the other indicators.

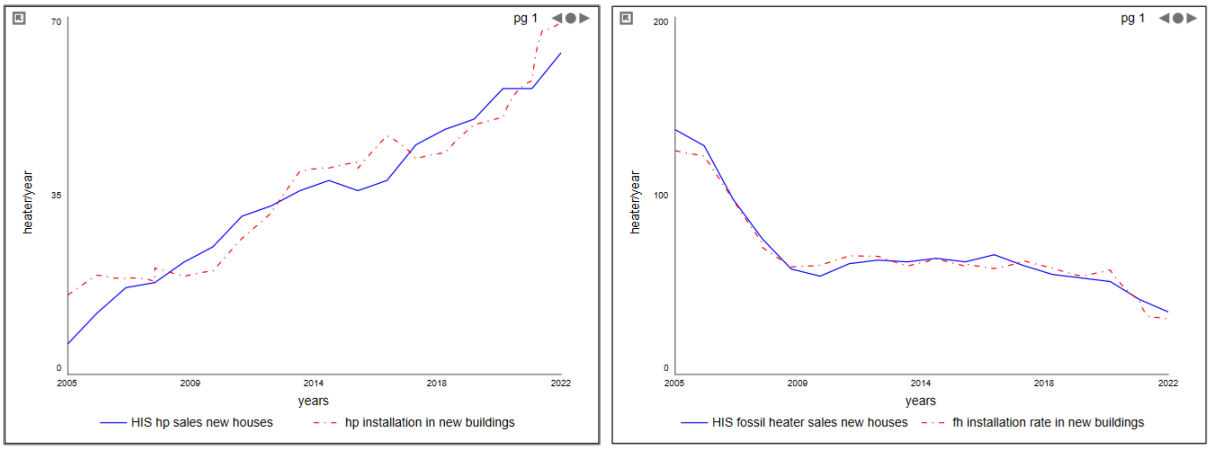

Figure 15 Behaviour replication for heater installations in new buildings.

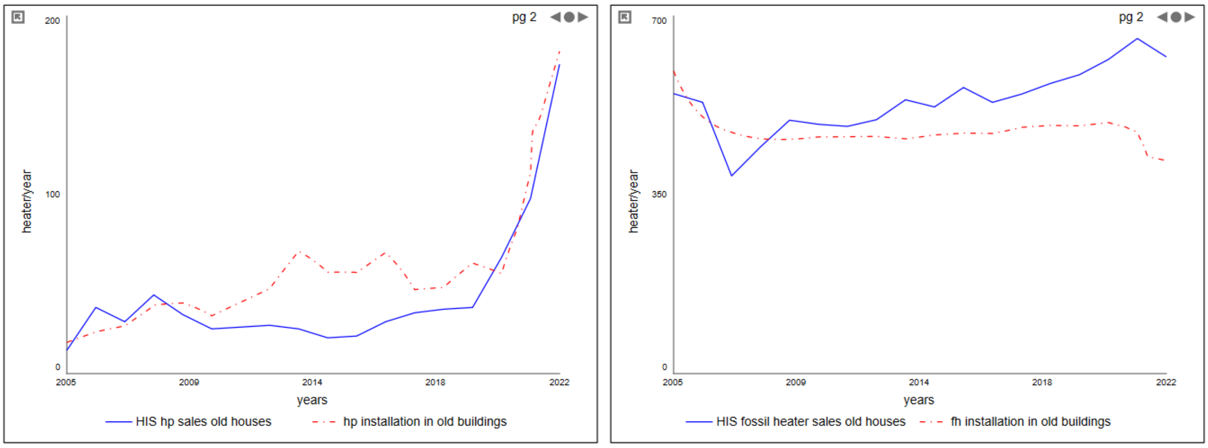

Figure 16 Behaviour replication for heater installations in old buildings.

Part of the difference in fit between new houses and old houses (Figure 16) can be explained by the difference in calculating the overall demand for heaters. The number of heaters needed for new constructions depends on exogenous input into the model. New residential building constructions are not an endogenized variable because they are not of key interest to the problem. Therefore, all deviations to the reference mode are caused by deviations in calculating the variable ‘probability to choose HP’. In general, a good fit was achieved here, with the only main deviation of overestimating the heat pump installation rate in the beginning up until the year 2007.

To calculate the number of heaters installed each year in existing houses, the difference between heaters needed (each house needs one heater in the model) and existing heaters is calculated, as well as the number of early exchanges. This increases the error margin: Part of the deviation is caused by deviations from the number of heaters needed and part by deviations in calculating the variable ‘probability to choose HP’. The difference between the simulation results and historical data has two causes: The overshoot of heat pump installations in the model, most significantly between 2012 and 2017, could be caused due to some factors not included in the model that made heat pump installations less attractive in real life. The undershoot in fossil heater sales beginning in 2016 is caused by too low heater demands in general in the model after that year. This could be caused by a decline in the heaters' lifetime. Modern gas heaters have a generally lower lifetime compared to earlier, however, in the model, the parameter is fixed for simplification. Another possible explanation is that homeowners renewed their gas heaters early leading up to 2024 in anticipation of new rules that would make the installation of a new gas heater more difficult or impossible.

In the beginning, the historical data for the percentage of housing units heated with HP and the simulation correlated closely, but after 2011, the gap between them widened (Figure 17). The percentage of housing units heated with HP is a proxy for the existing heat pump and the ratio of STFH and MFH. The differentiation is partly caused by the above-described overshoot of the model in heat pump installations, as well as the number of heat pumps in MFHs and the number of housing units heated by them. An average of 6,7 housing units per MFH is assumed while in reality, smaller MFHs are more likely to be heated with heat pumps, while bigger apartment blocks are likely to be heated with district heating. A further differentiation might lead to more exact results.

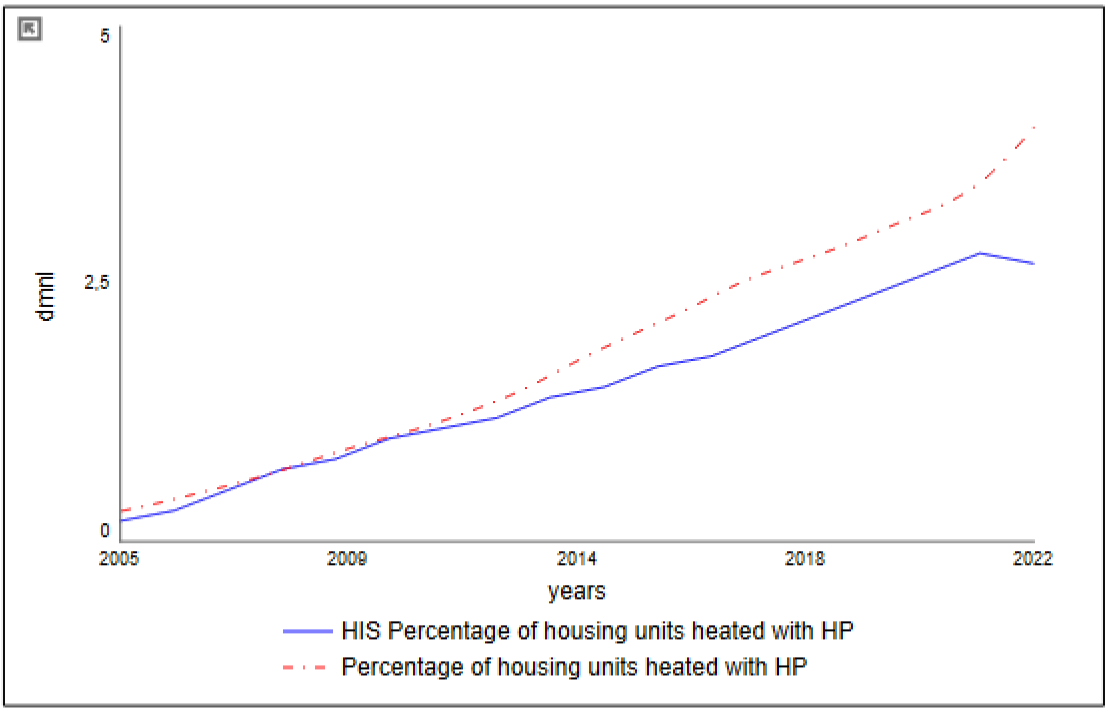

Figure 17 Behaviour replication for percentage of housing units heated with HP.

An exact replication of the historical data is not necessary for model validation, as models are purposefully simplifications of the real world, which leads to limitations. Historical behaviour can be caused by events, such as political changes, which are not included in the model. While adding structure could lead to more exact results, the additional work is often not reasonable concerning the additional insight; especially since SD models should not be used as prognosis but as an analysis tool. Despite the observed flaws in the reference mode replication, the model captures the overall dynamic behind the heat pump adoption. However, this test of behavioural patterns is limited by data availability. Parts of the model dealing with installation capacity can only be tested indirectly: The capacity should be at least as high as historical installation rates, furthermore, media reports suggested a shortage of installation capacity in 2022/23. While these basic conditions are fulfilled (see Figure 19), more detailed testing would further improve the confidence in the model, e.g. the number of installers that offer heat pump installation, installation price development, or the number of installers going through additional schooling each year to learn about HP installation.

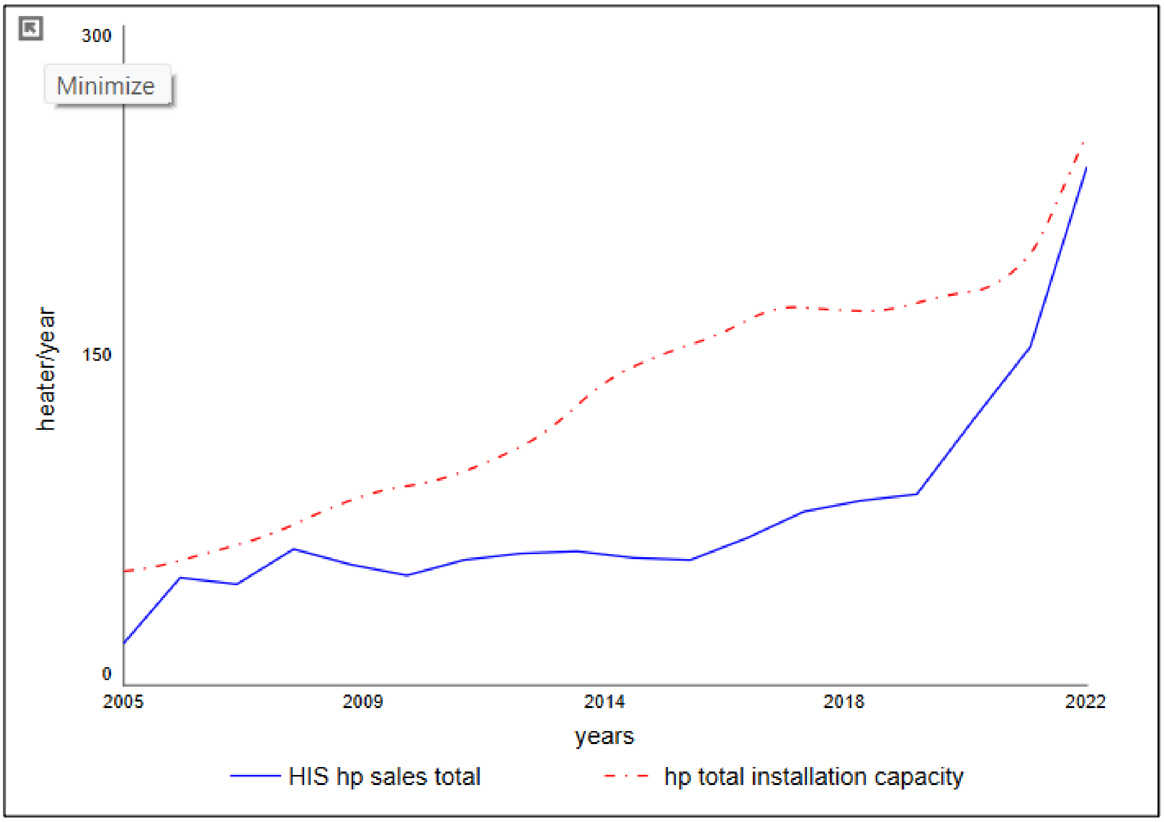

Figure 18 Capacity for HP installations compared to historical HP installation rate.

4. Model Analysis

This section addresses the simulation of the model beyond 2023 and discusses the endogenous and exogenous influences on the system. It answers the second research question: *How do the identified factors interact with each other and influence the behaviour of the system?* At first, the historic behaviour is discussed. While it is already tested against the reference mode, the analysis aims to explain the behaviour. Afterwards, the baseline scenario is discussed, this scenario is built on holding most exogenous variables stable on the stand of the latest available data point. Due to the exogenous but relevant influences on HP attractiveness, in the second step, scenarios have been developed and analysed. At last, policies will be introduced to the model. The baseline scenario, as well as other scenarios, are not to be seen as a prognosis. While numbers are used to describe the differences between the adoption of heat pumps in building types or depending on scenarios, they are not estimations about the development in real life. It is rather to analyse possible directions of future developments and sensitivity towards changes.

4.1. Analysis of Historic Behaviour

While the model structure is based on the above-described literature and interview, some parameters in the model could not be determined through research. In this case, they were specified via assumptions or calibrations. The fit towards the reference mode was the base for this calibration. Especially the weight of the different influences on the attractiveness of heat pumps is an important factor for the model. Therefore, the results of the calibration are reported in Table 3. For a better understanding, the formula is provided:

$$attractiveness\ of\ HP = desnity\ of HP^{imp\ density} * \ financial\ attractiveness^{imp\ finance} * \ gp\ atttactiveness^{\ imp\ gp}$$

$$imp\ finance = (1 - imp\ density) * distr\ imp$$

$$imp\ gp = (\ 1 - imp\ density) * (1 - distr\ imp)$$

However, since there is no historical data that differentiates between heating in STFH and MFH, especially the results of this for MFHs only have limited validity. Especially for the HP installation in new STFH, which has a good historical fit, this calibration is part of building the model and can be an insight in itself. The results show that the decision to install heat pumps in new STFH is mainly (64%) based on financial attractiveness, with density only coming second with 25%.

Building type	Importance of density	Importance of financial attractiveness	Importance of gas price
New STFH	0,25	0,637	0,113
Old STFH	0,45	0,138	0,413
New MFH	0,4	0,48	0,12
Old MFH	0,4	0,48	0,12

Table 3 Calibration results for the weights of influences on HP attractiveness.

Financial attractiveness, modelled going from 0 to 1, is not only influenced by the endogenized installation price but also exogenous variables such as the consumer price index and its relation to the average monthly income as well as the interest rate. Therefore, pumps in the installation price for HP in STFH are not reflected in the change of financial attractiveness. For MFH, where the general financial burden of installing a heat pump is higher, the price increase resulting from a capacity shortage is also visible in the financial attractiveness (see Figure 19).

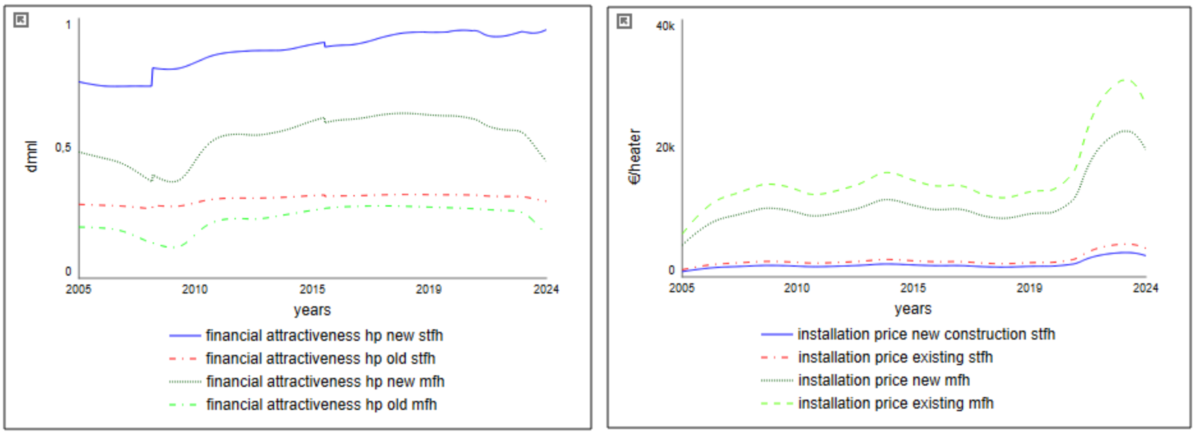

Figure 19 Financial attractiveness and installation price of HPs.

4.2. Baseline Scenario

In the baseline scenario after 2023, variables that were so far dependent on historical data, continue running with the latest available data. This means new construction in STFH and MFH, average wage, number of people starting an installer apprenticeship, subsidies CPI and interest rate stay stable, and the gas price changes according to an estimation by Pehnt et al. (2023). For more details see Table 4.

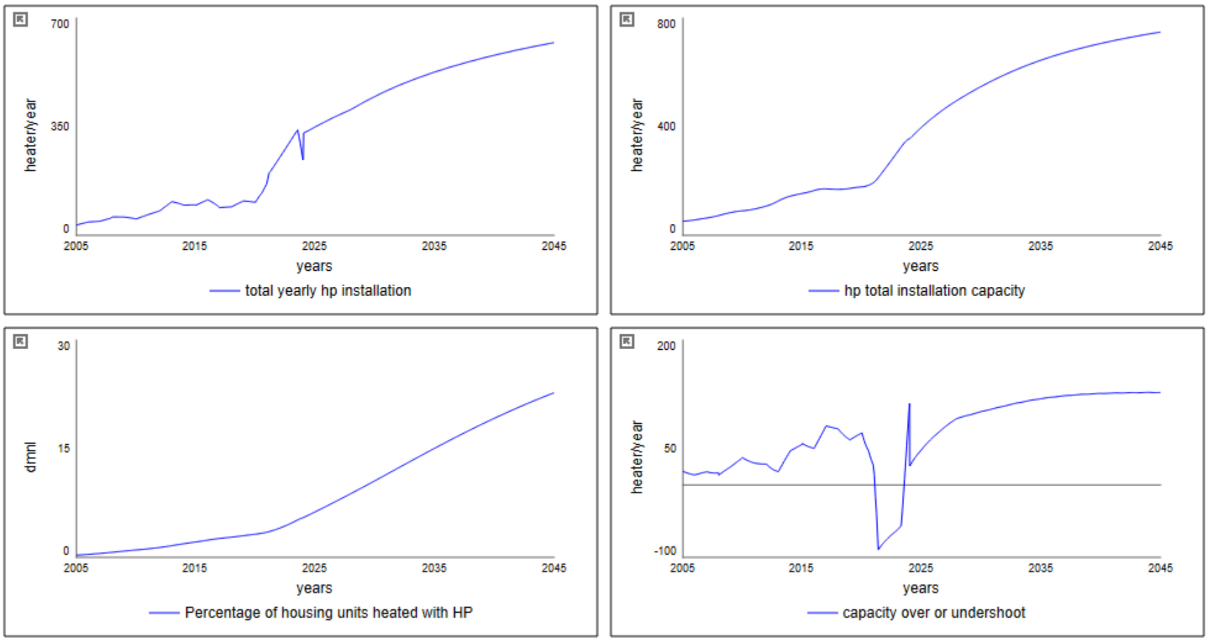

Figure 20 Baseline scenario

After 2023, in the baseline scenario depicted in Figure 20, the general trend seems positive: The number of HP installations increases with exponential decay, as is to be expected in an innovation diffusion model. The installation capacity also increases with exponential decay and therefore stabilises at a capacity overshoot. This development leads to a stable increase in housing units heated with heat pumps. This increase also is steeper than it was historically. However, compared with the ambitious goal, the baseline scenario is not compatible with reaching climate neutrality.

While new buildings could reach over 90% heat pump installations and therefore nearly fully sustainable heating (including district heating) in the relevant time frame, existing buildings stay behind in the retrofitting towards sustainability with only up to 60% heat pump installations (Figure 21). This is especially devasting considering that each new fossil heater will continue to pollute for another 20 to 30 years.

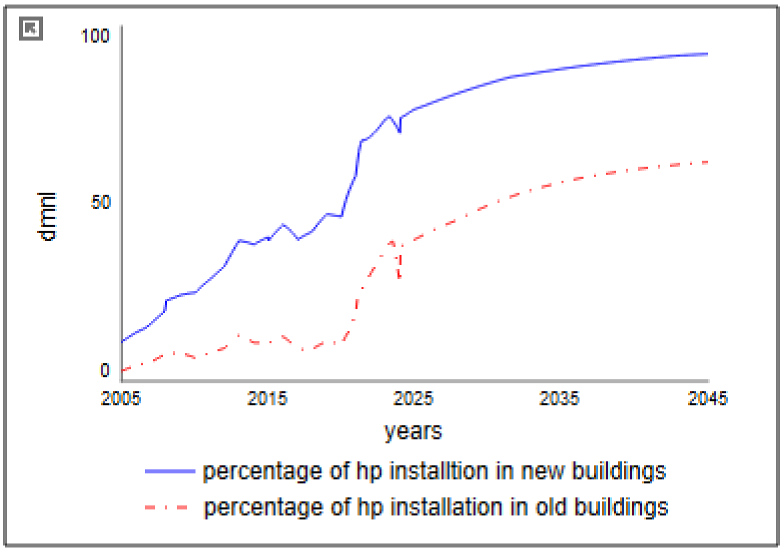

Figure 21 Baseline scenario difference between new and old buildings.

4.3. Future Scenarios

For so far historical data-driven variables different scenarios for the future have been created, as shown in Table 4. Economic variables have been summarized and can be controlled together with one switch to create coherent scenarios. Otherwise, different scenarios can be chosen via a Switch and freely combined. In this chapter, I will only analyse certain scenario combinations to showcase different possible developments (see Table 5). Worst-case and best-case scenarios are made to showcase the range of possible future developments, more realistic scenarios show the nuances. Showing a realistic scenario once for a flourishing economy and once for a pessimistic development, also shows the general influence of the economy on the development of HP adoption.

Switch	Affected variable	Baseline	Scenario 1	Scenario 2
Gas scenario	Gas price	Linear price increase from 12 to 18 cents per kilowatt hour of gas in 245 starting in 2024.	Linear price increase from 12 to 25 cents per kilowatt hour of gas in 245 starting in 2024.	Stable at 12 cent per kilowatt.
Economy	Interest rate	Stable at 4,5	Decreases to 0,5 by the year 2026 and then stays stable.	Linear increase up to 5,5 in 2045, starting at 4,5 in 2024.
	CPI	Stable at 1,167	Slight increase: Linearly increases to 1,23 by 2045.	Steep increase: Linearly increases to 1,287 by 2045.
	Average monthly income	Stable at 4100 € per house.	Steep increase: Linearly increases to 5600 by 2045.	Slight increase: Linearly increases to 4800 by 2045.
	New STFH	Stable at 89 houses per year.	Linearly increases to 100 houses by 2045.	Linearly decreases to 80 houses by 2045
	New MFH	Stable at 15 houses per year.	Linear increase to 20 houses by 2045.	Linear decrease to 10 houses by 2045
HP price	HP device price STFH	Stable at 12500 € per heater.	Increases according to CPI.	/
	HP device price MFH	Stable at 30.000 € per heater.	Increases according to CPI.	/
Apprentices	Start apprenticeship	Stable at 7,7 people per year.	Linearly increases to 10 by 2045.	Linearly decreases to 5 by 2045.

Table 4 Overview of possible scenarios for exogenous variables.

	Gas price	Economy	HP price	Apprentices
Worst case	Scenario 2	Scenario 2	Scenario 1	Scenario 2
Best case	Scenario 1	Scenario 1	Baseline	Scenario 1
Good economic but realistic case (Ec1_realistic)	Baseline	Scenario 1	Scenario 1	Baseline
Bad economic but realistic case (Ec2_realistic)	Baseline	Scenario 2	Scenario 1	Baseline

Table 5 Overview of possible scenario combinations.

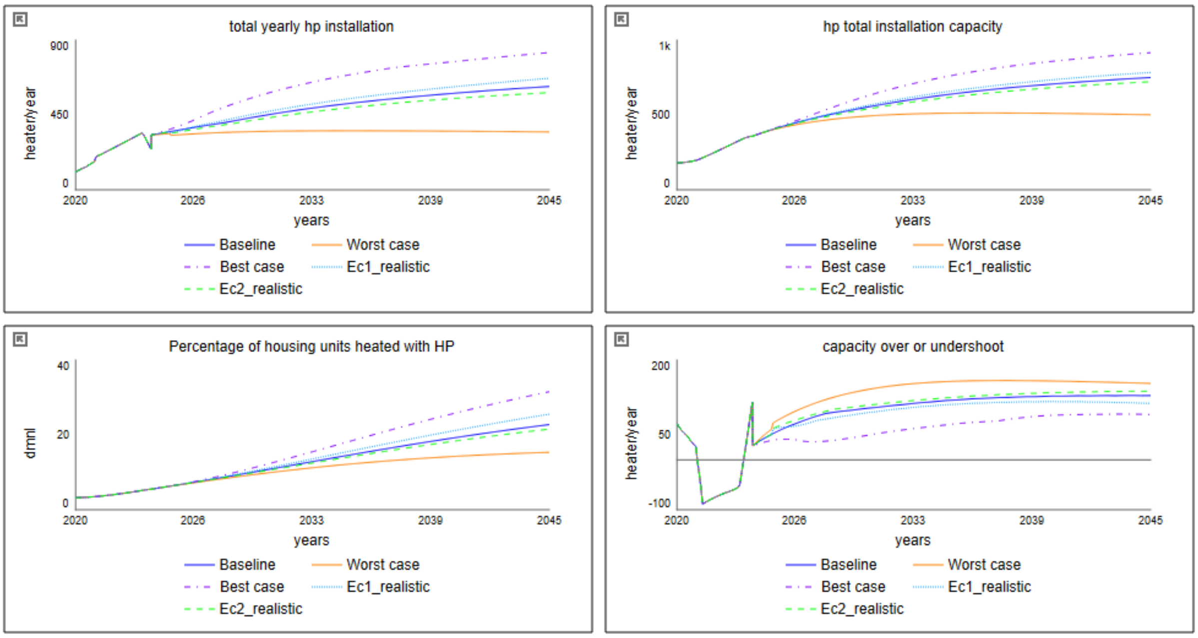

Figure 22 KPIs development for different scenarios.

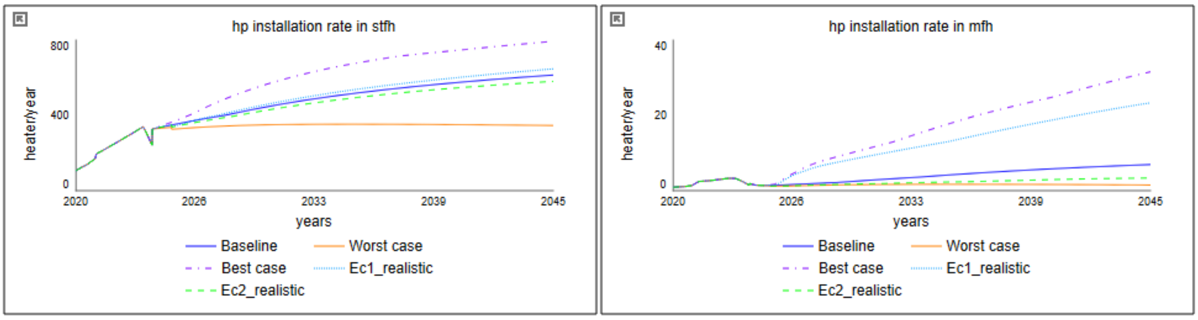

Figure 23 Difference for STFH and MFH HP installation for different scenarios.

The results have a large range, from mostly positive developments towards a worst-case that results in mostly stagnation. Total heat pump installation, as well as HP total installation capacity, varies from increasing decreasingly in various amounts of steepness towards a slight decline in the worst-case scenario. In all scenarios, the percentage of housing units heated with HP is growing. Even when the number of heat pump installations is declining, heat pumps are still accumulating as long as the yearly installation rate is above the yearly scrapping rate. The capacity overshoot is positive in all scenarios; therefore, capacity is not a limiting factor in the model after 2023. Surprisingly, the overshoot is the lowest in the best-case scenario. Despite the best-case scenario including a positive scenario for apprentices starting into the installer's job in the future, the high number of installations leads to the lowest overshoot.

The results also show the positive influence of a flourishing economy on heat pump adoption. The relationship between CPI and average income influences the affordability of heat pumps while interest rate is a decisive factor for the affordability and attractiveness of loans which can be necessary for larger projects necessary for retrofitting MFHs. Therefore, the influence of economic factors on HP adoption in MFH is even more significant than on HP adoption in STFHs, as can be seen in Figure 23.

5. Policy Design and Analysis

This chapter aims to use the gained understanding of the system to design, and test policies. The suggested policies are based on leverage points. This chapter does not aim to test policies announced or discussed by the government and does not want to predict their success. Implementation obstacles and trade-offs are mostly not considered. Therefore, the policies listed here are not recommendations, but starting points for discussions. It addresses the third research question: *What policy options can be identified to speed up the adoption of heat pumps?*

This work cannot assess the trade-offs of policies comprehensively. While policies may appear effective and yield positive results in the model, this does not guarantee their success in real life. A critical analysis of who will bear the potential burden of these policies is missing. Prohibitions and mandates that impose costs on affected individuals exemplify this burden. For instance, requiring people to replace their heaters prematurely can be costly and socially unfair. On the other hand, financial incentives can mitigate these burdens but strain the state budget and divert financial resources from other areas. Additionally, determining the appropriate cost-sharing between the state and private owners is challenging. Therefore, trade-offs will only shortly be reflected if known by the author.

All policies and their results must be seen in light of the limitations and uncertainties of the model.

5.1. Policy Design

The tested future scenarios suggest that scarcity of installation capacity does not seem to be an issue. Therefore, loop **R5 (Adapting installation capacity)** does not need to be strengthened and I will focus the policies on increasing the demand for heat pumps. This is also sensible given the lower confidence in the installer sector of the model. An effective policy should tackle a leverage point, a point where the model reacts sensitively to changes. To be feasible a policy needs to tackle a point where change is possible. Therefore, parameters that control the weight of influences have been excluded from policies. While it may be possible to change values long-term, this should not be the goal of a policy in this context. Attempting to change this would be unreliable and slow. Instead, policies should be designed with consideration for the weight that potential adopters assign to different influences. Additionally, policies should be designed with consideration for installation capacity and device availability. The demand should only be enhanced to a degree where the capacity is sufficient. If it goes beyond that additional policies should be implemented that allow the extension of the installation capacity.

Through the sensitivity and general analysis, two points that met the above-stated criteria were found: The FH total lifetime (especially for STFH, but both are considered here) and the costs of heat pumps in general, but especially the renovation costs.

5.2. Policy testing

I will first introduce the policies, briefly discuss possible implementations, and then test the models' influence compared to the baseline and best-case and worst-case scenarios. At last, the influence of the gas price is discussed. The scenario analysis already included some analysis of its influence, but further discussion seems necessary as it neither fully fits in the category of an exogenous variable nor a policy.

5.2.1. Fossil heater lifetime reduction

The first policy aims to reduce fossil heaters' lifetime (both in STFH and MFH), this increases the outflow of the ageing chain for fossil heaters and reduces their accumulation. It weakens the loop **R2 (Everything stays as it is).**

A reduction of the lifespan of heaters could either be mandated or incentivised. A mandate could order a legal maximum age up to which heaters can be used. This could be implemented in cooperation with chimney sweeps that are already responsible for controlling heater functionality. However, this might be an unpopular policy because it increases costs for homeowners and potentially indirectly also renters. Another option could be a scrapping premium, that reimburses homeowners that scrape old but functioning fossil heaters. Such as measure is in discussion at the moment (Traufetter, 2023). This is similar to a policy that was introduced in Germany during the financial crisis of 2008, which reimbursed car owners for scrapping their old but functioning cars. The performance of the policy could even be increased if this reimbursement is only paid out if the fossil heater is replaced with a sustainable alternative, however, this is not tested here.

A reduction of heater lifetime would need to be conducted in steps. A sudden decrease of several years is unrealistic to implement. Therefore, the policy decreases the average lifetime by one year each year starting in 2025 and ending in 2030. This reduces the lifetime from 33 to 28 years.

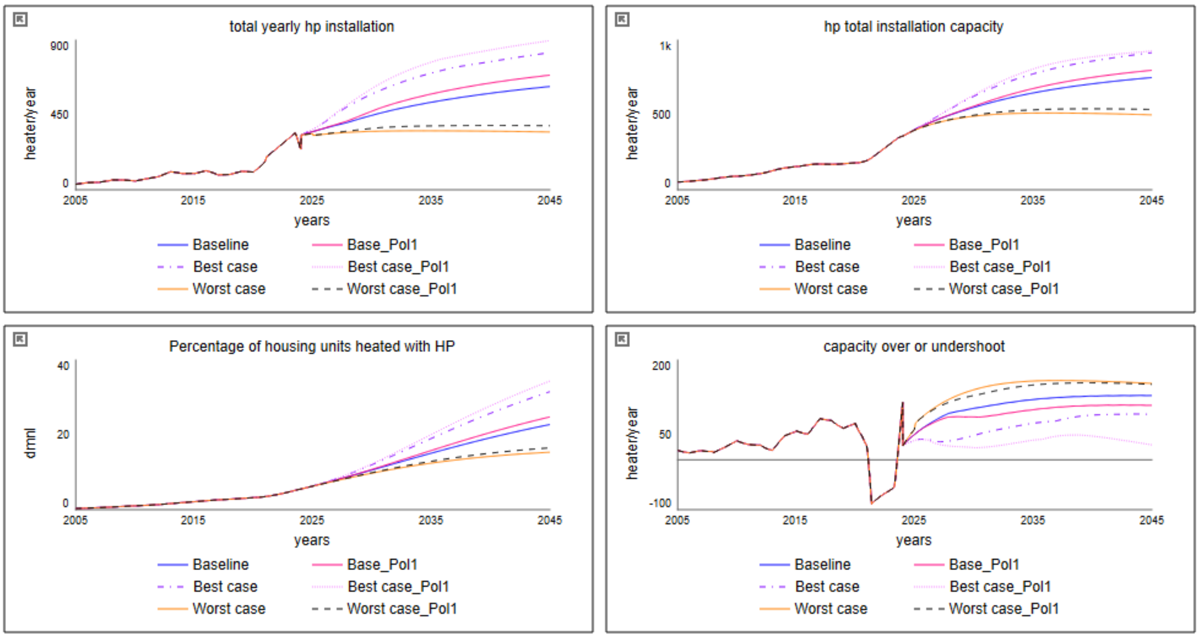

Figure 24 The influence of reducing heaters' lifespan under different circumstances.

As can be seen in Figure 24 the policy increases the HP installations under all tested scenarios as well as the percentage of housing units heated with HP. While the capacity overshoot reduces, it is still sufficient. The policy is effective, and the outcome is desirable.

5.2.2. Subsidies

The second policy influences the financial attractiveness of heat pumps and consequently weakens the loop **B2 (Short-term demand increases prices)**. There are already subsidies in place that reduce the costs for all four building types and they were kept during the baseline scenario. Additionally, the second policy introduces subsidies specifically for old buildings by subsidising energy-efficient renovations.

Since subsidies for heat pumps are already an established policy instrument, they are easy to implement. The two main issues with subsidies are that they are expensive for the state. This is mainly a matter of priorities of the government. The other issues are the applications to receive the subsidies. They need to be accessible and fast to process while still preventing fraud. A mechanism that is not included in the model but should be considered for policy design is how subsidies influence the price setting of HPs and HP installation services. While subsidies are intended to lower costs for consumers, they may inadvertently lead to price inflation as customers become more willing to pay higher prices knowing they will receive reimbursements. It is important for policymakers to carefully consider this potential consequence and implement measures to prevent such unintended outcomes. However, this is not inside the scope of this model.

Since the scenarios shown so far, all already include the subsidies, as they have been modelled to continue, I will instead test how the model reacts to the exclusion of subsidies (in Figures 25 and 26 included as noSub). Additionally, I will show how the model reacts to the inclusion of renovation subsidies. These subsidies reduce the renovation costs by 10%.

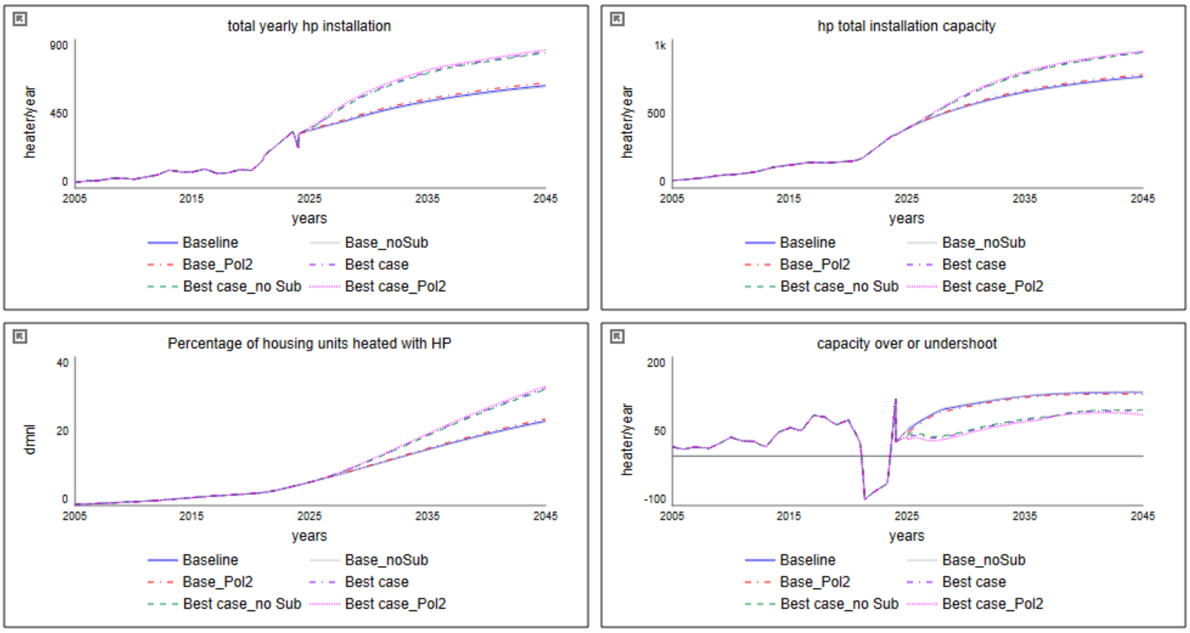

Figure 25 Influence of subsidies for best-case and baseline scenario.

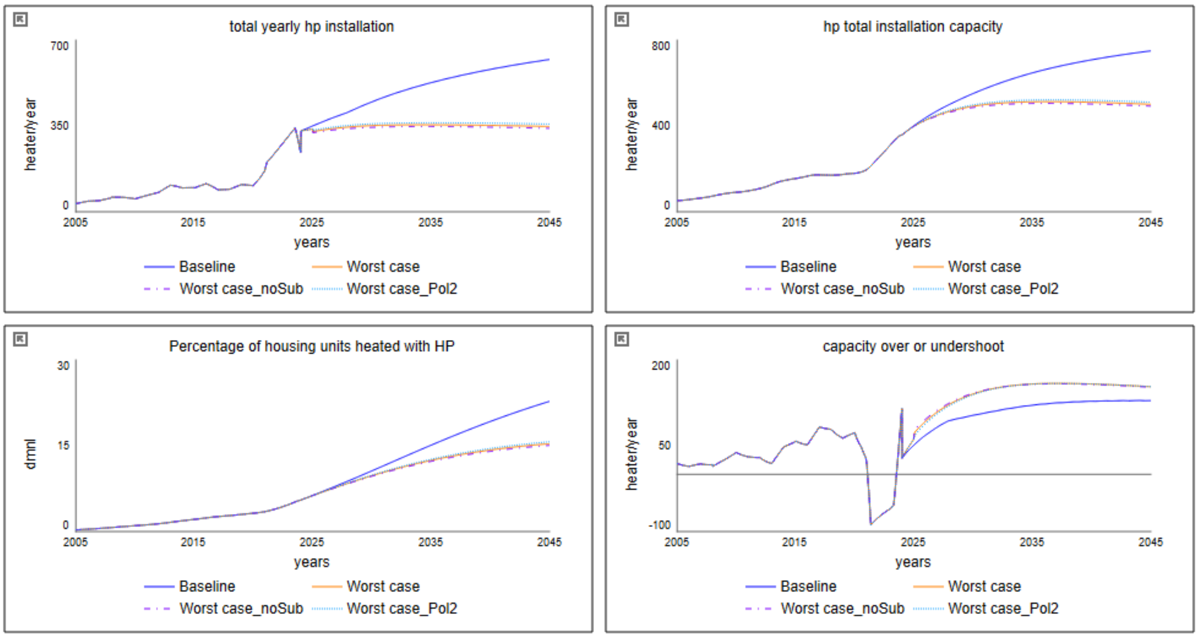

Figure 26 Influence of subsidies on worst-case scenario.

The difference between the scenarios of no subsidies, continuation of existing subsidies and introduction of additional subsidies is minimal. A very small positive numerical effect can be seen for the introduction of additional subsidies and a very small negative effect for the discontinuation of subsidies. The effect is merely neglectable, especially in the face of the costs those subsidies cause. However, this could also be caused by missing structure. The model e.g. does not differentiate for income groups.

However, subsidies might not only be seen as an instrument to enhance HP adoption numbers, but also as a measure to reduce social hardships. Therefore, this should not be seen as a general indicator against subsidies. Instead, it could be a starting point to discuss the goal of subsidies and how they need to be implemented to reach this goal. Especially the question of who policies should help and how to target these people with precision instead of scattering financial funds. However, this model is not equipped to help with these questions, as there is no differentiation between different groups of homeowners.

5.2.3. Gas price

While the gas price can be influenced by uncontrollable events and developments and therefore was part of the scenario building, it is also influenced by political regulations. Carbon-tax and gas price brake ("Gaspreisbremse") are examples. A carbon tax, conceptualised as a slowly rising fee per ton of emitted CO2, is supposed to increase financial incentives for sustainable consumer decisions (World Bank Group, 2019). Since burning gas or oil for heating produces CO2 this purposefully includes rising running costs for fossil heaters. Heat pumps are powered with electricity that can come from various sources, sustainable or non-sustainable, and therefore rising costs can be avoided by using sustainable electricity sources. A gas price brake on the other hand seems counterintuitive regarding environmental goals. Despite this, it was a temporary measure to avoid social hardships while gas prices were rising after the Russian invasion of Ukraine (*Preisbremsen für Strom und Gas | Bundesregierung*, 2024). The rising gas prices showed the dependence of the German economy on cheap gas. Therefore, a scenario like the best-case scenario for heat pumps – steep rising gas prices and a thriving economy – is unrealistic, at least with today's technology. The only exception might be if gas stays cheaper for the industry and rises only for private consumers.

This duality of gas prices warrants further investigation. Therefore, I analysed additional scenarios with varying gas price developments.

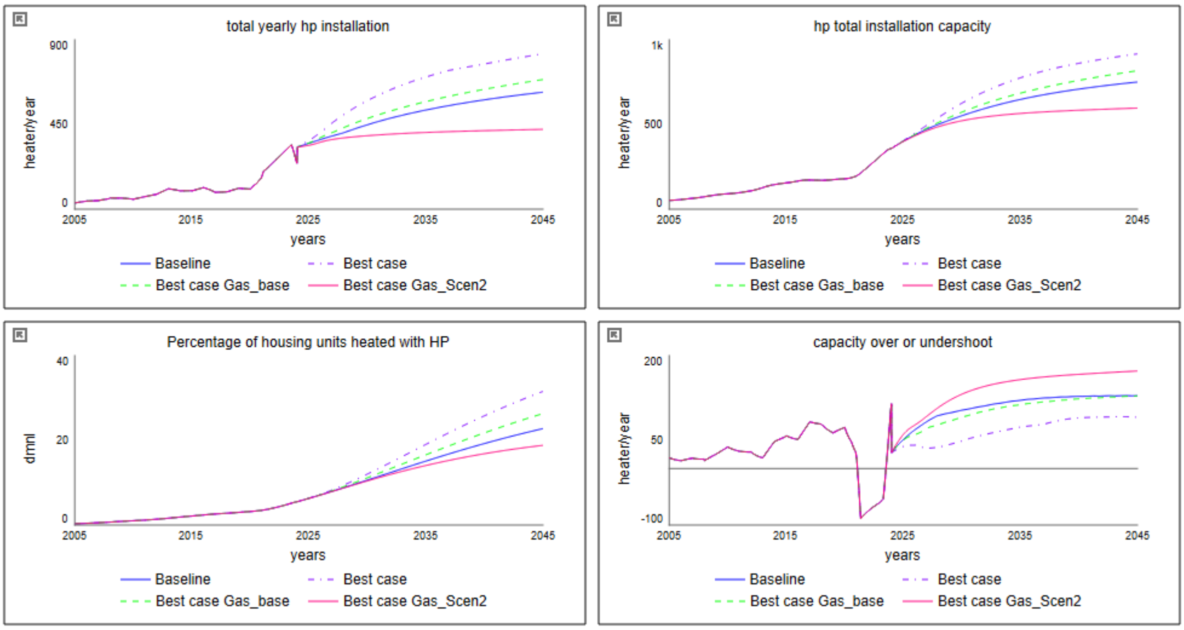

Figure 27 Influence of gas price on best-case scenario.

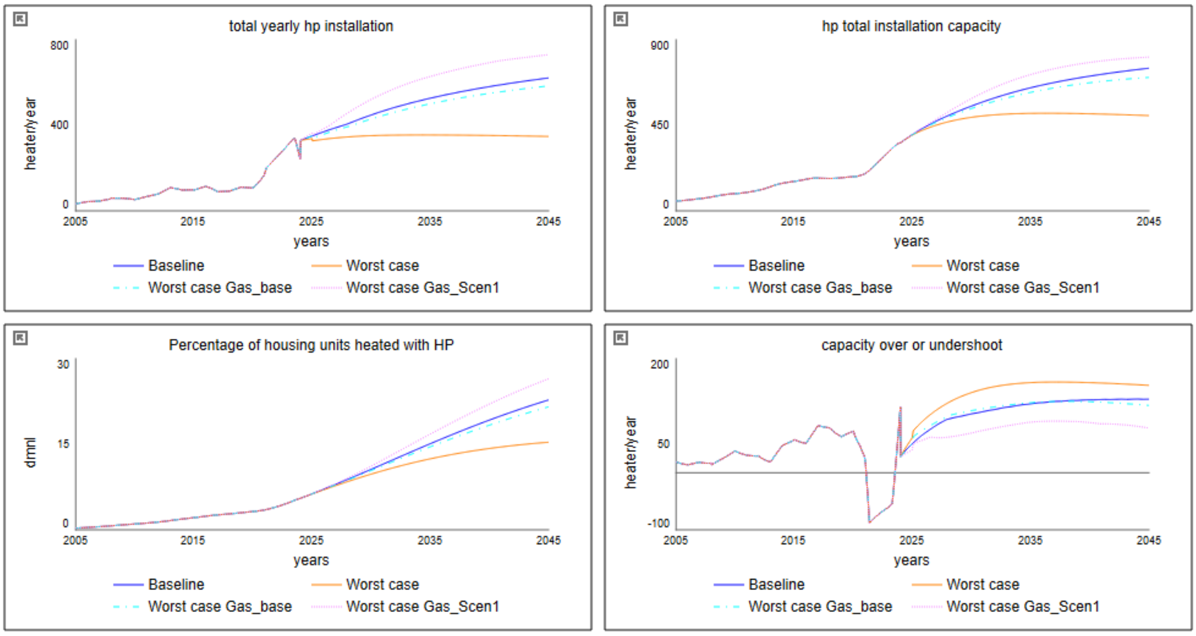

Figure 28 Influence of gas price on worst-case scenario.

No matter the other circumstances, as can be seen in Figures 27 and 28, a stagnating gas price leads to stagnating or in the worst case even slightly declining, heat pump installations. However, in all cases, the percentage of housing units heated with HP is increasing, since even stagnating sales still lead to accumulation, since they are still above the scrapping ratio. Therefore, the gas price is of high importance to the development of heat pump sales in Germany.

6. Discussion

The simulation indicates that HP installations have been increasing in popularity in recent years and are expected to continue to grow or remain stable, depending on gas price trends. However, even under the most optimistic scenarios, it appears that these trends may not align with the goals set by the German government. Despite falling short of these goals, the overall positive trend is expected to result in emissions savings. I forego a calculation of potential saved emissions, due to two factors:

1. Some refrigeration fluids used in HP systems have a negative impact on the environment, prompting research into more sustainable alternatives (Born et al., 2017). 2. It has been observed that many energy-saving initiatives can lead to rebound effects, as seen in the work by Guzzo et al. (2024). Rebound effects associated with the use of heat pumps may include increased heating usage when heating is more affordable and additional cooling in summer that was not previously achievable with fossil fuel heaters. As the model does not account for these effects, estimating emissions saved could be misleading.

6.1. Answers to the research questions

I will give a short summary of the answers to the research questions:

1. *What factors contribute to and slow down the adoption of heat pumps in Germany?*

Many STFH owners are primarily motivated to switch to heat pumps for financial reasons. They aim to save on energy costs, but the high upfront installation fees deter many from making the switch. Fluctuations in gas prices directly impact the perceived savings on energy costs. Furthermore, social interactions can play a role in the decision to adopt heat pumps. Seeing others in the neighbourhood or social circle using heat pumps helps to reduce fears about the technology and bridges the gap between theory and practical application. For MFHs, heat pumps are still in the early adopter stage and therefore lack research on motives. While technically feasible, solutions for HP installations might be economically unviable or lack social acceptance.

Heat pump adoptions can also be negatively impacted by bottlenecks in installation capacity and device supply. Not all installers offer heat pump installation and a shortage can lead to long waiting times and increased costs.

2. *How do these factors interact with each other and influence the behaviour of the system?*

Only a small percentage of heaters get exchanged every year due to age since they have a long lifespan, and the exchange is expensive. Therefore, the amount of fossil heaters that can be replaced with heat pumps each year is limited. The probability of adopting a heat pump is partly dependent on density and therefore on previous decisions to adopt heat pumps, but due to the small number of exchanges, accumulation is limited and therefore is an overall slow process. The system is “locked in” in a state where fossil heaters remain the norm.

While installation capacity shortages can have a significant negative impact on HP installations, overcapacity has no significant positive influence since prices are only slightly affected by it.

It became clear that certain exogenous variables, such as overall economic development and gas price have a significant influence on HP installation rates. Therefore, SD can only give limited insights into future development. A positive economic development positively influences heat pump adoption mainly due to higher purchase power. However, rising gas prices and positive economic development may be hard to achieve simultaneously.

3. *What policy options can be identified to speed up the adoption of heat pumps?*

Through policy testing in the model, a reduction of fossil heaters' lifetime and a steady increase in gas prices have shown to be most successful in increasing the HP adoption rate. Subsidies show little influence on the other side. However, they should be considered for other reasons such as reducing social hardships.

6.2. Limitations

The insights are limited by the boundaries of the model and uncertainties, mainly in the installers sector and the calculation of HP attractiveness for MFH.

Simplifications in the sector for heat pump installers reduce the explanatory power of the model since the sensitivity analysis showed this sector to be very important for the behaviour of the model. However, due to the focus of the problem, reduced complexity of the installer sector seemed to be a sensible option. Creating a more realistic model would encompass the inclusion of exogenous variables on the workload of installers, which is complex and not the goal of the model. SD tries to explain behaviour mainly through endogenous by the structure of the system, however, this approach might reach its limits here.

Uncertainties are introduced to the model, especially in the sector of MFHs. Knowledge of heat pump adoption there is lacking. Therefore, assumptions had to be made which increases the uncertainties of the results.

6.3. Future research

Future research should focus on heat pumps in MFH, as equipping MFHS with heat pumps makes sustainable heating accessible for many more people. Research on the motives of landlords and corporations in the housing market should be conducted to ensure that heat pumps become the standard not only in STFHs but MFHs as well. Different policies for smaller MFHs with owner-occupied flats and cooperations renting out large apartment complexes should be developed.

A possible extension of the model can include differentiation between smaller and bigger apartment buildings. Further investigation of the potential to which MFHs can be economically viable heated with HP is necessary. Including district heating and further exploring its potential is another step towards a more realistic MFH sector. Furthermore, I suggest testing more policies so far presented by the German government.

While the iterative process of SD model building has many advantages, it can lead to some frustrations, when insights during the modelling or testing process suggest further improvements, that cannot be implemented anymore due to the limited timeframe of the project. Therefore, I want to shortly list, improvements in model structure that could enhance the model accuracy:

So far, when heat pumps are scrapped due to age, the calculation of the attractiveness of adopting a heat pump again afterwards is the same as for a home that was previously heated with fossil heaters. This is incorrect, as renovations necessary for a heat pump have already been conducted and installation will be easier. A separate inflow for reinstallations could be calculated in a revision of the model. Alternatively, the scrapping of heat pumps due to age could be excluded from the model, however, this negatively influences the calculation of the capacity needed for heat pump installations.

The price for heat pump installations so far depends merely on the ratio of demand and supply. Additional influences might be the speed of installation, depending on skill. This already has an indirect influence via the increased capacity though gained skill but could also have a direct influence since workers are paid by the hour.

Additionally, while gas price certainly has a high influence on heat pump adoption, in the model, this influence depends on the rate of change. More ways of adding the gas price could be tested until the best reference behaviour reproduction is found: It might depend on the total price or needs to be set in comparison with the electricity price.

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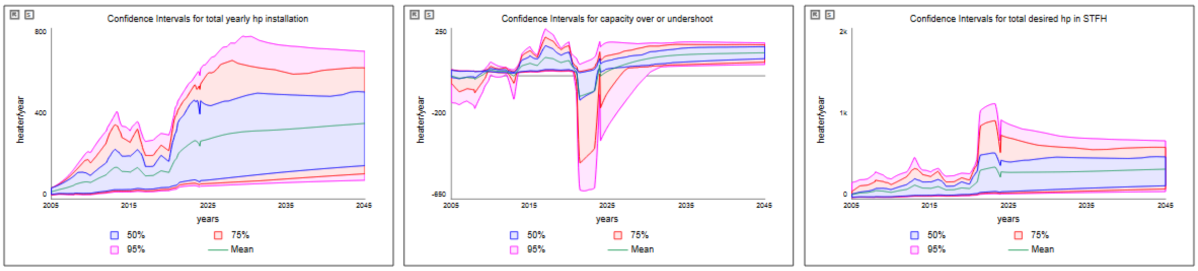
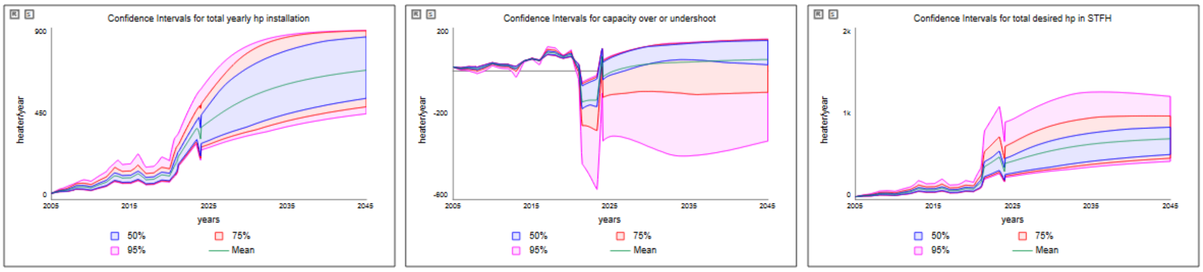
Appendix A: Sensitivity Analysis

Imp density old stfh & distr imp old stfh



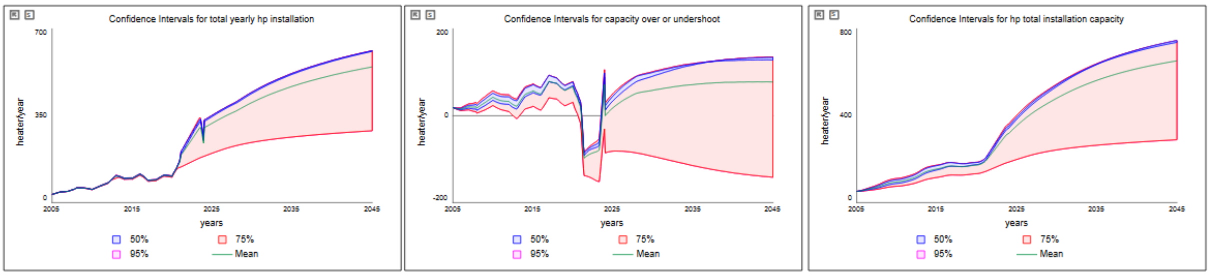
Combined testing for both values between 0 and 1. The model reacts appropriately sensitive to changes.

FH total lifetime stfh



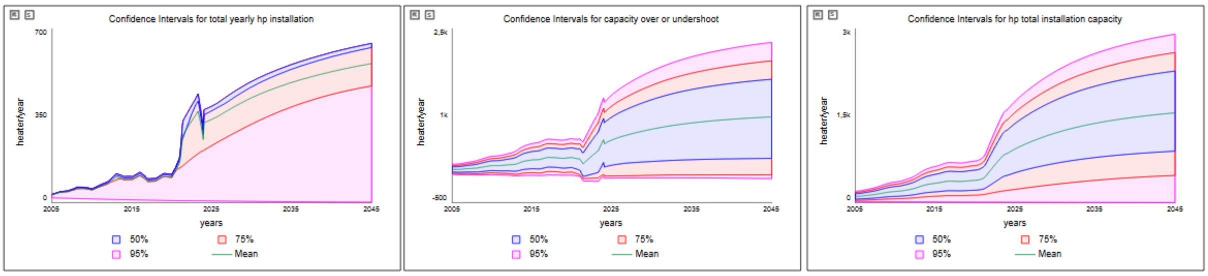
Tested for values between 10 and 50 years, original parameter value is 33 years. The model reacts appropriately sensitive to changes.

Willingness for further training



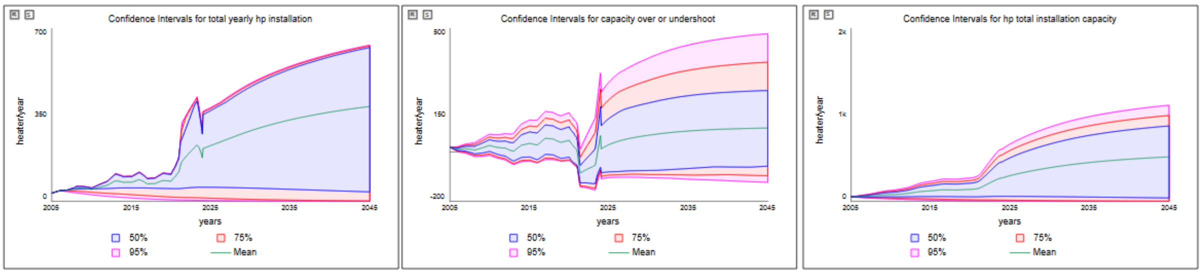
Tested for values between 0 and 1, the original parameter value is 0,15. The model reacts appropriately sensitive to changes.

Maximum capacity per hp installer



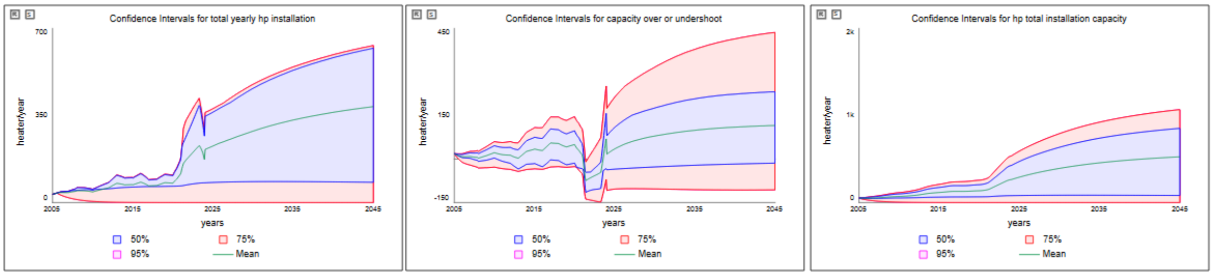
Tested for values between 1 and 20, the original parameter value is 5. Changes have the potential to stop a successful diffusion from happening.

Normal skill gain



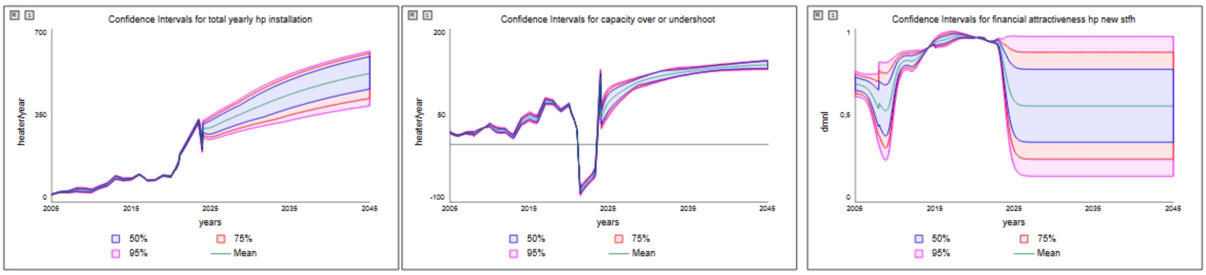
Tested for values between 0,01 and 0,1. Changes have the potential to stop a successful diffusion from happening.

Skill loss over time



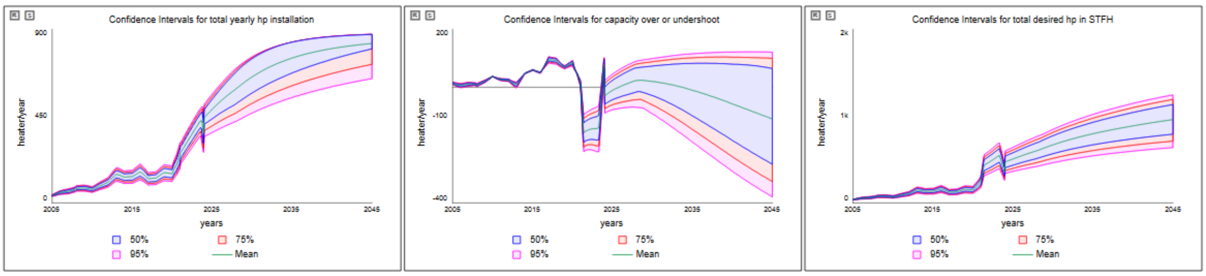
Tested values between 1 and 5. Changes have the potential to stop a successful diffusion from happening.

Importance of interest new stfh



Tested for values between 0 and 1. The model reacts appropriately sensitive to changes.

Heater per stfh



Tested for values between 1 and 2. The model reacts appropriately sensitive to changes.

Appendix B: Model Documentation

Total	Count	Including Array Elements
Variables	461	461
Modules	2	
Sectors	16	
Stocks	22	22
Flows	46	46
Converters	393	393
Constants	136	136
Equations	303	303
Graphicals	41	41
Macro Variables	24	

Run Specs	
Start Time	2005
Stop Time	2045
DT	1/64
Fractional DT	True
Save Interval	0,015625
Sim Duration	0
Time Units	years
Pause Interval	0
Integration Method	RK4
Track flow quantities	True
Keep all variable results	True
Run By	Run
Calculate loop dominance information	False

Top-Level Model:
apprentices(t) = apprentices(t - dt) + (start_apprenticeship - finish_apprenticeship) * dt
INIT apprentices = initial_apprentices_1
TRANSIT TIME = 3,5
CONTINUOUS
ACCEPT MULTIPLE BATCHES
UNITS: People
DOCUMENT: The apprenticeship for heating engineering and installation ('Installateur und Heizungsbauer') takes exactly 3 years. The conveyor represents the number of apprentices at the moment.

The unit is people.
average_hp_skill_level(t) = average_hp_skill_level(t - dt) + (gaining_experience - loss_of_experience) * dt
INIT average_hp_skill_level = 0,1
UNITS: dmnl
DOCUMENT: The stock hp skill level accumulates through the inflow gaining experience and drains through the outflow loss of experience. It represents the skill level achieved through repeating installations of heat pumps.

The average hp skill levels goes from 0 to 1. One is the maximum skill level.
The unit is dimensionless.
FH_MFH_one(t) = FH_MFH_one(t - dt) + (new_fh_mfh - fh_mfh_aging_1 - fh_scrapping_through_demolition_4) * dt
INIT FH_MFH_one = initial_fh_mfh_one
UNITS: heater
DOCUMENT: This stock represents the first part of an ageing chain (Sterman, 2000, Chapt. 12). It accumulates fossil heaters in MFH in the first part of their lifetime. It accumulates through the inflow new fh mfh and drains through the outflows fh mfh ageing 1 and fh scrapping through demolition 4.
The unit is heater.
FH_MFH_three(t) = FH_MFH_three(t - dt) + (fh_mfh_aging_2 - fh_mfh_scrapping - fh_scrapping_through_demolition_6) * dt
INIT FH_MFH_three = initial_fh_mfh_three
UNITS: heater
DOCUMENT: This stock represents the third and last part of an ageing chain (Sterman, 2000, Chapt. 12). It accumulates fossil heaters in MFH in the third part of their lifetime. It accumulates through the inflow fh mfh ageing 2 and drains through the outflows fh stfh scrapping and fh scrapping through demolition 6.
The unit is heater.
FH_MFH_two(t) = FH_MFH_two(t - dt) + (fh_mfh_aging_1 - fh_mfh_aging_2 - fh_scrapping_through_demolition_5) * dt
INIT FH_MFH_two = initial_fh_mfh_two
UNITS: heater
DOCUMENT: This stock represents the second part of an ageing chain (Sterman, 2000, Chapt. 12). It accumulates fossil heaters in MFH in the second part of their lifetime. It accumulates through the inflow fh mfh ageing 1 and drains through the outflows fh mfh ageing 2 and fh scrapping through demolition 5.

The unit is heater.
FH_STFH_one(t) = FH_STFH_one(t - dt) + (new_fh_stfh - fh_stfh_aging_1 - fh_scrapping_through_demolition_1) * dt
INIT FH_STFH_one = initial_fh_stfh_one
UNITS: heater
DOCUMENT: This stock represents the first part of an ageing chain (Sterman, 2000, Chapt. 12). It accumulates fossil heaters in STFH in the first part of their lifetime. It accumulates through the inflow new fh stfh and drains through the outflows fh stfh ageing 1 and fh scrapping through demolition.
The unit is heater.
FH_STFH_three(t) = FH_STFH_three(t - dt) + (fh_stfh_aging_2 - fh_stfh_scrapping - fh_scrapping_through_demolition_3 - early_exchange_stfh) * dt
INIT FH_STFH_three = initial_fh_stfh_three
UNITS: heater
DOCUMENT: This stock represents the third and last part of an ageing chain (Sterman, 2000, Chapt. 12). It accumulates fossil heaters in STFH in the thid part of their lifetime. It accumulates through the inflow fh stfh ageing 2 and drains through the outflows fh stfh scrapping and fh scrapping through demolition 3.
The unit is heater.

FH_STFH_two(t) = FH_STFH_two(t - dt) + (fh_stfh_aging_1 - fh_stfh_aging_2 - fh_scrapping_through_demolition_2) * dt
INIT FH_STFH_two = initial_fh_stfh_two
UNITS: heater
DOCUMENT: This stock represents the second part of an ageing chain (Sterman, 2000, Chapt. 12). It accumulates fossil heaters in STFH in the second part of their lifetime. It accumulates through the inflow fh stfh ageing 1 and drains through the outflows fh stfh ageing 2 and fh scrapping through demolition 2.
The unit is heater.
hp_installers(t) = hp_installers(t - dt) + (inflow_through_apprentices + further_training_inflow - outflow_through_retirement) * dt
INIT hp_installers = initial_installers*init_hp_installer_ratio
UNITS: People
DOCUMENT: The stock represents the number of installers that do heat pump installations. It accumulates through the two inflows 'inflow through apprentices' and 'further training inflow', representing that people can become hp installers right at the beginning of their work life or later on. It is drained through 'outflow through retirement', representing installers who retire.

The number of hp installers is used to calculate the installation capacity.
HP_MFH_one(t) = HP_MFH_one(t - dt) + (new_hp_mfh - hp_mfh_aging_1 - hp_scrapping_through_demolition_3) * dt
INIT HP_MFH_one = initial_hp_mfh_one
UNITS: heater
DOCUMENT: This stock represents the first part of an ageing chain (Sterman, 2000, Chapt. 12). It accumulates heat pumps in MFH in the first half of their lifetime. It accumulates through the inflow new hp mfh and drains through the outflows hp mfh ageing and hp scrapping through demolition 3.
The unit is heater.
HP_MFH_two(t) = HP_MFH_two(t - dt) + (hp_mfh_aging_1 - hp_mfh_scrapping - hp_scrapping_through_demolition_4) * dt
INIT HP_MFH_two = initial_hp_mfh_two
UNITS: heater
DOCUMENT: This stock represents the second half of an ageing chain (Sterman, 2000, Chapt. 12). It accumulates heat pumps in MFH in the second half of their lifetime. It accumulates through the inflow hp mfh ageing and drains through the outflows hp scrapping through demolition 4 and hp mfh scrapping.
The unit is heater.
hp_pressure_on_installers(t) = hp_pressure_on_installers(t - dt) + (change_of_pressure_on_installers) * dt
INIT hp_pressure_on_installers = initial_request_ratio_to_pressure_translation
UNITS: dmnl
DOCUMENT: The pressure on the installers through the ratio of demand and supply is modelled as a stock since there is an information delay, before a change is registered.
HP_STFH_one(t) = HP_STFH_one(t - dt) + (new_hp_stfh + early_exchange_stfh - hp_stfh_aging - hp_scrapping_through_demolition_1) * dt
INIT HP_STFH_one = Initial_hp_stfh_one
UNITS: heater
DOCUMENT: This stock represents the first part of an ageing chain (Sterman, 2000, Chapt. 12). It accumulates heat pumps in STFH in the first half of their lifetime. It accumulates through the inflow new hp stfh and drains through the outflows hp stfh ageing and hp scrapping through demolition.
The unit is heater.
HP_STFH_two(t) = HP_STFH_two(t - dt) + (hp_stfh_aging - hp_stfh_scrapping - hp_scrapping_through_demolition_2) * dt
INIT HP_STFH_two = Initial_hp_stfh_two
UNITS: heater
DOCUMENT: This stock represents the second half of an ageing chain (Sterman, 2000, Chapt. 12). It accumulates heat pumps in STFH in the second half of their lifetime. It accumulates through the inflow hp stfh ageing and drains through the outflows hp scrapping through demolition 2 and hp stfh scrapping.
The unit is heater.
installers1(t) = installers1(t - dt) + (finish_apprenticeship + hiring_unskilled_workers - instal_ageing) * dt
INIT installers1 = initial_inst_1
UNITS: people
DOCUMENT: The stock contains installers relevant to heat pump installations during the first part of the duration of their working time.

Craftspeople relevant to heat pump installations are defined as people who work in craft workshops related to heating engineering and installation and electrotechnology. This includes unskilled labourers and non-craft-related employees of these workshops.

The stock accumulates through the inflows 'finish apprenticeship' and 'hiring unskilled workers' and drains through the outflow 'instal ageing' which represents the entering of the second part of the duration of the working time.

The unit is people.
installers2(t) = installers2(t - dt) + (instal_ageing - retirement) * dt
INIT installers2 = initial_inst_2
UNITS: people
DOCUMENT: The stock contains installers relevant to heat pump installations during the second part of the duration of their working time.

Craftspeople relevant to heat pump installations are defined as people who work in craft workshops related to heating engineering and installation. This includes unskilled labourers and non-craft-related employees of these workshops.

The stock accumulates through the inflows 'instal ageing' which represents the entering of the second part of the duration of the working time and drains through the outflow 'retiring'.

The unit is people.
"MFH_0-30"(t) = "MFH_0-30"(t - dt) + (mfh_new_constructions - mfh_aging_1) * dt
INIT "MFH_0-30" = "Init_MFH_0-30"
UNITS: house
DOCUMENT: The stock MFH 0-30 represents the number of multi-family houses (apartment buildings) between 0 and 30 years old.

The inflow to the stock is mfh new constructions, the outflow is mfh aging 1. Houses can only age out of the stock, but not be demolished, since buildings are usually last longer than 30 years.

The stock is part of an ageing chain (Sterman, 2000, Chapt. 12). An ageing chain is necessary due to the different qualities of buildings depending on their age (e.g. buildings of a higher age have on average worse insulation and higher renovation costs).

The unit is house.
"MFH_31-60"(t) = "MFH_31-60"(t - dt) + (mfh_aging_1 - mfh_aging_2 - mfh_demolishing_1) * dt
INIT "MFH_31-60" = "Init_MFH_31-60"
UNITS: house
DOCUMENT: The stock MFH 31-60 represents the number of multi-family houses (apartment buildings) between 0 and 30 years old.

The inflow to the stock is mfh ageing 1. Houses leave the stock either via outflow mfh demolishing 1, which represents houses between the age of 30 and 60 that become demolished or by aging out of the stock and leaving via the outflow mfh ageing 2.

The stock is part of an ageing chain (Sterman, 2000, Chapt. 12). An ageing chain is necessary due to the different qualities of buildings depending on their age (e.g. buildings of a higher age have on average worse insulation and higher renovation costs).

The unit is house.
MFH_above_61(t) = MFH_above_61(t - dt) + (mfh_aging_2 - mfh_demolishing_2) * dt
INIT MFH_above_61 = Init_MFH_above_61
UNITS: house
DOCUMENT: The stock MFH above 61 represents the number of multi-family houses (apartment buildings) above 61 years old.

The inflow to the stock is mfh ageing 2. Houses leave the stock via outflow mfh demolishing 2, which represents houses above 61 that become demolished.

The stock is part of an ageing chain (Sterman, 2000, Chapt. 12). An ageing chain is necessary due to the different qualities of buildings depending on their age (e.g. buildings of a higher age have on average worse insulation and higher renovation costs).

The unit is house.
"STFH_0-30"(t) = "STFH_0-30"(t - dt) + (stfh_new_constructions - stfh_ageing_1) * dt
INIT "STFH_0-30" = "Init_STFH_0-30"
UNITS: house
DOCUMENT: The stock STFH 0-30 represents the number of single- and two-family houses between 0 and 30 years old.

The inflow to the stock is stfh new constructions, the outflow is stfh ageing 1. Houses can only age out of the stock, but not be demolished, since buildings are usually last longer than 30 years.

The stock is part of an ageing chain (Sterman, 2000, Chapt. 12). An ageing chain is necessary due to the different qualities of buildings depending on their age (e.g. buildings of a higher age have on average worse insulation and higher renovation costs).

The unit is house.
"STFH_31-60"(t) = "STFH_31-60"(t - dt) + (stfh_ageing_1 - stfh_ageing_2 - stfh_demolishing_1) * dt
INIT "STFH_31-60" = "Init_STFH_31-60"
UNITS: house
DOCUMENT: The stock STFH 31-60 represents the number of single- and two-family houses between 30 and 60 years old.

The inflow to the stock is stfh ageing 1. Houses leave the stock either via outflow stfh demolishing 1, which represents houses between the age of 30 and 60 that become demolished or by aging out of the stock and leaving via the outflow stfh ageing 2.

The stock is part of an ageing chain (Sterman, 2000, Chapt. 12). An ageing chain is necessary due to the different qualities of buildings depending on their age (e.g. buildings of a higher age have on average worse insulation and higher renovation costs).

The unit is house.
STFH_above_61(t) = STFH_above_61(t - dt) + (stfh_ageing_2 - stfh_demolishing_2) * dt
INIT STFH_above_61 = Init_STFH_above_61
UNITS: house
DOCUMENT: The stock STFH above 61 represents the number of single- and two-family houses above 61 years.

The inflow to the stock is stfh ageing 2. Houses leave the stock via outflow stfh demolishing 2, which represents houses above 61 that become demolished

The stock is part of an ageing chain (Sterman, 2000, Chapt. 12). An ageing chain is necessary due to the different qualities of buildings depending on their age (e.g. buildings of a higher age have on average worse insulation and higher renovation costs).

The unit is house.
change_of_pressure_on_installers = (request_ratio_to_pressure_translation-hp_pressure_on_installers)/time_to_register_pressure
UNITS: dmnl/year
DOCUMENT: Biflow that accumulates in or drains the stock hp pressure on installers. It depends on the request ratio to pressure translation and the time to register pressure. The unit is dimensionless per year.
early_exchange_stfh = IF SWITCH_capacity = 1 THEN MIN(desired_early_exchange_stfh; capacity_for_early_exchange_stfh) ELSE desired_early_exchange_stfh
UNITS: heater/year
DOCUMENT: This is one of two inflows to the stock HP STFH one and therefore the ageing chain for HPs in STFHs, as well as the outflow of FH STFH three. It represents the exchange of heaters before the end of the fossil heaters' lifetime.

For normal model testing (Switch capacity = 1), a MIN function is active. This ensures that only as many heaters get exchanged as there is capacity to install. The other limiting factor is the desired early exchange stfh variable. For Switch capacity = 0, there is no MAX function and all desired exchanges are conducted.

The unit is heater per year.
fh_mfh_aging_1 = FH_MFH_one/fh_first_lifetime_mfh
UNITS: heater/year
DOCUMENT: Outflow of FH MFH one and inflow to FH MFH two, is calculated by dividing HP MFH one by fh first lifetime mfh.

The unit is heater per year.
fh_mfh_aging_2 = FH_MFH_two/fh_second_life_time_mfh
UNITS: heater/year
DOCUMENT: Outflow of FH MFH two and inflow to FH MFH three, is calculated by dividing HP MFH two by fh second lifetime mfh.

The unit is heater per year.
fh_mfh_scrapping = FH_MFH_three/fh_third_life_time_mfh
UNITS: heater/year
DOCUMENT: The outflow of FH MFH three represents the scrapping of fossil heaters after their lifetime is over. It is calculated by dividing the stock FH MFH three by the fh third life time mfh.
The unit is heater per year.
fh_scrapping_through_demolition_1 = yearly_stfh_demolition*heater_per_stfh *(FH_STFH_one/existing_heaters_in_stfh)
UNITS: heater/year
DOCUMENT: The outflow to the ageing represents heaters scrapped when buildings are demolished and depends on the yearly demolitions and the fraction of heaters in the stock compared to the overall amount of heaters.
The unit is heater per year,
fh_scrapping_through_demolition_2 = yearly_stfh_demolition*heater_per_stfh *(FH_STFH_two/existing_heaters_in_stfh)
UNITS: heater/year
DOCUMENT: The outflow to the ageing represents heaters scrapped when buildings are demolished and depends on the yearly demolitions and the fraction of heaters in the stock compared to the overall amount of heaters.
The unit is heater per year,
fh_scrapping_through_demolition_3 = yearly_stfh_demolition*heater_per_stfh *(FH_STFH_three/existing_heaters_in_stfh)
UNITS: heater/year
DOCUMENT: The outflow to the ageing represents heaters scrapped when buildings are demolished and depends on the yearly demolitions and the fraction of heaters in the stock compared to the overall amount of heaters.
The unit is heater per year,
fh_scrapping_through_demolition_4 = yearly_mfh_demolition*heater_per_mfh *(FH_MFH_one/existing_heaters_in_mfh)
UNITS: heater/year
DOCUMENT: The outflow to the ageing represents heaters scrapped when buildings are demolished and depends on the yearly demolitions and the fraction of heaters in the stock compared to the overall amount of heaters.
The unit is heater per year,
fh_scrapping_through_demolition_5 = yearly_mfh_demolition*heater_per_mfh *(FH_MFH_two/existing_heaters_in_mfh)
UNITS: heater/year
DOCUMENT: The outflow to the ageing represents heaters scrapped when buildings are demolished and depends on the yearly demolitions and the fraction of heaters in the stock compared to the overall amount of heaters.
The unit is heater per year,
fh_scrapping_through_demolition_6 = yearly_mfh_demolition*heater_per_mfh *(FH_MFH_three/existing_heaters_in_mfh)
UNITS: heater/year

DOCUMENT: The outflow to the ageing represents heaters scrapped when buildings are demolished and depends on the yearly demolitions and the fraction of heaters in the stock compared to the overall amount of heaters.

The unit is heater per year,

fh_stfh_aging_1 = FH_STFH_one/fh_first_lifetime_stfh

UNITS: heater/year

DOCUMENT: Outflow of FH STFH one and inflow to FH STFH two, is calculated by dividing HP STFH one by fh first lifetime stfh.

The unit is heater per year.

fh_stfh_aging_2 = FH_STFH_two/fh_second_life_time_stfh

UNITS: heater/year

DOCUMENT: Outflow of FH STFH two and inflow to FH STFH three, is calculated by dividing HP STFH two by fh second lifetime stfh.

The unit is heater per year.

fh_stfh_scrapping = FH_STFH_three/fh_third_life_time_stfh

UNITS: heater/year

DOCUMENT: The outflow of FH STFH three represents the scrapping of fossil heaters after their lifetime is over. It is calculated by dividing the stock FH STFH three by the fh third life time stfh.

The unit is heater per year.

finish_apprenticeship = CONVEYOR OUTFLOW

UNITS: people/year

DOCUMENT: When finishing their apprenticeship, people become part of the stock installers 1, representing the first part of their work life.

The unit is people per year.

further_training_inflow = (installers_total-hp_installers)*hp_ratio_expectation*willingness_for_further_training

UNITS: people/year

DOCUMENT: Inflow to hp installers, represents the number of installers that conduct additional training to learn how to install heat pumps after their apprenticeship. it is based on the number of installers that have not yet had this training and the fraction of these per year that do the training. This fraction is a multiplication of the fraction of willingness for further training and the ratio of heat pumps that is expected by installers.

gaining_experience = effect_of_hp_installations_on_skill_level*normal_skill_gain*limit_to_skill_gain

UNITS: dmnl/year

DOCUMENT: Gaining experience is an inflow to average hp skill level. Gaining experience represents the skill the installers learn with every additional installation.

It depends on the

hiring_unskilled_workers = installer_starting_apprenticeship*unskilled_labour_share

UNITS: people/year

DOCUMENT: The hiring of unskilled workers and non-craft-related employees. To keep a reasonable ratio between skilled and unskilled workers it is assumed that the hiring is in a ratio ('unskilled labour share') to the training of employees.

It is an inflow to craftspeople 1 and therefore their start into their working life in crafts.

The unit is people per year.

hp_mfh_aging_1 = HP_MFH_one/hp_first_lifetime_mfh

UNITS: heater/year

DOCUMENT: Outflow of HP MFH one and inflow to HP MFH two, is calculated by dividing HP MFH one by hp first lifetime mfh.

The unit is heater per year.

hp_mfh_scrapping = HP_MFH_two/hp_second_life_time_1

UNITS: heater/year

DOCUMENT: The outflow of HP MFH two represents the scrapping of heat pumps after their lifetime is over. It is calculated by dividing the stock HP MFH two by the hp second life time mfh.

The unit is heater per year.

hp_scrapping_through_demolition_1 = yearly_stfh_demolition*heater_per_stfh *(HP_STFH_one/existing_heaters_in_stfh)

UNITS: heater/year
DOCUMENT: The outflow to the ageing represents heaters scrapped when buildings are demolished and depends on the yearly demolitions and the fraction of heaters in the stock compared to the overall amount of heaters.
The unit is heater per year,
hp_scrapping_through_demolition_2 = yearly_stfh_demolition*heater_per_stfh *(HP_STFH_two/existing_heaters_in_stfh)
UNITS: heater/year
DOCUMENT: The outflow to the ageing represents heaters scrapped when buildings are demolished and depends on the yearly demolitions and the fraction of heaters in the stock compared to the overall amount of heaters.
The unit is heater per year,
hp_scrapping_through_demolition_3 = yearly_mfh_demolition*heater_per_mfh *(HP_MFH_one/existing_heaters_in_mfh)
UNITS: heater/year
DOCUMENT: The outflow to the ageing represents heaters scrapped when buildings are demolished and depends on the yearly demolitions and the fraction of heaters in the stock compared to the overall amount of heaters.
The unit is heater per year,
hp_scrapping_through_demolition_4 = yearly_mfh_demolition*heater_per_mfh *(HP_MFH_two/existing_heaters_in_mfh)
UNITS: heater/year
DOCUMENT: The outflow to the ageing represents heaters scrapped when buildings are demolished and depends on the yearly demolitions and the fraction of heaters in the stock compared to the overall amount of heaters.
The unit is heater per year,
hp_stfh_aging = HP_STFH_one/hp_first_lifetime_stfh
UNITS: heater/year
DOCUMENT: Outflow of HP STFH one and inflow to HP STFH two, is calculated by dividing HP STFH one by hp first lifetime stfh.

The unit is heater per year.
hp_stfh_scrapping = HP_STFH_two/hp_second_life_time_stfh
UNITS: heater/year
DOCUMENT: The outflow of HP STFH two represents the scrapping of heat pumps after their lifetime is over. It is calculated by dividing the stock HP STFH two by the hp second life time stfh.
The unit is heater per year.
inflow_through_apprentices = finish_apprenticeship*hp_ratio_expectation
UNITS: people/year
DOCUMENT: This is one inflow to the stock hp installers, it represents the number of installers who finished their apprenticeship and already learned about installing HP during this time. It is co-flow to 'finish apprenticeship' and is calculated by multiplying it by the expected ratio of heat pump installations. The more heat pump installations are expected the higher is the number of apprentices that learn about heat pump installations to prepare for their future work life.

The number is people per year.
instal_ageing = installers1/working_life_1
UNITS: people/year
DOCUMENT: This flow is part of an ageing chain, it is the outflow to installers 1nad the inflow to installers2 and depends on the stock installer1 and the the lenght of working life1.

The unit is people per year.
loss_of_experience = average_hp_skill_level/skill_loss_over_time
UNITS: dmnl/year
DOCUMENT: Outflow of average hp skill level is calculated by dividing the stock by the skill loss over time. it represents that skills can be forgotten over time.
mfh_aging_1 = "MFH_0-30"/mfh_aging_time_3
UNITS: house/year
DOCUMENT: Outflow of MFH 0-30, inflow to MFH 31-60, based on ageing. The unit is house per year.
mfh_aging_2 = "MFH_31-60"/mfh_aging_time_4
UNITS: house/year

DOCUMENT: Outflow of MFH 31-60, inflow to MFH above 60, based on ageing.

The unit is house per year.
mfh_demolishing_1 = yearly_mfh_demolition*mfh_demol_calibration
UNITS: house/year
DOCUMENT: This is an outflow to MFH 31-60 and represents houses between the ages 30 to 60 that are being demolished. It is calculated by multiplying the yearly demolishing fraction by mfh demol calibration, which represents the fraction of demolishment that is done in this age group.

The unit is house per year.
mfh_demolishing_2 = yearly_mfh_demolition*(1-mfh_demol_calibration)
UNITS: house/year
DOCUMENT: This is an outflow to MFH above 61 and represents houses above 61years that are being demolished. It is calculated by multiplying the yearly demolishing fraction by 1 minus mfh demol calibration, which represents the fraction of demolishment that is done in this age group.
The unit is house per year.
mfh_new_constructions = new_mfh_per_year
UNITS: house/year
DOCUMENT: Inflow to the ageing chain MFH, based on new mfh per year.
The unit is house per year.
new_fh_mfh = fh_installation_rate_mfh
UNITS: heater/year
DOCUMENT: The inflow to the ageing chain FH MFH, it is controlled by the fh installation rate mfh.

The unit is heater per year.
new_fh_stfh = fh_installation_rate_stfh
UNITS: heater/year
DOCUMENT: The inflow to the ageing chain FH STFH, it is controlled by the fh installation rate stfh.

The unit is heater per year.
new_hp_mfh = installation_rate_hp_in_new_mfh+installation_rate_hp_in_old_mfh
UNITS: heater/year
DOCUMENT: This is one of two inflows to the stock HP MFH one and therefore the ageing chain for HPs in MFHs. It is the sum of the number of heat pumps installed because of new construction and after a regular heater exchange.

The unit is heater per year.
new_hp_stfh = hp_installation_rate_new_stfh+hp_installation_rate_old_stfh_without_early_exch
UNITS: heater/year
DOCUMENT: This is one of two inflows to the stock HP STFH one and therefore the ageing chain for HPs in STFHs. It is the sum of the number of heat pumps installed because of new construction and after a regular heater exchange.

The unit is heater per year.
outflow_through_retirement = (hp_installers/installers_total)*retirement
UNITS: people/year
DOCUMENT: 'Outflow through retirement' drains the stock hp installers and represents installers who know how to install heat pumps and who retire. It is a co-flow to 'retirement' and is calculated using the ratio of installers that are also hp installers and the retirement flow.

The unit is people per year.
retirement = installers2/working_life_2
UNITS: people/year
DOCUMENT: People retire after working and therefore leave the stock craftspeople 2.

The unit is people per year.
start_apprenticeship = installer_starting_apprenticeship
UNITS: people/year
DOCUMENT: Number of people strating an apprenticeship to become an installer
stfh_ageing_1 = "STFH_0-30"/stfh_aging_time_1
UNITS: house/year

DOCUMENT: Outflow of STFH 0-30, inflow to STFH 31-60, based on ageing. The unit is house per year.
stfh_ageing_2 = "STFH_31-60"/stfh_aging_time_2
UNITS: house/year
DOCUMENT: Outflow of STFH 31-60, inflow to STFH above 60, based on ageing.

The unit is house per year.
stfh_demolishing_1 = stfh_demol_calibration*yearly_stfh_demolition
UNITS: house/year
DOCUMENT: This is an outflow to STFH 31-60 and represents houses between the ages 30 to 60 that are being demolished. It is calculated by multiplying the yearly demolishing fraction by stfh demol calibration, which represents the fraction of demolishment that is done in this age group.
stfh_demolishing_2 = yearly_stfh_demolition*(1-stfh_demol_calibration)
UNITS: house/year
DOCUMENT: This is an outflow to STFH above 61 and represents houses above 61years that are being demolished. It is calculated by multiplying the yearly demolishing fraction by 1 minus stfh demol calibration, which represents the fraction of demolishment that is done in this age group.
The unit is house per year.
stfh_new_constructions = new_stfh_per_year
UNITS: house/year
DOCUMENT: Inflow to the ageing chain STFH, based on new stfh per year.
The unit is house per year.
additional_effort_renovation_mfh = 5
UNITS: dmnl
DOCUMENT: This depicts the additional effort a renovation in an MFH costs compared to an STFH and therefore influences the price. Due to a lack of data availability, it is based on an assumption.

The unit is dimensionless.
after_subsidies_hp_costs_new_mfh = total_hp_price_new_mfh-MAP_support_new_mfh_1-MAP_support_new_mfh_2
UNITS: €/house
DOCUMENT: Costs for an HP in a new mfh (including device and installation) after subtracting subsidies. The unit is Euro per house.
after_subsidies_hp_costs_old_mfh = total_hp_price_old_mfh-MAP_support_old_mfh_1-MAP_support_old_mfh_2
UNITS: €/house
DOCUMENT: Costs for an HP in an old mfh (including device and installation) after subtracting subsidies. The unit is Euro per house.
after_subsidies_total_hp_price_new_stfh = IF TIME < 2015 THEN total_hp_price_new_stfh-MAP_support_new_stfh1 ELSE total_hp_price_new_stfh-MAP_support_new_stfh2
UNITS: €/house
DOCUMENT: Costs for an HP in a new stfh (including device and installation) after subtracting subsidies. The unit is Euro per house.
after_subsidies_total_hp_price_old_stfh = IF TIME < 2015 THEN total_hp_price_old_stfh-MAP_support_old_stfh_1 ELSE total_hp_price_old_stfh-MAP_support_old_stfh_2
UNITS: €/house
DOCUMENT: Costs for an HP in an old stfh (including device and installation) after subtracting subsidies. The unit is Euro per house.
age_ration_initial_installers = 0,75
UNITS: dmnl
DOCUMENT: The ratio of the initial number of workers in the first half of their working life in the start of the simulation. The number is the result of hand calibration.

the unit is dimensionless.
apartments_with_district_heating = Rate_of_apartments_with_district_heating*total_housing_units
UNITS: housing unit
DOCUMENT: Number of apartments heated with district heat networks, it is calculated by multiplying the (historic) rate of of apartments heated with district heating by the total housing units (apartments).

The unit is housing unit.
attractiveness_of_hp_in_existing_mfh = density_of_hp_overall^imp_density_old_mfh *financial_attractiveness_hp_old_mfh^imp_financ_old_mfh *gp_attractiveness^imp_gp_old_mfh

UNITS: dmnl

DOCUMENT: The attractiveness of heat pumps in existing (or old) MFH is calculated via a weighted multiplication. The three influences density, gp attractiveness and financial attractiveness are put to the power of their respective weight and then multiplied with each other. The higher each influence the higher is the resulting attractiveness. And the higher their weight is the bigger is its influence on the end result. All influences go from 0 to 1 and therefore the results also vary from 0 to 1. The higher the number the more attractive HPs are perceived. All weights together sum up to 1.

The attractiveness of heat pumps in mfh and stfh is calculated separately due to different influences and conditions, as well as for new constructions and existing buildings. This is further discussed in the thesis.

The unit is dimensionless.

attractiveness_of_hp_in_existing_stfh = density_of_hp_in_stfh^imp_density_old_stfh *financial_attractiveness_hp_old_stfh^imp_financ_old_stfh *gp_attractiveness^imp_gp_old_stfh

UNITS: dmnl

DOCUMENT: The attractiveness of heat pumps in existing (or old) is calculated via a weighted multiplication. The three influences density, gp attractiveness and financial attractiveness are put to the power of their respective weight and than multiplied with each other. The higher each influence the higher is the resulting attractiveness. And the higher their weight is the bigger is its influence on the end result. All influences go from 0 to 1 and therefore the results also vary from 0 to 1. The higher the number the more attractive HPs are perceived. All weights together sum up to 1.

The attractiveness of heat pumps in mfh and stfh is calculated separately due to different influences and conditions, as well as for new constructions and existing buildings. This is further discussed in the thesis.

The unit is dimensionless.

attractiveness_of_hp_in_new_mfh = density_of_hp_overall^imp_density_new_mfh *financial_attractiveness_hp_new_mfh^imp_financ_new_mfh *gp_attractiveness^imp_gp_new_mfh

UNITS: dmnl

DOCUMENT: The attractiveness of heat pumps in new MFH is calculated via a weighted multiplication. The three influences density, gp attractiveness and financial attractiveness are put to the power of their respective weight and then multiplied with each other. The higher each influence the higher is the resulting attractiveness. And the higher their weight is the bigger is its influence on the end result. All influences go from 0 to 1 and therefore the results also vary from 0 to 1. The higher the number the more attractive HPs are perceived. All weights together sum up to 1.

The attractiveness of heat pumps in mfh and stfh is calculated separately due to different influences and conditions, as well as for new constructions and existing buildings. This is further discussed in the thesis.

The unit is dimensionless.

attractiveness_of_hp_in_new_stfh = density_of_hp_in_stfh^imp_density_new_stfh *financial_attractiveness_hp_new_stfh^imp_financ_new_stfh *gp_attractiveness^imp_gp_new_stfh

UNITS: dmnl

DOCUMENT: The attractiveness of heat pumps in new stfh is calculated via a weighted multiplication. The three influences density, gp attractiveness and financial attractiveness are put to the power of their respective weight and than multiplied with each other. The higher each influence the higher is the resulting attractiveness. And the higher their weight is the bigger is its influence on the end result. All influences go from 0 to 1 and therefore the results also vary from 0 to 1. The higher the number the more attractive HPs are perceived. All weights together sum up to 1.

The attractiveness of heat pumps in mfh and stfh is calculated separately due to different influences and conditions, as well as for new constructions and existing buildings. This is further discussed in the thesis.

The unit is dimensionless.

average_monthly_income = IF TIME < 2024 THEN HIS_average_monthly_income ELSE future_average_monthly_income

UNITS: €/house
DOCUMENT: Average monthly income depending on historical data until 2023 and scenarios afterwards.

The unit is Euro per house.
average_renovation_costs = 30000
UNITS: €/house
DOCUMENT: Depicts the average costs that a renovation for increasing insulation and adapting the house to a heat pump causes. This can include adding insulation, and changing pipes and radiators, depending on the state of the house. The price applies to existing STFHs.

The price for renovation can vary a lot and since there is no data available for the average price of renovation that is necessary or desired before installing a heat pump, the costs are therefore based on an assumption.

The unit is Euro per house.
c_gas_heater_rate = 0,83
UNITS: dmnl
DOCUMENT: Estimation of the fraction of fh sales that are for STFHs, it is used to create an estimated reference mode for fh sales stfh and fh sales mfh.
c_hp_sales_stfh_rate = 0,98
UNITS: dmnl
DOCUMENT: Estimation of the fraction of hp sales that are for STFHs, it is used to create an estimated reference mode for hp sales stfh and hp sales mfh. The unit is dimensionless.
capacity_for_early_exchange_stfh = MAX(0; capacity_for_hp_in_old_mfh-desired_hp_in_existing_mfh_per_year)
UNITS: heater/year
DOCUMENT: This is the capacity for hp installations as part of early exchnage, after the hp installations in new stfh, new mfh and old stfh and old mfh were already considered. Early exchanges have the lowest priority since they still have a functioning heating system and theoretically could wait.

The unit is heater per year.
capacity_for_hp_in_new_mfh = MAX(0; hp_total_installation_capacity-desired_hp_in_new_stfh)
UNITS: heater/year
DOCUMENT: This is the capacity for hp installations in new mfh, after the hp installations in new stfh were already considered. New stfh hp installations have first priority. New constructions have priority over existing buildings since they are planned longer in advance.

The unit is heater per year.
capacity_for_hp_in_old_mfh = MAX(0; capacity_for_hp_in_old_stfh-desired_hp_in_existing_stfh_per_year)
UNITS: heater/year
DOCUMENT: This is the capacity for hp installations in old mfh (not early exchange), after the hp installations in new stfh, new mfh and old stfh were already considered.

The unit is heater per year.
capacity_for_hp_in_old_stfh = MAX(0; capacity_for_hp_in_new_mfh-desired_hp_in_new_mfh)
UNITS: heater/year
DOCUMENT: This is the capacity for hp installations in old stfh (not early exchnage), after the hp installations in new stfh and new mfh were already considered. New constructions have priority over existing buildings since they are planned longer in advance.

The unit is heater per year.
capacity_over_or_undershoot = hp_total_installation_capacity-total_desired_hp
UNITS: heater/year
capacity_per_hp_installer = Maximum_capacity_per_hp_installer*average_hp_skill_level
UNITS: heater/person/year
DOCUMENT: The actual capacity per hp installer depends on the maximum capacity per hp installer and the average hp skill level. The higher the skill level the closer to the maximum installation capacity.

The unit is heater per person per year.
CPI = IF TIME < 2024 THEN HIS_CPI ELSE future_CPI
UNITS: dmnl

DOCUMENT: The Consumer price index is based on historical data until 2023 and afterwards depending on scenarios.

the unit is dimensionless.
CPI_scenario_1 = GRAPH(TIME)
Points: (2024,00, 1,167), (2024,525, 1,169), (2025,05, 1,17), (2025,575, 1,172), (2026,10, 1,173), (2026,625, 1,175), (2027,15, 1,176), (2027,675, 1,178), (2028,20, 1,18), (2028,725, 1,181), (2029,25, 1,183), (2029,775, 1,184), (2030,30, 1,186), (2030,825, 1,187), (2031,35, 1,189), (2031,875, 1,191), (2032,40, 1,192), (2032,925, 1,194), (2033,45, 1,195), (2033,975, 1,197), (2034,50, 1,199), (2035,025, 1,2), (2035,55, 1,202), (2036,075, 1,203), (2036,60, 1,205), (2037,125, 1,206), (2037,65, 1,208), (2038,175, 1,21), (2038,70, 1,211), (2039,225, 1,213), (2039,75, 1,214), (2040,275, 1,216), (2040,80, 1,217), (2041,325, 1,219), (2041,85, 1,221), (2042,375, 1,222), (2042,90, 1,224), (2043,425, 1,225), (2043,95, 1,227), (2044,475, 1,228), (2045,00, 1,23)
UNITS: dmnl
CPI_scenario_2 = GRAPH(TIME)
Points: (2024,00, 1,1670), (2024,525, 1,1700), (2025,05, 1,1730), (2025,575, 1,1760), (2026,10, 1,1790), (2026,625, 1,1820), (2027,15, 1,1850), (2027,675, 1,1880), (2028,20, 1,1910), (2028,725, 1,1940), (2029,25, 1,1970), (2029,775, 1,2000), (2030,30, 1,2030), (2030,825, 1,2060), (2031,35, 1,2090), (2031,875, 1,2120), (2032,40, 1,2150), (2032,925, 1,2180), (2033,45, 1,2210), (2033,975, 1,2240), (2034,50, 1,2270), (2035,025, 1,2300), (2035,55, 1,2330), (2036,075, 1,2360), (2036,60, 1,2390), (2037,125, 1,2420), (2037,65, 1,2450), (2038,175, 1,2480), (2038,70, 1,2510), (2039,225, 1,2540), (2039,75, 1,2570), (2040,275, 1,2600), (2040,80, 1,2630), (2041,325, 1,2660), (2041,85, 1,2690), (2042,375, 1,2720), (2042,90, 1,2750), (2043,425, 1,2780), (2043,95, 1,2810), (2044,475, 1,2840), (2045,00, 1,2870)
UNITS: dmnl
delayed_relative_interest_rate = SMTH3(key_interest_rate//guide_value_interest_rate; 1)
UNITS: dmnl
DOCUMENT: The key interest rate is divided by a guide value, underneath the guide value the interest rate is positive for investors and above negative. Additionally, an information delay is added.

The unit is dimensionless.
density_of_hp_in_mfh = HP_MFH_total/(HP_MFH_total+FH_MFH_total+district_heating_connections)
UNITS: dmnl
DOCUMENT: The variable is calculated by dividing the number of heat pumpsby the number of total installed heaters in multi-family homes. The density of a new product has a strong influence on the further adoption of the product (Bass, 1969).

The reasons for separating between stfh and mfh are explained in the thesis.

The unit is dimensionless.
density_of_hp_in_stfh = HP_STFH_total/(HP_STFH_total+FH_STFH_total)
UNITS: dmnl
DOCUMENT: The variable is calculated by dividing the number of heat pumps by the number of total installed heaters in single- and two-family homes (stfh). The density of a new product has a strong influence on the further adoption of the product (Bass, 1969).

The reasons for separating between stfh and mfh are explained in the thesis.

The unit is dimensionless.
density_of_hp_overall = Total_HP/(Total_FH+Total_HP+district_heating_connections)
UNITS: dmnl
DOCUMENT: Density of HP overall accounting for heaters in STFH and MFH as well as MFHs heated with district heating. Calculated by dividing the number of heat pumps by the number of total heaters (sum of fossil heaters, heat pumps and district heating connections).

the unit is dimensionless.
desired_early_exchange_stfh = early_exchange_fraction*FH_STFH_three
UNITS: heater/year
DOCUMENT: The variable represents the actual number of fossil heaters that are desired to be exchanged before the end of their lifetime. It is calculated by multiplying the early exchange fraction with the number of heaters in question (third stock of the FH ageing chain).

The unit is heater per year.

desired_fh_in_existing_mfh = (missing_heaters_in_mfh-desired_hp_in_existing_mfh)/time_to_install
UNITS: heater/year
DOCUMENT: The number of desired new fossil heaters is calculated by subtracting the number of desired new heat pumps from the total heater demand. The heater demand for old MFH is based on the variable missing heaters in MFH. The assumption is that every house owner who decides not to install a heat pump will install a fossil heater instead since the model only accounts for these two heating systems.

The unit is heater per year.
desired_fh_in_existing_stfh = (missing_heaters_in_stfh-desired_hp_in_existing_stfh)/time_to_install
UNITS: heater/year
DOCUMENT: The number of desired new gas heaters is calculated by subtracting the number of desired new heat pumps from the total heater demand. The heater demand for old STFH is based on the variable missing heaters in STFH. The assumption is that every house owner who decides not to install a heat pump will install a gas heater instead since the model only accounts for these two heating systems.

The unit is heater per year.
desired_fh_in_new_mfh = (mfh_new_construction_without_district_heating*heater_per_mfh)-desired_hp_in_new_mfh
UNITS: heater/year
DOCUMENT: The number of desired new fossil heaters is calculated by subtracting the number of desired new heat pumps from the total heater demand in new mfh (the total heater demand in new mfh accounts for all new mfh constructions without district heating). The assumption is that every house owner who decides not to install a heat pump or use district heating, will install a fossil heater, since these are the only options in the model due to necessary simplifications.

The unit is heater per year.
desired_fh_in_new_stfh = (new_stfh_per_year*heater_per_stfh)-desired_hp_in_new_stfh
UNITS: heater/year
DOCUMENT: The number of desired new gas heaters is calculated by subtracting the number of desired new heat pumps from the total heater demand. The heater demand for new STFH is calculated by the number of STFH constructed per year and the number of heaters per STFH. The assumption is that every house owner who decides not to install a heat pump will install a gas heater instead since the model only accounts for these two heating systems.

The unit is heater per year.
desired_hp_in_existing_buildings_per_year = desired_hp_in_existing_stfh_per_year+desired_hp_in_existing_mfh_per_year
UNITS: heater/year
desired_hp_in_existing_mfh = probabilty_hp_old_mfh*missing_heaters_in_mfh
UNITS: heater
DOCUMENT: Number of HP that are wished to be installed in existing STFH. It is based on the probability of choosing HP for existing STFH and the number of missing heaters at the moment.

The units are heater.
desired_hp_in_existing_mfh_per_year = desired_hp_in_existing_mfh/time_to_install
UNITS: heater/year
DOCUMENT: Number of HP that are wished to be installed in existing STFH per year, considering the time to install. The unit sis heater per year.
desired_hp_in_existing_stfh = probabilty_hp_old_stfh*missing_heaters_in_stfh
UNITS: heater
DOCUMENT: Number of HP that are wished to be installed in existing STFH. It is based on the probability of choosing HP for existing STFH and the number of missing heaters at the moment.

The units are heater.
desired_hp_in_existing_stfh_per_year = desired_hp_in_existing_stfh/time_to_install
UNITS: heater/year
desired_hp_in_new_buildings = desired_hp_in_new_stfh+desired_hp_in_new_mfh
UNITS: heater/year
desired_hp_in_new_mfh = probabilty_hp_new_mfh*heater_per_mfh*mfh_new_construction_without_district_heating
UNITS: heater/year

DOCUMENT: Number of HP that are wished to be installed in new MFH. It is based on the probability of choosing HP for new MFH and the number of new MFH without district heating built this year and the number of heaters per MFH.

The units are heater per year.
desired_hp_in_new_stfh = probabilty_hp_new_stfh* new_stfh_per_year*heater_per_stfh
UNITS: heater/year
DOCUMENT: Number of HP that are wished to be installed in new STFH. It is based on the probability of choosing HP for new STFH and the number of new STFH built this year and the number of heaters per STFH.

The units are heater per year.
desired_hp_to_fh_ratio = total_desired_hp/(total_desired_hp+total_fh_installation_rate)
UNITS: dmnl
DOCUMENT: The desired hp to fh ratio is used, rather than the actual installation ratio for calculating the forecast because installers have insight into demand.

The unit is dimensionless.
distr_imp_new_mfh = 0,8
UNITS: dmnl
DOCUMENT: This parameter determines the distribution of the weight after subtracting the imp density. It varies between 0 and 1, the higher this parameter, the higher is the imp fianc and the lower is imp gp.
The exact number is the result of hand calibration.

The unit is dimensionless.
distr_imp_new_stfh = 0,85
UNITS: dmnl
DOCUMENT: This parameter determines the distribution of the weight after subtracting the imp density. It varies between 0 and 1, the higher this parameter, the higher is the imp fianc and the lower is imp gp.

The exact number is the result of hand calibration.

The unit is dimensionless.
distr_imp_old_mfh = 0,8
UNITS: dmnl
DOCUMENT: This parameter determines the distribution of the weight after subtracting the imp density. It varies between 0 and 1, the higher this parameter, the higher is the imp fianc and the lower is imp gp.
The exact number is the result of hand calibration.

The unit is dimensionless.
distr_imp_old_stfh = 0,25
UNITS: dmnl
DOCUMENT: This parameter determines the distribution of the weight after subtracting the imp density. It varies between 0 and 1, the higher this parameter, the higher is the imp fianc and the lower is imp gp.
The exact number is the result of hand calibration.

The unit is dimensionless.
district_heating_connections = mfh_buildings_with_district_heating*heater_per_mfh
UNITS: heater
DOCUMENT: The number of connections for the district heating network. A district heating connection replaces a heating unit in a building. It is calculated by multiplying the mfh buildings with district heating by heater per mfh.

The unit is heaters.
duration_working_life = 45
UNITS: year
DOCUMENT: The duration of a regular working life in Germany is 45 years.

The unit is years.
early_exchange_fraction = maximum_early_exchange_fraction*probabilty_hp_old_stfh
UNITS: dmnl/year

DOCUMENT: The early exchange fraction is the fraction of of fossil heater owners per year in the last third of their heater's lifetime that wants to exchange their heater for a heat pump before the end of their usual lifetime.

The unit is dimensionless per year.
effect_of_hp_installations_on_skill_level = GRAPH(new_hp_per_hp_installer)
Points: (0,000, 0,000), (0,200, 0,1567), (0,400, 0,2969), (0,600, 0,4225), (0,800, 0,5348), (1,000, 0,6353), (1,200, 0,7253), (1,400, 0,8058), (1,600, 0,8778), (1,800, 0,9423), (2,000, 1,000)
UNITS: dmnl
DOCUMENT: The graphical function translates the number of installations per hp installer into a skill level that is gained through it. The more installations the higher the influence on the skill level. The unit is dimensionless.
existing_heaters_in_mfh = HP_MFH_total+FH_MFH_total
UNITS: heater
DOCUMENT: The number of existing heating units in mfh, includes fossil heaters and heat pumps but not district heating connections.

The unit is heaters.
existing_heaters_in_stfh = FH_STFH_total+HP_STFH_total
UNITS: heater
DOCUMENT: The number of existing heating units in stfh, includes fossil heaters and heat pumps.

The unit is heaters.
fh_age_relative_distribution = 0,5
UNITS: dmnl
fh_first_lifetime_mfh = fh_total_lifetime_mfh/3
UNITS: years
DOCUMENT: Length of the first third of the lifetime of FHs in MFH. Calculated by dividing FH total lifetime mfh by three. The unit is years.
fh_first_lifetime_stfh = FH_total_lifetime_stfh/3
UNITS: years
DOCUMENT: Length of the first third of the lifetime of FHs in STFH. Calculated by dividing FH total lifetime stfh by three. The unit is years.
fh_installation_in_old_buildings = desired_fh_in_existing_stfh+desired_fh_in_existing_mfh
UNITS: heater/year
fh_installation_rate_in_new_buildings = desired_fh_in_new_stfh+desired_fh_in_new_mfh
UNITS: heater/year
fh_installation_rate_mfh = desired_fh_in_existing_mfh+desired_fh_in_new_mfh
UNITS: heater/year
DOCUMENT: The total installation rate of fossil heaters is the sum of fossil heater installations in new and old MFHs.

The unit is heater per year.
fh_installation_rate_stfh = desired_fh_in_existing_stfh+desired_fh_in_new_stfh
UNITS: heater/year
DOCUMENT: The total installation rate of fossil heaters is the sum of fossil heater installations in new and old STFHs.

The unit is heater per year.
FH_MFH_total = FH_MFH_one + FH_MFH_three + FH_MFH_two
UNITS: heater
DOCUMENT: The total number of fossil heaters installed in multi-family houses, sums up the three stocks of the ageing chain for fossil heaters in mfh.

The unit is heater.
fh_second_life_time_mfh = fh_total_lifetime_mfh/3
UNITS: years
DOCUMENT: Length of the fsecond third of the lifetime of FHs in MFH. Calculated by dividing FH total lifetime mfh by three. The unit is years.
fh_second_life_time_stfh = FH_total_lifetime_stfh/3
UNITS: years
DOCUMENT: Length of the second third of the lifetime of FHs in STFH. Calculated by dividing FH total lifetime stfh by three. The unit is years.

FH_STFH_total = FH_STFH_one + FH_STFH_three + FH_STFH_two
UNITS: heater
DOCUMENT: The total number of fossil heaters installed in single and two family houses, sums up the three stocks of the ageing chain for fossil heaters in stfh.

The unit is heater.
fh_third_life_time_mfh = fh_total_lifetime_mfh/3
UNITS: year
DOCUMENT: Length of the third third of the lifetime of FHs in MFH. Calculated by dividing FH total lifetime mfh by three. The unit is years.
fh_third_life_time_stfh = FH_total_lifetime_stfh/3
UNITS: year
DOCUMENT: Length of the third third of the lifetime of FHs in STFH. Calculated by dividing FH total lifetime stfh by three. The unit is years.
fh_total_lifetime_mfh = IF SWITCH_heater_lifetime = 0 THEN 33 ELSE 33+heater_lifetime_policy
UNITS: years
DOCUMENT: While most gas heater producers suggest a lifespan of 20 years (Kunde, 2021), data shows that 13 per cent of heaters in Germany in 2023 are older than 30 years (Erhebung Des Schornsteinfegerverbands 2022, 2022). Therefore 33 years was chosen as the average lifetime.

The variable is influenced by the heater lifetime policy if the Switch heater lifetime is activated (=1). This leads to the average lifetime reducing according to the policy.

The unit is years.
FH_total_lifetime_stfh = IF SWITCH_heater_lifetime = 0 THEN 33 ELSE 33+heater_lifetime_policy
UNITS: years
DOCUMENT: While most gas heater producers suggest a lifespan of 20 years (Kunde, 2021), data shows that 13 per cent of heaters in Germany in 2023 are older than 30 years (Erhebung Des Schornsteinfegerverbands 2022, 2022). Therefore 33 years was chosen as the average lifetime.

The variable is influenced by the heater lifetime policy if the Switch heater lifetime is activated (=1). This leads to the average lifetime reducing according to the policy.

The unit is years.
financial_attractiveness_hp_new_mfh = interest_attractiveness*importance_of_interest_new_mfh + price_attractiveness_new_mfh*(1-importance_of_interest_new_mfh)
UNITS: dmnl
DOCUMENT: The financial attractiveness of heat pumps for each building type depends on the two influences of the individually calculated price attractiveness and the interest rate.

The two influences are combined with weighted addition.

The financial attractiveness of heat pumps in MFH and STFH, as well as old and new buildings, is calculated separately due to different costs as well as different priorities of the responsible people (homeowners, landlords, investors).

The unit is dimensionless.
financial_attractiveness_hp_new_stfh = interest_attractiveness*importance_of_interest_new_stfh + price_attract_hp_new_stfh*(1-importance_of_interest_new_stfh)
UNITS: dmnl
DOCUMENT: The financial attractiveness of heat pumps for each building type depends on the two influences of the individually calculated price attractiveness and the interest rate.
The two influences are combined with weighted addition.

The financial attractiveness of heat pumps in MFH and STFH, as well as old and new buildings, is calculated separately due to different costs as well as different priorities of the responsible people (homeowners, landlords, investors).

The unit is dimensionless.
financial_attractiveness_hp_old_mfh = interest_attractiveness*importance_of_interest_old_mfh + price_attractiveness_old_mfh*(1-importance_of_interest_old_mfh)

UNITS: dmnl
DOCUMENT: The financial attractiveness of heat pumps for each building type depends on the two influences of the individually calculated price attractiveness and the interest rate.

The two influences are combined with weighted addition.

The financial attractiveness of heat pumps in MFH and STFH, as well as old and new buildings, is calculated separately due to different costs as well as different priorities of the responsible people (homeowners, landlords, investors).

The unit is dimensionless.
financial_attractiveness_hp_old_stfh = interest_attractiveness*importance_of_interest_old_stfh + price_attract_hp_old_stfh*(1-importance_of_interest_old_stfh)
UNITS: dmnl
DOCUMENT: The financial attractiveness of heat pumps for each building type depends on the two influences of the individually calculated price attractiveness and the interest rate.
The two influences are combined with weighted addition.

The financial attractiveness of heat pumps in MFH and STFH, as well as old and new buildings, is calculated separately due to different costs as well as different priorities of the responsible people (homeowners, landlords, investors).

The unit is dimensionless.
forecast_averaging_time = 5
UNITS: year
DOCUMENT: The averaging time is important for the forecast built-in, it represents the time that is considered to make the forecast. 5 years are an assumption. The unit is years.
forecast_horizon = 3
UNITS: year
DOCUMENT: The forecast horizon is the years due to the assumption that the installers are oriented towards the time when they finish their apprenticeship. The unit is years.
future_average_monthly_income = IF SWITCH_economy = 0 THEN 4100 ELSE IF SWITCH_economy = 1 THEN income_scenario_1 ELSE income_scenario_2
UNITS: €/house
DOCUMENT: Controls scenarios for the future average income depending on the Switch economy:

0 = Stable at 4100 € per house.
1 = Steep increase: Linearly increases to 5600 by 2045.
2 = Slight increase: Linearly increases to 4800 by 2045.
The unit is Euro per house.
future_CPI = IF SWITCH_economy = 0 THEN 1,167 ELSE IF SWITCH_economy = 1 THEN CPI_scenario_1 ELSE CPI_scenario_2
UNITS: dmnl
DOCUMENT: Controls scenarios for the future CPI depending on the Switch economy:

0 = Stable at 1,167
1 = Slight increase: Linearly increases to 1,23 by 2045.
2 = Steep increase: Linearly increases to 1,287 by 2045.
The unit is dimensionless.
future_gas_price = IF SWITCH_gas_scenario = 0 THEN gas_price_scenario_bau ELSE IF SWITCH_gas_scenario = 1 THEN gas_price_scenario_1 ELSE gas_price_scenario_2
UNITS: cent/kilowatt hour
DOCUMENT: Controls scenarios for the future gas price depending on SWITCH gas scenario:

0 = Linear price increase from 12 to 18 cents per kilowatt hour of gas in 245 starting in 2024.
1 = Linear price increase from 12 to 25 cents per kilowatt hour of gas in 245 starting in 2024.
2 = Stable at 12 cent per kilowatt.
The unit is cent per kilowatt.
future_installer_starting_apprenticeship = IF SWITCH_apprentices = 0 THEN 7,7 ELSE IF SWITCH_apprentices = 1 THEN installer_starting_apprenticeship_scen_1 ELSE installer_starting_apprenticeship_scen_2

UNITS: people/year
DOCUMENT: Controls scenarios for the future installers starting apprenticeship depending on Switch apprentices:

0 = Stable at 7,7 people per year.
1 = Linearly increases to 10 by 2045.
2 = Linearly decreases to 5 by 2045.
The unit is people per year.
future_interest_rate = IF SWITCH_economy = 0 THEN 4,5 ELSE IF SWITCH_economy = 1 THEN interest_rate_scenario_1 ELSE interest_rate_scenario_2
UNITS: dmnl
DOCUMENT: Controls scenarios for the future interest rate depending on the Switch economy:

0 = Stable at 4,5
1 = Decreases to 0,5 by the year 2026 and then stays stable.
2 = Linear increases up to 5,5 in 2045, starting at 4,5 in 2024.

The unit is dimensionless.
future_new_mfh = IF SWITCH_economy = 0 THEN 15 ELSE IF SWITCH_economy = 1 THEN new_mfh_scenario_1 ELSE new_mfh_scenario_2
UNITS: House/year
DOCUMENT: Controls scenarios for the future new mfh depending on the Switch economy:

0 = Stable at 15 houses per year
1 = Linearly increases to 100 houses by 2045.
2 = Linear decrease to 10 houses by 2045
The unit is house per year.
future_new_stfh = IF SWITCH_economy = 0 THEN 89 ELSE IF SWITCH_economy = 1 THEN new_stfh_scenario_1 ELSE new_stfh_scenario_2
UNITS: House/year
DOCUMENT: Controls scenarios for the future new stfh depending on the Switch economy:

0 = Stable at 89 houses per year.
1 = Linearly increases to 100 houses by 2045.
2 = Linearly decreases to 80 houses by 2045
The unit is house per year.
gas_heater_for_mfh = heater_per_mfh*CPI*gas_heater_price_2020*installation_effort_mfh_gas
UNITS: €/house
gas_heater_price_2020 = 12500
UNITS: €/heater
gas_price = IF TIME < 2024 THEN HISTORIC_gas_price ELSE future_gas_price
UNITS: cent/kilowatt hour
DOCUMENT: The gas price for households consists of the historical data up until 2023 and a scenario afterwards.

The unit is cent per kilowatt hour.
gas_price_scenario_1 = GRAPH(TIME)
Points: (2024,00, 12,00), (2024,46666667, 12,29), (2024,93333333, 12,58), (2025,40, 12,87), (2025,86666667, 13,16), (2026,33333333, 13,44), (2026,80, 13,73), (2027,26666667, 14,02), (2027,73333333, 14,31), (2028,20, 14,60), (2028,66666667, 14,89), (2029,13333333, 15,18), (2029,60, 15,47), (2030,06666667, 15,76), (2030,53333333, 16,04), (2031,00, 16,33), (2031,46666667, 16,62), (2031,93333333, 16,91), (2032,40, 17,20), (2032,86666667, 17,49), (2033,33333333, 17,78), (2033,80, 18,07), (2034,26666667, 18,36), (2034,73333333, 18,64), (2035,20, 18,93), (2035,66666667, 19,22), (2036,13333333, 19,51), (2036,60, 19,80), (2037,06666667, 20,09), (2037,53333333, 20,38), (2038,00, 20,67), (2038,46666667, 20,96), (2038,93333333, 21,24), (2039,40, 21,53), (2039,86666667, 21,82), (2040,33333333, 22,11), (2040,80, 22,40), (2041,26666667, 22,69), (2041,73333333, 22,98), (2042,20, 23,27), (2042,66666667, 23,56), (2043,13333333, 23,84), (2043,60, 24,13), (2044,06666667, 24,42), (2044,53333333, 24,71), (2045,00, 25,00)
UNITS: cent/kilowatt hour
DOCUMENT:
Scenario 1:

After 2023 the gas price first normalises on a higher level than before 2022 (12 cent per kilowatthour), but still lower than the peak (2022-2023). It then contentiously rises due to an increase in CO2-price and increasing scarcity. The steepness of the increase is based on a projection by Pehnt et al. (2023), that predicts a gas price of circa 17 cents per kilowatt hour in 2042.

The unit is cent per kilowatt hour.
gas_price_scenario_2 = 12
UNITS: cent/kilowatt hour
DOCUMENT: Scenario 2:
After 2023 the gas price normalizes on a higher level than before 2022 and stays there continuously.

The unit is cant per kilowatt hour.
gas_price_scenario_bau = GRAPH(TIME)
Points: (2024,00, 12,000), (2024,46666667, 12,130), (2024,93333333, 12,270), (2025,40, 12,400), (2025,86666667, 12,530), (2026,33333333, 12,670), (2026,80, 12,800), (2027,26666667, 12,930), (2027,73333333, 13,070), (2028,20, 13,200), (2028,66666667, 13,330), (2029,13333333, 13,470), (2029,60, 13,600), (2030,06666667, 13,730), (2030,53333333, 13,870), (2031,00, 14,000), (2031,46666667, 14,130), (2031,93333333, 14,270), (2032,40, 14,400), (2032,86666667, 14,530), (2033,33333333, 14,670), (2033,80, 14,800), (2034,26666667, 14,930), (2034,73333333, 15,070), (2035,20, 15,200), (2035,66666667, 15,330), (2036,13333333, 15,470), (2036,60, 15,600), (2037,06666667, 15,730), (2037,53333333, 15,870), (2038,00, 16,000), (2038,46666667, 16,130), (2038,93333333, 16,270), (2039,40, 16,400), (2039,86666667, 16,530), (2040,33333333, 16,670), (2040,80, 16,800), (2041,26666667, 16,930), (2041,73333333, 17,070), (2042,20, 17,200), (2042,66666667, 17,330), (2043,13333333, 17,470), (2043,60, 17,600), (2044,06666667, 17,730), (2044,53333333, 17,870), (2045,00, 18,000)
UNITS: cent/kilowatt hour
DOCUMENT: Scenario 1:
After 2023 the gas price first normalises on a higher level than before 2022 (12 cent per kilowatthour), but still lower than the peak (2022-2023). It then contentiously rises due to an increase in CO2-price and increasing scarcity. The steepness of the increase is based on a projection by Pehnt et al. (2023), that predicts a gas price of circa 17 cents per kilowatt hour in 2042.

The unit is cent per kilowatt hour.
gp_attractiveness = GRAPH(gp_perception_sensitivity)
Points: (-0,2000, 0,000), (-0,1200, 0,100), (-0,0400, 0,200), (0,0400, 0,300), (0,1200, 0,400), (0,2000, 0,500), (0,2800, 0,600), (0,3600, 0,700), (0,4400, 0,800), (0,5200, 0,900), (0,6000, 1,000)
UNITS: dmnl
DOCUMENT: The graphical function translates the gp perception sensitivity into a number from 0 to 1. The start and end point of the linear function depend on hand calibration. The unit is dimensionless.
gp_perception = TREND(gas_price; trending_time)
UNITS: dmnl/year
DOCUMENT: The gp perception is calculated using the TREND built-in, therefore the influence depends on the rate of change. The unit is dimensionless per year.
gp_perception_sensitivity = gp_perception//gp_perception_threshold_to_change
UNITS: dmnl
DOCUMENT: The gp perception is divided by the gp perception threshold to change. The unit is dimensionless.
gp_perception_threshold_to_change = 0,12
UNITS: dmnl/year
DOCUMENT: The parameter is based on an assumption. It influences the strength of the reaction to change.
guide_value_interest_rate = 2,5
UNITS: dmnl
heat_pump_device_price_mfh = 30000
UNITS: €/heater
DOCUMENT: The costs for heat pumps in MFH can vary a lot, 30.000€ is a approximation based on Thermondo.de/ Reiche (2023).

The unit is heater per house.
heat_pump_device_price_stfh = 12500
UNITS: €/heater

DOCUMENT: The heat pump device price is 12.500€ per heater, this reflects the price of air heat pump. In contrast to other costs, it is not multiplied with the CPI. There is no consistent data on the price, but there is data from 2010 (Platt et al. 2010) as well as data from 2024 (Bruderus, n.d.; Vaillant, n.d.) that both show a price of around this range. However, prices fluctuate depending on the source (e.g. Statista 2023).

The price is Euro per heater.
heater_lifetime_policy = RAMP(-1; 2025; 2030)
UNITS: year
DOCUMENT: The policy decreases the average lifetime by one year each year starting in 2025 and ending in 2030. This reduces the lifetime from 33 to 28 years. The unit is years.
heater_per_mfh = 1
UNITS: heater/house
DOCUMENT: Number of heaters per multi-family home. The number 1 is an assumption.

The unit is heater per house.
heater_per_stfh = 1
UNITS: heater/house
DOCUMENT: Th number of heaters per STFH. The number one is a simplification that excludes hybrid heating systems.

The unit is heater per house.
HIS_all_fh_and_hp_sales = HIS_hp_and_fh_sales_new_houses+HIS_hp_and_fh_sales_old_houses
UNITS: heater/year
DOCUMENT: Sum of heat pumps and fossil heater sales for all building types. the unit is heater per year.
HIS_average_monthly_income = GRAPH(TIME)
Points: (2005,00, 2901), (2006,00, 2950), (2007,00, 3023), (2008,00, 3103), (2009,00, 3141), (2010,00, 3227), (2011,00, 3311), (2012,00, 3391), (2013,00, 3449), (2014,00, 3527), (2015,00, 3612), (2016,00, 3703), (2017,00, 3771), (2018,00, 3880), (2019,00, 3994), (2020,00, 3975), (2021,00, 4100)
UNITS: €/house
HIS_CPI = GRAPH(TIME)
Points: (2005,00, 0,815), (2006,00, 0,828), (2007,00, 0,847), (2008,00, 0,869), (2009,00, 0,872), (2010,00, 0,881), (2011,00, 0,900), (2012,00, 0,917), (2013,00, 0,931), (2014,00, 0,940), (2015,00, 0,945), (2016,00, 0,950), (2017,00, 0,964), (2018,00, 0,981), (2019,00, 0,995), (2020,00, 1,000), (2021,00, 1,031), (2022,00, 1,102), (2023,00, 1,167)
UNITS: dmnl
HIS_demolished_mfh_per_year = GRAPH(TIME)
Points: (2005,00, 4,0), (2006,00, 4,0), (2007,00, 4,0), (2008,00, 3,0), (2009,00, 3,0), (2010,00, 2,0), (2011,00, 2,0), (2012,00, 2,0), (2013,00, 2,0), (2014,00, 2,0), (2015,00, 2,0), (2016,00, 2,0), (2017,00, 1,0), (2018,00, 2,0), (2019,00, 1,0), (2020,00, 1,0), (2021,00, 1,0), (2022,00, 1,0)
UNITS: house/year
DOCUMENT: Historic data showing the number of multi-family houses demolished per year in Germany from 2005 to 2022. From 2010 on the data includes dorms ("Wohnheime"). The data is adapted to the model size by dividing by thousand.

Data source: Destatis, 2023 (Baufertigstellungen im Hochbau)

The unit is house.
HIS_demolished_stfh_per_year = GRAPH(TIME)
Points: (2005,00, 5,0), (2006,00, 5,0), (2007,00, 5,0), (2008,00, 4,0), (2009,00, 4,0), (2010,00, 4,0), (2011,00, 5,0), (2012,00, 5,0), (2013,00, 5,0), (2014,00, 5,0), (2015,00, 5,0), (2016,00, 6,0), (2017,00, 5,0), (2018,00, 5,0), (2019,00, 4,0), (2020,00, 4,0), (2021,00, 4,0), (2022,00, 4,0)
UNITS: house/year
DOCUMENT: Historic data showing the number of single- and two-family houses demolished per year in Germany from 2005 to 2022. The data is adapted to the model size by dividing by thousand.

Data source: Destatis, 2023 (Baufertigstellungen im Hochbau)

The unit is house.
HIS_fh_sales_mfh = HIS_fossil_heater_sales_total*(1-c_gas_heater_rate)
UNITS: heater/year

DOCUMENT: Estimation of fh sales for mfh. The units is heater per year. Depending on historical data and an estimated fraction
HIS_fh_sales_stfh = c_gas_heater_rate*HIS_fossil_heater_sales_total
UNITS: heater/year
DOCUMENT: Estimation of fh sales for stfh. The units is heater per year. Depending on historical data and an estimated fraction
HIS_fossil_heater_sales_new_houses = GRAPH(TIME)
Points: (2005,00, 137,0), (2006,00, 128,0), (2007,00, 98,0), (2008,00, 76,0), (2009,00, 59,0), (2010,00, 55,0), (2011,00, 62,0), (2012,00, 64,0), (2013,00, 63,0), (2014,00, 65,0), (2015,00, 63,0), (2016,00, 67,0), (2017,00, 61,0), (2018,00, 56,0), (2019,00, 54,0), (2020,00, 52,0), (2021,00, 42,0), (2022,00, 35,0)
UNITS: heater/year
DOCUMENT: Historic development of fossil heater sales for new houses (gas and oil sales), data from Deutsche-Energie-Agentur (2023). Adapted to model size by dividing by 1.000.
The unit is heater per year
HIS_fossil_heater_sales_old_houses = GRAPH(TIME)
Points: (2005,00, 548,0), (2006,00, 531,0), (2007,00, 387,0), (2008,00, 444,0), (2009,00, 496,0), (2010,00, 488,0), (2011,00, 484,0), (2012,00, 497,0), (2013,00, 536,0), (2014,00, 522,0), (2015,00, 560,0), (2016,00, 531,0), (2017,00, 547,0), (2018,00, 568,0), (2019,00, 585,0), (2020,00, 615,0), (2021,00, 656,0), (2022,00, 620,0)
UNITS: heater/year
DOCUMENT: Historic development of fossil heater sales for old (existing) houses (gas and oil sales), data from Deutsche-Energie-Agentur (2023). Adapted to model size by dividing by 1.000.
The unit is heater per year
HIS_fossil_heater_sales_total = HIS_fossil_heater_sales_new_houses+HIS_fossil_heater_sales_old_houses
UNITS: heater/year
DOCUMENT: Sum of historic fossil heater sales for all building types. The unit is heater per year.
HIS_heating_installers = GRAPH(TIME)
Points: (2005,00, 346,0), (2006,00, 336,0), (2007,00, 334,0), (2008,00, 330,0), (2009,00, 336,0), (2010,00, 339,0), (2011,00, 339,0), (2012,00, 347,0), (2013,00, 354,0), (2014,00, 366,0), (2015,00, 357,0), (2016,00, 355,0), (2017,00, 366,0), (2018,00, 376,0), (2019,00, 379,0), (2020,00, 385,0), (2021,00, 390,0), (2022,00, 392,0), (2023,00, 392,0)
UNITS: people
DOCUMENT: Historic number of people employed in craft workshops related to heating engineering and installation ("Sanitär-Heizungs-Klima-Handwerk"). This includes unskilled workers and non-craft-related employees of these workshops. The data is adapted to the model size by dividing it by 1000.

Data from Scholle (2024) via Statista.de.

The unit is people.
HIS_heating_installers_starting_apprenticeship = GRAPH(TIME)
Points: (2005,00, 7,600), (2006,00, 7,300), (2007,00, 7,500), (2008,00, 7,700), (2009,00, 7,200), (2010,00, 7,400), (2011,00, 7,300), (2012,00, 7,000), (2013,00, 6,900), (2014,00, 7,000), (2015,00, 7,100), (2016,00, 6,900), (2017,00, 7,000), (2018,00, 7,100), (2019,00, 7,700)
UNITS: people/year
DOCUMENT: Historic number of people starting their apprenticeship in heating engineering and installation and electrotechnology ('Installateur und Heizungsbauer' and 'Elektrotechniker'). The number is based on the available data (Zentralverband des deutschen Handwerks, 2023) for graduates and dates back 3 years. This simplification assumes that there are no dropouts.

The unit is people per year.
HIS_hp_and_fh_sales_new_houses = HIS_hp_sales_new_houses+HIS_fossil_heater_sales_new_houses
UNITS: heater/year
DOCUMENT: Sum of historical heat pump and fossil heater sales for new houses. The unit is heater per house.
HIS_hp_and_fh_sales_old_houses = HIS_fossil_heater_sales_old_houses+HIS_hp_sales_old_houses
UNITS: heater/year
DOCUMENT: Sum of historical heat pump and fossil heater sales for old (existing) houses. The unit is heater per house.
HIS_hp_sales_mfh = HIS_hp_sales_total*(1-c_hp_sales_stfh_rate)
UNITS: heater/year
DOCUMENT: Estimation of hp sales for mfh. The units is heater per year. Depending on historical data and an estimated fraction

HIS_hp_sales_new_houses = GRAPH(TIME)
Points: (2005,00, 6,0), (2006,00, 12,0), (2007,00, 17,0), (2008,00, 18,0), (2009,00, 22,0), (2010,00, 25,0), (2011,00, 31,0), (2012,00, 33,0), (2013,00, 36,0), (2014,00, 38,0), (2015,00, 36,0), (2016,00, 38,0), (2017,00, 45,0), (2018,00, 48,0), (2019,00, 50,0), (2020,00, 56,0), (2021,00, 56,0), (2022,00, 63,0)
UNITS: heater/year
DOCUMENT: Historic development of heat pump sales for new houses, data from Deutsche-Energie-Agentur (2023). Adapted to model size by dividing by 1.000.
The unit is heater per year
HIS_hp_sales_old_houses = GRAPH(TIME)
Points: (2005,00, 13,0), (2006,00, 37,0), (2007,00, 29,0), (2008,00, 44,0), (2009,00, 33,0), (2010,00, 25,0), (2011,00, 26,0), (2012,00, 27,0), (2013,00, 25,0), (2014,00, 20,0), (2015,00, 21,0), (2016,00, 29,0), (2017,00, 34,0), (2018,00, 36,0), (2019,00, 37,0), (2020,00, 65,0), (2021,00, 98,0), (2022,00, 173,0)
UNITS: heater/year
DOCUMENT: Historic development of heat pump sales for old (existing) houses, data from Deutsche-Energie-Agentur (2023). Adapted to model size by dividing by 1.000.
The unit is heater per year
HIS_hp_sales_stfh = c_hp_sales_stfh_rate*HIS_hp_sales_total
UNITS: heater/year
DOCUMENT: Estimation of hp sales for stfh. The units is heater per year. Depending on historical data and an estimated fraction
HIS_hp_sales_total = HIS_hp_sales_old_houses+HIS_hp_sales_new_houses
UNITS: heater/year
DOCUMENT: Sum of historic heat pump sales for all building types. The unit is heater per year.
HIS_interest_rate = GRAPH(TIME)
Points: (2005,00, 2,000), (2005,92, 2,250), (2006,17, 2,500), (2006,33, 2,750), (2006,58, 3,000), (2006,67, 3,250), (2006,92, 3,500), (2007,17, 3,750), (2007,33, 4,000), (2008,42, 4,250), (2008,50, 3,750), (2008,83, 3,250), (2008,92, 2,500), (2009,00, 2,000), (2009,17, 1,500), (2009,25, 1,250), (2009,33, 1,000), (2011,33, 1,250), (2011,50, 1,500), (2011,83, 1,250), (2011,92, 1,000), (2012,50, 0,750), (2013,33, 0,500), (2013,83, 0,250), (2014,42, 0,150), (2014,67, 0,050), (2015,92, 0,050), (2016,17, 0,000), (2022,50, 0,500), (2022,67, 1,250), (2022,83, 2,000), (2022,92, 2,500), (2023,08, 3,000), (2023,17, 3,500), (2023,33, 3,750), (2023,42, 4,000), (2023,58, 4,250), (2023,67, 4,500)
UNITS: dmnl
HIS_new_mfh_per_year = GRAPH(TIME)
Points: (2005,00, 8,0), (2006,00, 9,0), (2007,00, 7,0), (2008,00, 7,0), (2009,00, 6,0), (2010,00, 6,0), (2011,00, 7,0), (2012,00, 9,0), (2013,00, 10,0), (2014,00, 12,0), (2015,00, 12,0), (2016,00, 13,0), (2017,00, 14,0), (2018,00, 14,0), (2019,00, 15,0), (2020,00, 15,0), (2021,00, 15,0), (2022,00, 15,0)
UNITS: house/year
DOCUMENT: Historic data showing the number of multi-family houses completed per year in Germany from 2005 to 2022. From 2010 on the data includes dorms ("Wohnheime"). The data is adapted to the model size by dividing by thousand.

Data source: Destatis, 2023 (Baufertigstellungen im Hochbau)

The unit is house.
HIS_new_stfh_per_year = GRAPH(TIME)
Points: (2005,00, 137,0), (2006,00, 137,0), (2007,00, 113,0), (2008,00, 88,0), (2009,00, 76,0), (2010,00, 78,0), (2011,00, 89,0), (2012,00, 92,0), (2013,00, 94,0), (2014,00, 97,0), (2015,00, 94,0), (2016,00, 97,0), (2017,00, 96,0), (2018,00, 93,0), (2019,00, 93,0), (2020,00, 98,0), (2021,00, 88,0), (2022,00, 89,0)
UNITS: house/year
DOCUMENT: Historic data showing the number of single- and two-family houses completed per year in Germany from 2005 to 2022. The data is adapted to the model size by dividing by thousand.

Data source: Destatis, 2023 (Baufertigstellungen im Hochbau)

The unit is house.
HIS_percent_hp_installation_in_new_houses = PERCENT(HIS_hp_sales_new_houses/(HIS_hp_sales_new_houses+HIS_fossil_heater_sales_new_houses))
UNITS: dmnl
HIS_percentage_hp_installation_in_old_houses = PERCENT(HIS_hp_sales_old_houses/(HIS_hp_sales_old_houses+HIS_fossil_heater_sales_old_houses))
UNITS: heater/year

HIS_Percentage_of_housing_units_heated_with_HP = GRAPH(TIME)
Points: (2005,00, 0,2), (2006,00, 0,3), (2007,00, 0,5), (2008,00, 0,7), (2009,00, 0,8), (2010,00, 1,0), (2011,00, 1,1), (2012,00, 1,2), (2013,00, 1,4), (2014,00, 1,5), (2015,00, 1,7), (2016,00, 1,8), (2017,00, 2,0), (2018,00, 2,2), (2019,00, 2,4), (2020,00, 2,6), (2021,00, 2,8), (2022,00, 2,7)
UNITS: dmnl
DOCUMENT: Heat sources of housing units in Germany in per cent based on data from BDEW (2023). the unit is dimensionless.
HIS_percentage_of_hp_installations_total = PERCENT(HIS_hp_sales_total/(HIS_hp_sales_total+HIS_fossil_heater_sales_old_houses))
UNITS: dmnl
HIS_total_mfh = GRAPH(TIME)
Points: (2005,00, 3043,0), (2006,00, 3052,0), (2007,00, 3059,0), (2008,00, 3066,0), (2009,00, 3072,0), (2010,00, 3094,0), (2011,00, 3102,0), (2012,00, 3111,0), (2013,00, 3121,0), (2014,00, 3134,0), (2015,00, 3147,0), (2016,00, 3162,0), (2017,00, 3177,0), (2018,00, 3194,0), (2019,00, 3211,0), (2020,00, 3229,0), (2021,00, 3248,0)
UNITS: house
DOCUMENT: Historic data showing the number of multifamily houses (above 3 housing units per building, excluding dorms ("Wohnheime")) in Germany from 2005 to 2021, yearly steps.
The data is adapted to the model size by dividing by thousand. Data source: Statistisches Bundesamt (Destatis), 2022 (Gebäude und Wohnungen).

The unit is house.
HIS_total_residential_buildings = HIS_total_mfh+HIS_total_stfh
UNITS: house
DOCUMENT: Historic data showing the number of residential buildings, excluding dorms ("Wohnheime") in Germany from 2005 to 2021, yearly steps. Calculated by adding HIS total stfh and HIS total mfh.

Data source: Statistisches Bundesamt (Destatis), 2022 (Gebäude und Wohnungen).

The unit is house.
HIS_total_stfh = GRAPH(TIME)
Points: (2005,00, 14557,0), (2006,00, 14690,0), (2007,00, 14800,0), (2008,00, 14884,0), (2009,00, 14958,0), (2010,00, 15141,0), (2011,00, 15222,0), (2012,00, 15310,0), (2013,00, 15401,0), (2014,00, 15494,0), (2015,00, 15585,0), (2016,00, 15678,0), (2017,00, 15771,0), (2018,00, 15859,0), (2019,00, 15950,0), (2020,00, 16044,0), (2021,00, 16128,0)
UNITS: house
DOCUMENT: Historic data showing the number of single- and two-family houses in Germany from 2005 to 2021, yearly steps. The data is adapted to the model size by dividing by thousand.

Data source: Statistisches Bundesamt (Destatis), 2022 (Gebäude und Wohnungen).

The unit is house.
HISTORIC_gas_price = GRAPH(TIME)
Points: (2005,00, 5,475), (2006,00, 6,34), (2007,00, 6,6), (2008,00, 7,375), (2009,00, 7,025), (2010,00, 6,095), (2011,00, 6,345), (2012,00, 6,585), (2013,00, 7,805), (2014,00, 6,68), (2015,00, 6,46), (2016,00, 6,85), (2017,00, 5,795), (2018,00, 5,71), (2019,00, 6,05), (2020,00, 5,735), (2021,00, 7,32), (2022,00, 17,195), (2023,00, 15,025), (2024,00, 10,0)
UNITS: cent/kilowatt hour
housing_units_heated_by_heat_pumps = housing_units_in_stfh*density_of_hp_in_stfh + density_of_hp_in_mfh*housing_units_in_mfh
UNITS: housing unit
housing_units_in_mfh = total_MFH*housing_units_per_mfh
UNITS: housing unit
DOCUMENT: The variable shows number of housing units (or apartments) in MFHs and is calculated using the number MHs and the average number of housing units per MFH. It is used to calculate the total number of housing units.

the unit is housing unit.
housing_units_in_stfh = total_STFH*housing_units_per_stfh
UNITS: housing unit

DOCUMENT: The variable shows number of housing units in STFHs and is calculated using the number of STFHs and the average number of housing units per STFH. It is used to calculate the total number of housing units.

the unit is housing unit.
housing_units_per_mfh = 6,7
UNITS: housing unit/house
DOCUMENT: Shows the average number of housing units (apartments) per multi-family home (apartment building). The number 6,7 is the result of calculations based on based on Statistisches Bundesamt (Destatis), 2022 (Gebäude und Wohnungen).

The unit is housing unit per house.
housing_units_per_stfh = 1,2
UNITS: housing unit/house
DOCUMENT: Shows the average number of housing units (apartments) per single- and two-family home. The number 1,2 is the result of calculations based on based on Statistisches Bundesamt (Destatis), 2022 (Gebäude und Wohnungen).

The unit is housing unit per house.
hp_device_plus_renovation_mfh = IF TIME > 2025 AND SWITCH_subsidies = 1 THEN renovation_costs_mfh+total_hp_price_old_mfh ELSE renovation_costs_mfh+after_subsidies_hp_costs_old_mfh
UNITS: €/house
DOCUMENT: All costs together, device, installation and renovation for MFH.

Depending on the chosen scenario after 2024 either the costs with or without subsidies are considered.
The unit is Euro per house.
hp_device_plus_renovation_stfh = IF TIME > 2025 AND SWITCH_subsidies = 1 THEN renovation_price_stfh+total_hp_price_old_stfh ELSE after_subsidies_total_hp_price_old_stfh+renovation_price_stfh
UNITS: €/house
DOCUMENT: All costs together, device, installation and renovation for a HP in an old STFH.

Depending on the chosen scenario after 2024 either the costs with or without subsidies are considered.
hp_first_lifetime_mfh = HP_total_lifetime_mfh/2
UNITS: years
DOCUMENT: Length of the first half of the lifetime of HPs in MFH. Calculated by dividing HP total lifetime mfh by two. The unit is years.
hp_first_lifetime_stfh = HP_total_lifetime_stfh/2
UNITS: years
DOCUMENT: Length of the first half of the lifetime of HPs in STFH. Calculated by dividing HP total lifetime stfh by two. The unit is years.
hp_installation_in_new_buildings = hp_installation_rate_new_stfh+installation_rate_hp_in_new_mfh
UNITS: heater/year
hp_installation_in_old_buildings = hp_installation_rate_old_stfh_without_early_exch+installation_rate_hp_in_old_mfh+early_exchange_stfh
UNITS: heater/year
hp_installation_rate_in_mfh = installation_rate_hp_in_new_mfh+installation_rate_hp_in_old_mfh
UNITS: heater/year
DOCUMENT: Total number of hp installations per year in mfh
hp_installation_rate_in_stfh = hp_installation_rate_new_stfh+hp_installation_rate_old_stfh_without_early_exch+early_exchange_stfh
UNITS: heater/year
DOCUMENT: Total number of hp installations per year in stfh.
hp_installation_rate_new_stfh = IF SWITCH_capacity = 1 THEN MIN(desired_hp_in_new_stfh; hp_total_installation_capacity) ELSE desired_hp_in_new_stfh
UNITS: heater/year
DOCUMENT: XX

For normal model testing (Switch capacity = 1), a MIN function is active. This ensures that only as many heaters get exchanged as there is capacity to install. The other limiting factor is the desired early exchange stfh variable. For Switch capacity = 0, there is no MAX function and all desired exchanges are conducted

hp_installation_rate_old_stfh_without_early_exch = IF SWITCH_capacity = 1 THEN MIN(desired_hp_in_existing_stfh_per_year; capacity_for_hp_in_old_stfh) ELSE desired_hp_in_existing_stfh_per_year
UNITS: heater/year
DOCUMENT: XX

For normal model testing (Switch capacity = 1), a MIN function is active. This ensures that only as many heaters get exchanged as there is capacity to install. The other limiting factor is the desired early exchange stfh variable. For Switch capacity = 0, there is no MAX function and all desired exchanges are conducted
HP_MFH_total = HP_MFH_one + HP_MFH_two
UNITS: heater
DOCUMENT: Total number of heat pumps installed in multi-family houses, sums up the two stocks of the ageing chain for heat pumps in mfh.

The unit is heater.
hp_ratio_expectation = MIN(1; FORCST(desired_hp_to_fh_ratio; forecast_averaging_time; forecast_horizon))
UNITS: dmnl
DOCUMENT: Fraction of heater installations that are heat pumps that are expected to be installed 3 years in the future. It is calculated using the forecast built in and a MIN function to ensure it does not exceed 1.

The unit is dimensionless.
hp_second_life_time_1 = HP_total_lifetime_mfh/2
UNITS: years
DOCUMENT: Length of the second half of the lifetime of HPs in MFH. Calculated by dividing HP total lifetime mfh by two. The unit is years.
hp_second_life_time_stfh = HP_total_lifetime_stfh/2
UNITS: years
DOCUMENT: Length of the second half of the lifetime of HPs in STFH. Calculated by dividing HP total lifetime stfh by two. The unit is years.
HP_STFH_total = HP_STFH_one + HP_STFH_two
UNITS: heater
DOCUMENT: Total number of heat pumps installed in single- and two-family houses, sums up the two stocks of the ageing chain for heat pumps in mfh.

The unit is heater.
hp_total_installation_capacity = hp_installers*capacity_per_hp_installer
UNITS: heater/year
DOCUMENT: The total capacity for hp installation depends on the number of hp installers and the capacity per hp installer. The unit is heater per year.
HP_total_lifetime_mfh = 18
UNITS: years
DOCUMENT: The average lifespan of heat pumps is 18 years.
HP_total_lifetime_stfh = 18
UNITS: Years
DOCUMENT: The average lifespan of heat pumps is 18 years.
imp_density_new_mfh = 0,4
UNITS: dmnl
DOCUMENT: The weights/importance for attractiveness are based on two parameters and two resulting variables. At first, the importance of density is determined. This influences the imp finance and the imp gp, the higher the imp density the smaller the other two variables, all three imp-variables together have to add up to 1.

The exact number is the result of hand calibration.

the unit is dimensionless.
imp_density_new_stfh = 0,25
UNITS: dmnl
DOCUMENT: The weights/importance for attractiveness are based on two parameters and two resulting variables. At first, the importance of density is determined. This influences the imp finance and the imp gp, the higher the imp density the smaller the other two variables, all three imp-variables together have to add up to 1.

The exact number is the result of hand calibration.

the unit is dimensionless.
imp_density_old_mfh = 0,4
UNITS: dmnl
DOCUMENT: The weights/importance for attractiveness are based on two parameters and two resulting variables. At first, the importance of density is determined. This influences the imp finance and the imp gp, the higher the imp density the smaller the other two variables, all three imp-variables together have to add up to 1.

The exact number is the result of hand calibration.

the unit is dimensionless.
imp_density_old_stfh = 0,45
UNITS: dmnl
DOCUMENT: The weights/importance for attractiveness are based on two parameters and two resulting variables. At first, the importance of density is determined. This influences the imp finance and the imp gp, the higher the imp density the smaller the other two variables, all three imp-variables together have to add up to 1.

The exact number is the result of hand calibration.

the unit is dimensionless.
imp_financ_new_mfh = (1-imp_density_new_mfh)*distr_imp_new_mfh
UNITS: dmnl
DOCUMENT: Imp fiance depends on imp density and distr imp. It can vary between 0 and 1 and determines the strength the financial attractiveness has on the overall attractiveness of hp.

The unit is dimensionless.
imp_financ_new_stfh = (1-imp_density_new_stfh)*distr_imp_new_stfh
UNITS: dmnl
DOCUMENT: Imp fiance depends on imp density and distr imp. It can vary between 0 and 1 and determines the strength the financial attractiveness has on the overall attractiveness of hp.

The unit is dimensionless.
imp_financ_old_mfh = (1-imp_density_old_mfh)*distr_imp_old_mfh
UNITS: dmnl
DOCUMENT: Imp fiance depends on imp density and distr imp. It can vary between 0 and 1 and determines the strength the financial attractiveness has on the overall attractiveness of hp.

The unit is dimensionless.
imp_financ_old_stfh = (1-imp_density_old_stfh)*distr_imp_old_stfh
UNITS: dmnl
DOCUMENT: Imp fiance depends on imp density and distr imp. It can vary between 0 and 1 and determines the strength the financial attractiveness has on the overall attractiveness of hp.

The unit is dimensionless.
imp_gp_new_mfh = (1-imp_density_new_mfh)*(1-distr_imp_new_mfh)
UNITS: dmnl
DOCUMENT: Imp gp depends on imp density and distr imp. It can vary between 0 and 1 and determines the strength the gas price attractiveness has on the overall attractiveness of hp.

The unit is dimensionless.
imp_gp_new_stfh = (1-imp_density_new_stfh)*(1-distr_imp_new_stfh)
UNITS: dmnl
DOCUMENT: Imp gp depends on imp density and distr imp. It can vary between 0 and 1 and determines the strength the gas price attractiveness has on the overall attractiveness of hp.

The unit is dimensionless.
imp_gp_old_mfh = (1-imp_density_old_mfh)*(1-distr_imp_old_mfh)
UNITS: dmnl
DOCUMENT: Imp gp depends on imp density and distr imp. It can vary between 0 and 1 and determines the strength the gas price attractiveness has on the overall attractiveness of hp.

The unit is dimensionless.
imp_gp_old_stfh = (1-imp_density_old_stfh)*(1-distr_imp_old_stfh)
UNITS: dmnl
DOCUMENT: Imp gp depends on imp density and distr imp. It can vary between 0 and 1 and determines the strength the gas price attractiveness has on the overall attractiveness of hp.

The unit is dimensionless.
importance_of_interest_new_mfh = 0,3
UNITS: dmnl
DOCUMENT: A parameter that represents the weight the interest has on the financial attractiveness of HP in the specific building type. The number is an assumption. The unit is dimensionless.
importance_of_interest_new_stfh = 0,05
UNITS: dmnl
DOCUMENT: A parameter that represents the weight the interest has on the financial attractiveness of HP in the specific building type. The number is an assumption. The unit is dimensionless.
importance_of_interest_old_mfh = 0,2
UNITS: dmnl
DOCUMENT: A parameter that represents the weight the interest has on the financial attractiveness of HP in the specific building type. The number is an assumption. The unit is dimensionless.
importance_of_interest_old_stfh = 0,05
UNITS: dmnl
DOCUMENT: A parameter that represents the weight the interest has on the financial attractiveness of HP in the specific building type. The number is an assumption. The unit is dimensionless.
income_scenario_1 = GRAPH(TIME)
Points: (2024,00, 4100), (2024,525, 4138), (2025,05, 4175), (2025,575, 4213), (2026,10, 4250), (2026,625, 4288), (2027,15, 4325), (2027,675, 4363), (2028,20, 4400), (2028,725, 4438), (2029,25, 4475), (2029,775, 4513), (2030,30, 4550), (2030,825, 4588), (2031,35, 4625), (2031,875, 4663), (2032,40, 4700), (2032,925, 4738), (2033,45, 4775), (2033,975, 4813), (2034,50, 4850), (2035,025, 4888), (2035,55, 4925), (2036,075, 4963), (2036,60, 5000), (2037,125, 5038), (2037,65, 5075), (2038,175, 5113), (2038,70, 5150), (2039,225, 5188), (2039,75, 5225), (2040,275, 5263), (2040,80, 5300), (2041,325, 5338), (2041,85, 5375), (2042,375, 5413), (2042,90, 5450), (2043,425, 5488), (2043,95, 5525), (2044,475, 5563), (2045,00, 5600)
UNITS: €/house
income_scenario_2 = GRAPH(TIME)
Points: (2024,00, 4100,0), (2024,525, 4118,0), (2025,05, 4135,0), (2025,575, 4153,0), (2026,10, 4170,0), (2026,625, 4188,0), (2027,15, 4205,0), (2027,675, 4223,0), (2028,20, 4240,0), (2028,725, 4258,0), (2029,25, 4275,0), (2029,775, 4293,0), (2030,30, 4310,0), (2030,825, 4328,0), (2031,35, 4345,0), (2031,875, 4363,0), (2032,40, 4380,0), (2032,925, 4398,0), (2033,45, 4415,0), (2033,975, 4433,0), (2034,50, 4450,0), (2035,025, 4468,0), (2035,55, 4485,0), (2036,075, 4503,0), (2036,60, 4520,0), (2037,125, 4538,0), (2037,65, 4555,0), (2038,175, 4573,0), (2038,70, 4590,0), (2039,225, 4608,0), (2039,75, 4625,0), (2040,275, 4643,0), (2040,80, 4660,0), (2041,325, 4678,0), (2041,85, 4695,0), (2042,375, 4713,0), (2042,90, 4730,0), (2043,425, 4748,0), (2043,95, 4765,0), (2044,475, 4783,0), (2045,00, 4800,0)
UNITS: €/house
income_to_price_relation_gas_heater = average_monthly_income/real_gas_heater_price_stfh
UNITS: dmnl
DOCUMENT: Relationship between the average income and the total costs for a gas heater (including installation), is calculated by dividing the income with the total costs. The higher the number the more affordable the gas heater is. This is important to make it comparable with the relation of income and heat pump prices.

The units are dimensionless.
income_to_price_relation_hp_new_stfh = IF TIME > 2025 AND SWITCH_subsidies = 1 THEN average_monthly_income/total_hp_price_new_stfh ELSE average_monthly_income/after_subsidies_total_hp_price_new_stfh
UNITS: dmnl
DOCUMENT: Relationship between the average income and the total costs for a heat pump installation in a new STFH, is calculated by dividing the income with the total costs. The higher the number the more affordable is a heat pump. This relationship is important because in STFHs the homeowners are often normal working people and if they can afford something depends on their income.

Depending on the chosen scenario after 2024 either the costs with or without subsidies are considered.

The unit is dimensionless.

income_to_price_relation_hp_old_stfh = average_monthly_income/hp_device_plus_renovation_stfh
UNITS: dmnl
DOCUMENT: Relationship between the average income and the total costs for a heat pump installation in an old STFH (including renovation),is calculated by dividing the income with the total costs. The higher the number the more affordable is a heat pump. This relationship is important because in STFHs the homeowners are often normal working people and if they can afford something depends on their income.

the unit is dimensionless.
init_hp_installer_ratio = 0,3
UNITS: dmnl
"Init_MFH_0-30" = 1003
UNITS: house
DOCUMENT: Shows the initial number of multi-family houses (apartment buildings) between 0 and 30 years old in 2005.

The number is the result of my own calculations based on Statistisches Bundesamt (Destatis), 2022 (Gebäude und Wohnungen) and Deutsche Energie-Agentur, 2023 (dena).

The unit is house.
"Init_MFH_31-60" = 1262
UNITS: house
DOCUMENT: Shows the initial number of multi-family houses (apartment buildings) between 31 and 60 years old in 2005.

The number is the result of my own calculations based on Statistisches Bundesamt (Destatis), 2022 (Gebäude und Wohnungen) and Deutsche Energie-Agentur, 2023 (dena).

The unit is house.
Init_MFH_above_61 = 782
UNITS: house
DOCUMENT: Shows the initial number of multi-family houses (apartment buildings) above 61 years old in 2005.

The number is the result of my own calculations based on Statistisches Bundesamt (Destatis), 2022 (Gebäude und Wohnungen) and Deutsche Energie-Agentur, 2023 (dena).

The unit is house.
Init_mfh_withouth_dh = Init_total_MFH-mfh_buildings_with_district_heating
UNITS: house
DOCUMENT: The initial number of MFHs without district heating is calculated by subtracting the number of MFHs with district heating from the total number of MFHs. This number is used for the initialisation of the ageing chain FH MFH, since it is assumed that there are no heat pumps in MFHs in the year 2005.

The unit is house.
"Init_STFH_0-30" = 4797
UNITS: house
DOCUMENT: Shows the initial number of single- and two-family homes between 0 and 30 years old in 2005.

The number is the result of my own calculations based on Statistisches Bundesamt (Destatis), 2022 (Gebäude und Wohnungen) and Deutsche Energie-Agentur, 2023 (dena).

The unit is house.
"Init_STFH_31-60" = 6038
UNITS: house
DOCUMENT: Shows the initial number of single- and two-family homes between 31 and 60 years old in 2005.

The number is the result of my own calculations based on Statistisches Bundesamt (Destatis), 2022 (Gebäude und Wohnungen) and Deutsche Energie-Agentur, 2023 (dena).

The unit is house.
Init_STFH_above_61 = 3743

UNITS: house
DOCUMENT: Shows the initial number of single- and two-family homes above 61 years old in 2005.

The number is the result of my own calculations based on Statistisches Bundesamt (Destatis), 2022 (Gebäude und Wohnungen) and Deutsche Energie-Agentur, 2023 (dena).

The unit is house.
Init_total_MFH = "Init_MFH_0-30"+"Init_MFH_31-60"+Init_MFH_above_61
UNITS: house
DOCUMENT: Initial total number of MFHs in 2005. It is calculated by adding the MFHs of the different age groups together and it is used to calculate the total number of heaters needed in MFHs.

The unit is house.
Init_total_STFH = "Init_STFH_0-30"+"Init_STFH_31-60"+Init_STFH_above_61
UNITS: house
DOCUMENT: Initial total number of STFHs in 2005. It is calculated by adding the STFHs of the different age groups together and it is used to calculate the total number of heaters needed in STFHs.

The unit is heater.
initial_apprentices_1 = 23
UNITS: people
DOCUMENT: Rounded sum of people who started apprenticeship between 2002 and 2004.
initial_fh_mfh_one = Init_mfh_withouth_dh*heater_per_mfh*rate_of_fh_age_one_1
UNITS: heater
initial_fh_mfh_three = Init_mfh_withouth_dh*heater_per_mfh*rate_of_fh_age_three_1 - mfh_heater_sales_first_year
UNITS: heater
initial_fh_mfh_two = Init_mfh_withouth_dh*heater_per_mfh*rate_of_fh_age_two_1
UNITS: heater
Initial_fh_stfh = Init_total_STFH*heater_per_stfh-Initial_hp_stfh
UNITS: heater
DOCUMENT: This variable determines how many fossil heaters are part of the ageing chain FH STFH at the start of the model in 2005.

The initial total number of fossil heaters in STFH is calculated by subtracting the number of heat pumps from the number of heaters needed in STFH. The number of heaters needed in STFH is calculated by multiplying the initial number of STFHs by the number of heaters per STFH.

The unit is heater.
initial_fh_stfh_one = Initial_fh_stfh*rate_of_fh_age_one
UNITS: heater
initial_fh_stfh_three = Initial_fh_stfh*rate_of_fh_age_three -stfh_heater_sales_first_year
UNITS: heater
initial_fh_stfh_two = Initial_fh_stfh*rate_of_fh_age_two
UNITS: heater
initial_hp_experience = 0,1
UNITS: dmnl
initial_hp_mfh_one = 0
UNITS: heater
DOCUMENT: This parameter is the initial variable for the stock HP MFH one. Due to the low number of heat pumps overall in 2005 and the low rate installed in MFHs, the number is zero.

The unit is heater.
initial_hp_mfh_two = 0
UNITS: heater
DOCUMENT: This parameter is the initial variable for the stock HP MFH two. Due to the low number of heat pumps overall in 2005 and the low rate installed in MFHs, the number is zero.

The unit is heater.
Initial_hp_stfh = 90

UNITS: heater
DOCUMENT: This parameter determines how many heat pumps are part of the ageing chain HP STFH at the start of the model in 2005.

Due to sales data about heat pumps from 1995 to 2004 (Deutsche Energie-Agentur, 2023) it is calculated that at least 80 heat pumps were already installed in 2005. Especially in the past heat pumps were almost exclusvly used in STFHs (Born et al., 2017). Therefore 90 heat pumps is a good estimation for the initial number of heat pumps in STFH.

The unit is heater.
Initial_hp_stfh_one = Initial_hp_stfh*initital_hp_stfh_age_rate
UNITS: heater
DOCUMENT: This variable is the initial number of heat pumps in the stock HP STFH one and therefore the number of heat pumps below nine years old installed in STFHs at the start of the model 2005. It is calculated by multiplying the initial total number of heat pumps in STFHs by the initial hp stfh age rate.

The unit is heater.
Initial_hp_stfh_two = Initial_hp_stfh*(1-initital_hp_stfh_age_rate)
UNITS: heater
DOCUMENT: This variable is the initial number of heat pumps in the stock HP STFH two and therefore the number of heat pumps above nine years old installed in STFHs at the start of the model 2005. It is calculated by multiplying the initial total number of heat pumps in STFHs by 1 minus the initial hp stfh age rate.

The unit is heater.
initial_inst_1 = initial_installers*age_ration_initial_installers
UNITS: People
DOCUMENT: The initialisation for the stock craftspeople 1, based on 'initial craftspeople' and 'ratio initial cp'.
initial_inst_2 = initial_installers*(1-age_ration_initial_installers)
UNITS: People
DOCUMENT: The initialisation for the stock craftspeople 2, based on 'initial craftspeople' and 1minus 'ratio initial cp'.
initial_installer_capacity_to_request_ratio = HIS_hp_sales_total/hp_total_installation_capacity
UNITS: dmnl
initial_installers = HISTORY(HIS_heating_installers; STARTTIME)
UNITS: people
initial_request_ratio_to_pressure_translation = GRAPH(initial_installer_capacity_to_request_ratio)
Points: (0,000, 0,000), (0,200, 0,100), (0,400, 0,200), (0,600, 0,300), (0,800, 0,400), (1,000, 0,500), (1,200, 0,600), (1,400, 0,700), (1,600, 0,800), (1,800, 0,900), (2,000, 1,000)
UNITS: dmnl
DOCUMENT: Calculation of initial pressure to avoid circularity. The graphical function is based on an assumption. The unit is dimensionless.
initital_hp_stfh_age_rate = 0,9
UNITS: dmnl
DOCUMENT: This parameter determines the ratio of heat pumps that are in the first stock of the ageing chain HP STFH. The ratio is 0,9 since the data shows that most heat pumps are below 9 years old.

The unit is dimensionless.
installation_effort_existing_building = 1,35
UNITS: dmnl
DOCUMENT: The parameter represents the additional efforts installers have in an already existing building, not originally designed for the use of heat pumps. The additional effort translates into a higher price due to additional working hours or more complicated work.

The additional effort is derived by comparing the average price difference between hp installation prices in 2008, based on data from Platt et al. (2010, p. 57).

The unit is dimensionless.
installation_effort_mfh = 6
UNITS: dmnl
DOCUMENT: Number with which the effort increases when installing an HP in an MFH instead of an STFH. The number is an assumption. The unit is dimensionless.

installation_effort_mfh_gas = 1,5
UNITS: dmnl
DOCUMENT: Number with which the effort increases when installing an FH in an MFH instead of an STFH. The number is an assumption. The unit is dimensionless.
installation_price_existing_mfh = installation_price_new_mfh*installation_effort_existing_building
UNITS: €/heater
DOCUMENT: The installation price for old mfh depends on the installation price for hp in new mfh multiplied by the additional effort for existing buildings. The unit is Euro per heater.
installation_price_existing_stfh = installation_price_new_construction_stfh*installation_effort_existing_building
UNITS: €/heater
DOCUMENT: The installation price for old mfh depends on the installation price for hp in new mfh multiplied by the additional effort for existing buildings. The unit is Euro per heater.
installation_price_new_construction_stfh = MAX(real_normal_price_per_installation*hp_pressure_on_installers; real_minimum_price_per_installation)
UNITS: €/heater
DOCUMENT: The installation price for heat pump installations in new constructions is depending on the hp pressure on installers and the real normal price per installation as well as the real minimum price per installation.

To calculate the price the pressure (representing the ratio of demand to supply in the installation market) is multiplied by the real maximum price per installation. This calculation is added to a MAX function that also includes the real minimum price per installation. This is based on the logic, that even when there is low demand the prices can only be lowered to a certain degree because they still need to pay a living wage, it was added after extreme condition testing.

The unit is € per heater.

installation_price_new_mfh = installation_effort_mfh*installation_price_new_construction_stfh
UNITS: €/heater
installation_rate_hp_in_new_mfh = IF SWITCH_capacity = 1 THEN MIN(desired_hp_in_new_mfh; capacity_for_hp_in_new_mfh) ELSE desired_hp_in_new_mfh
UNITS: heater/year
DOCUMENT: XX

For normal model testing (Switch capacity = 1), a MIN function is active. This ensures that only as many heaters get exchanged as there is capacity to install. The other limiting factor is the desired early exchange stfh variable. For Switch capacity = 0, there is no MAX function and all desired exchanges are conducted
installation_rate_hp_in_old_mfh = IF SWITCH_capacity = 1 THEN MIN(desired_hp_in_existing_mfh_per_year; capacity_for_hp_in_old_mfh) ELSE desired_hp_in_existing_mfh_per_year
UNITS: heater/year
DOCUMENT: XX

For normal model testing (Switch capacity = 1), a MIN function is active. This ensures that only as many heaters get exchanged as there is capacity to install. The other limiting factor is the desired early exchange stfh variable. For Switch capacity = 0, there is no MAX function and all desired exchanges are conducted
installer_capacity_to_request_ratio = total_desired_hp/hp_total_installation_capacity
UNITS: dmnl
DOCUMENT: Set the number of desired installations in relation to the capacity. The unit is dimensionless.
installer_starting_apprenticeship = IF TIME < 2024 THEN HIS_heating_installers_starting_apprenticeship ELSE future_installer_starting_apprenticeship
UNITS: people/year
DOCUMENT: The number of installers starting an apprenticeship is based on historical data until .2022 and afterwards depends on scenarios. The unit is people per year.
installer_starting_apprenticeship_scen_1 = GRAPH(TIME)
Points: (2024,00, 7,700), (2024,525, 7,758), (2025,05, 7,815), (2025,575, 7,873), (2026,10, 7,930), (2026,625, 7,988), (2027,15, 8,045), (2027,675, 8,103), (2028,20, 8,160), (2028,725, 8,218), (2029,25, 8,275), (2029,775, 8,333), (2030,30, 8,390), (2030,825, 8,448), (2031,35, 8,505), (2031,875, 8,563), (2032,40, 8,620), (2032,925, 8,678), (2033,45, 8,735), (2033,975, 8,793), (2034,50, 8,850), (2035,025, 8,908), (2035,55, 8,965), (2036,075, 9,023), (2036,60, 9,080), (2037,125, 9,138), (2037,65, 9,195), (2038,175, 9,253), (2038,70, 9,310), (2039,225, 9,368), (2039,75, 9,425), (2040,275, 9,483), (2040,80, 9,540), (2041,325, 9,598), (2041,85, 9,655), (2042,375, 9,713), (2042,90, 9,770), (2043,425, 9,828), (2043,95, 9,885), (2044,475, 9,943), (2045,00, 10,000)
UNITS: people/year

installer_starting_apprenticeship_scen_2 = GRAPH(TIME)
Points: (2024,00, 7,700), (2024,525, 7,633), (2025,05, 7,565), (2025,575, 7,498), (2026,10, 7,430), (2026,625, 7,363), (2027,15, 7,295), (2027,675, 7,228), (2028,20, 7,160), (2028,725, 7,093), (2029,25, 7,025), (2029,775, 6,957), (2030,30, 6,890), (2030,825, 6,823), (2031,35, 6,755), (2031,875, 6,688), (2032,40, 6,620), (2032,925, 6,553), (2033,45, 6,485), (2033,975, 6,417), (2034,50, 6,350), (2035,025, 6,283), (2035,55, 6,215), (2036,075, 6,148), (2036,60, 6,080), (2037,125, 6,013), (2037,65, 5,945), (2038,175, 5,877), (2038,70, 5,810), (2039,225, 5,743), (2039,75, 5,675), (2040,275, 5,608), (2040,80, 5,540), (2041,325, 5,473), (2041,85, 5,405), (2042,375, 5,338), (2042,90, 5,270), (2043,425, 5,203), (2043,95, 5,135), (2044,475, 5,068), (2045,00, 5,000)
UNITS: people/year
installers_total = installers1 + installers2
UNITS: People
DOCUMENT: Total craftspeople relevant to heat pump installations including apprentices.

Sum of the stocks craftspeople 1 and craftspeople 2 and the conveyor apprentices.

Craftspeople relevant to heat pump installations are defined as people who work in craft workshops related to heating engineering and installation and electrotechnology. This includes unskilled labourers and non-craft-related employees of these workshops.

The unit is people.
interest_attractiveness = GRAPH(delayed_relative_interest_rate)
Points: (0,000, 1,000), (0,200, 0,900), (0,400, 0,800), (0,600, 0,700), (0,800, 0,600), (1,000, 0,500), (1,200, 0,400), (1,400, 0,300), (1,600, 0,200), (1,800, 0,100), (2,000, 0,000)
UNITS: dmnl
DOCUMENT: The graphical function translates the delayed relative interest rate into a vlaue from 0 to 1. The unit is dimensionless.
interest_rate_scenario_1 = GRAPH(TIME)
Points: (2024,000, 4,500), (2024,050, 4,491), (2024,100, 4,480), (2024,150, 4,467), (2024,200, 4,449), (2024,250, 4,428), (2024,300, 4,401), (2024,350, 4,368), (2024,400, 4,326), (2024,450, 4,274), (2024,500, 4,210), (2024,550, 4,131), (2024,600, 4,034), (2024,650, 3,917), (2024,700, 3,778), (2024,750, 3,616), (2024,800, 3,430), (2024,850, 3,221), (2024,900, 2,993), (2024,950, 2,750), (2025,000, 2,500), (2025,050, 2,250), (2025,100, 2,007), (2025,150, 1,779), (2025,200, 1,570), (2025,250, 1,384), (2025,300, 1,222), (2025,350, 1,083), (2025,400, 0,9661), (2025,450, 0,8694), (2025,500, 0,790), (2025,550, 0,7256), (2025,600, 0,6736), (2025,650, 0,6319), (2025,700, 0,5985), (2025,750, 0,5718), (2025,800, 0,5505), (2025,850, 0,5335), (2025,900, 0,5199), (2025,950, 0,5089), (2026,000, 0,500)
UNITS: dmnl
interest_rate_scenario_2 = GRAPH(TIME)
Points: (2024,00, 4,500), (2024,525, 4,525), (2025,05, 4,550), (2025,575, 4,575), (2026,10, 4,600), (2026,625, 4,625), (2027,15, 4,650), (2027,675, 4,675), (2028,20, 4,700), (2028,725, 4,725), (2029,25, 4,750), (2029,775, 4,775), (2030,30, 4,800), (2030,825, 4,825), (2031,35, 4,850), (2031,875, 4,875), (2032,40, 4,900), (2032,925, 4,925), (2033,45, 4,950), (2033,975, 4,975), (2034,50, 5,000), (2035,025, 5,025), (2035,55, 5,050), (2036,075, 5,075), (2036,60, 5,100), (2037,125, 5,125), (2037,65, 5,150), (2038,175, 5,175), (2038,70, 5,200), (2039,225, 5,225), (2039,75, 5,250), (2040,275, 5,275), (2040,80, 5,300), (2041,325, 5,325), (2041,85, 5,350), (2042,375, 5,375), (2042,90, 5,400), (2043,425, 5,425), (2043,95, 5,450), (2044,475, 5,475), (2045,00, 5,500)
UNITS: dmnl
key_interest_rate = IF TIME < 2024 THEN HIS_interest_rate ELSE future_interest_rate
UNITS: dmnl
limit_to_skill_gain = GRAPH(average_hp_skill_level)
Points: (0,7500, 1,000), (0,7750, 0,9848), (0,8000, 0,9638), (0,8250, 0,9345), (0,8500, 0,8939), (0,8750, 0,8375), (0,9000, 0,7593), (0,9250, 0,6507), (0,9500, 0,4999), (0,9750, 0,2906), (1,0000, 0,000)
UNITS: dmnl
DOCUMENT: The graphical function makes a ceiling for the inflow to the stock average skill level. The concept behind it is that the higher the skill level already is the lower is the additional experience that is gained with an additional installation. The unit is dimensionless.
MAP_support_new_mfh_1 = STEP(MIN(0,09*total_hp_price_new_mfh; 3752); 2008) - STEP(MIN(0,09*total_hp_price_new_mfh; 3752); 2015)
UNITS: €/house
DOCUMENT: Since 2008 the Marktanreizprogramm (MAP), a subsidy programme of the German government, also supports the installation of heat pumps. According to Platt et al. (2010, pp. 58–60) until 2010 69% of the applications did get support. The exact sum differs depending on the type of heat pump installed and the size of the building.

For existing MFH, the refund depends on the size of the living space. MAP pays between 10€ and 20€ per square meter, or a maximum of 10 or 15% of the investment costs depending on the type of heat pump. Therefore assuming 12€ per square meter and based on the average 80 square meters per housing unit (Statistisches Bundesamt (Destatis), 2021) in an MFH and an average of 6,7 housing units, a refund of 6.432€ can be expected.

The subsidy is introduced via a STEP function that starts in 2008. The caps for the refund amount are enforced by using a MIN function. and a maximum of 9%.

The unit is € per house.
MAP_support_new_mfh_2 = STEP(1200; 2015)
UNITS: €/house
DOCUMENT: In 2015 the MAP subsidies were changed; they are now dependent on the power of the heat pump in kilowatts. There are different subsidies available depending on the type of heat pump (Bundesamt für Wirtschaft und Ausfuhrkontrolle, 2019). For simplification, I choose to work with the "Basisförderung" (base subsidy) for the air-to-water heat pump if possible. The air-to-water heat pump is the most common type of heat pump in Germany and the other possible type of subsidy, "Innovationsförderung" (innovation subsidy), has higher requirements and is therefore less likely to be applied.

For new constructions, there is no base subsidy, therefore I choose to work with the innovation subsidy. However, I cannot assume everyone meets the higher criteria. Therefore I work with only 75% of the actual refund to account for heat pumps that are not covered by subsidies. The 75% are an assumption.

For new buildings, the innovation subsidy has a minimum refund of 1.300€ or 40€ per kilowatt. Assuming an average MFH needs 40 kilowatts (number derivates from Reiche (2023)), the refund would be 1.600€. Multiplied by 0,75 the refund is 1.200€.

The subsidy is introduced via a STEP function that starts in 2015.

The unit is € per house.
MAP_support_new_stfh1 = STEP(1260; 2008)
UNITS: €/house
DOCUMENT: Since 2008 the Marktanreizprogramm (MAP), a subsidy programme of the German government, also supports the installation of heat pumps. According to Platt et al. (2010, pp. 58–60) until 2010 69% of the applications did get support. The exact sum differs depending on the type of heat pump installed and the size of the building.

For newly constructed STFH, the refund depends on the size of the living space. MAP pays between 5€ and 10€ per square meter, or a maximum of 2.000€ per housing unit. Therefore assuming 7€ per square meter and based on the average 150 square meters per housing unit (Statistisches Bundesamt (Destatis), 2021) in an STFH and an average of 1,2 housing units, a refund of 1.260 can be expected.

The subsidy is introduced via a STEP function that starts in 2008.

The unit is € per house.
MAP_support_new_stfh2 = STEP(975; 2015)
UNITS: €/house
DOCUMENT: In 2015 the MAP subsidies were changed; they are now dependent on the power of the heat pump in kilowatts. There are different subsidies available depending on the type of heat pump (Bundesamt für Wirtschaft und Ausfuhrkontrolle, 2019). For simplification, I choose to work with the "Basisförderung" (base subsidy) for the air-to-water heat pump if possible. The air-to-water heat pump is the most common type of heat pump in Germany and the other possible type of subsidy, "Innovationsförderung" (innovation subsidy), has higher requirements and is therefore less likely to be applied.

For new constructions, there is no base subsidy, therefore I choose to work with the innovation subsidy. However, I cannot assume everyone meets the higher criteria. Therefore I work with only 75% of the actual refund to account for heat pumps that are not covered by subsidies. The 75% are an assumption.

For new buildings, the innovation subsidy has a minimum refund of 1.300€ or 40€ per kilowatt. However, since a one-family home usually needs a heat pump of about 10 kilowatts (Vattenfall, n.d.), the minimum refund is relevant. Multiplied by 0,75 the refund is 975€.

The subsidy is introduced via a STEP function that starts in 2015.
The unit is € per house.
MAP_support_old_mfh_1 = STEP(MIN(0,12*total_hp_price_old_mfh; 6432); 2008) - STEP(MIN(0,12*total_hp_price_old_mfh; 6432); 20015)
UNITS: €/house
DOCUMENT: Since 2008 the Marktanreizprogramm (MAP), a subsidy programme of the German government, also supports the installation of heat pumps. According to Platt et al. (2010, pp. 58–60) until 2010 69% of the applications did get support. The exact sum differs depending on the type of heat pump installed and the size of the building.

For existing MFH, the refund depends on the size of the living space. MAP pays between 10€ and 20€ per square meter, or a maximum of 10 or 15% of the investment costs depending on the type of heat pump. Therefore assuming 12€ per square meter and based on the average 80 square meters per housing unit (Statistisches Bundesamt (Destatis), 2021) in an MFH and an average of 6,7 housing units, a refund of 6.432€ can be expected.

The subsidy is introduced via a STEP function that starts in 2008. The caps for the refund amount are enforced by using a MIN function, and a maximum of 12%.

The unit is € per house
MAP_support_old_mfh_2 = STEP(1600; 2015)
UNITS: €/house
DOCUMENT: In 2015 the MAP subsidies were changed; they are now dependent on the power of the heat pump in kilowatts. There are different subsidies available depending on the type of heat pump (Bundesamt für Wirtschaft und Ausfuhrkontrolle, 2019). For simplification, I choose to work with the "Basisförderung" (base subsidy) for the air-to-water heat pump if possible. The air-to-water heat pump is the most common type of heat pump in Germany and the other possible type of subsidy, "Innovationsförderung" (innovation subsidy), has higher requirements and is therefore less likely to be applied.

For existing buildings, the base subsidy has a minimum refund of 1.300€ or 40€ per kilowatt. Assuming an average MFH needs 40 kilowatts (number derivates from Reiche (2023)), the refund would be 1.600€.

The subsidy is introduced via a STEP function that starts in 2015.
The unit is € per house.
MAP_support_old_stfh_1 = STEP(2160; 2008)
UNITS: €/house
DOCUMENT: Since 2008 the Marktanreizprogramm (MAP), a subsidy programme of the German government, also supports the installation of heat pumps. According to Platt et al. (2010, pp. 58–60) until 2010 69% of the applications did get support. The exact sum differs depending on the type of heat pump installed and the size of the building.

For existing STFH, the refund depends on the size of the living space. MAP pays between 10€ and 20€ per square meter, or a maximum of 3.000€ per housing unit. Therefore assuming 12€ per square meter and based on the average 150 square meters per housing unit (Statistisches Bundesamt (Destatis), 2021) in an STFH and an average of 1,2 housing units, a refund of 2160 can be expected.

The subsidy is introduced via a STEP function that starts in 2008.

The unit is € per house
MAP_support_old_stfh_2 = STEP(1300; 2015)
UNITS: €/house
DOCUMENT: In 2015 the MAP subsidies were changed; they are now dependent on the power of the heat pump in kilowatts. There are different subsidies available depending on the type of heat pump (Bundesamt für Wirtschaft und Ausfuhrkontrolle, 2019). For simplification, I choose to work with the "Basisförderung" (base subsidy) for the air-to-water heat pump if possible. The air-to-water heat pump is the most common type of heat pump in Germany and the other possible type of subsidy, "Innovationsförderung" (innovation subsidy), has higher requirements and is therefore less likely to be applied.

For existing buildings, the base subsidy has a minimum refund of 1.300€ or 40€ per kilowatt. However, since a one-family home usually needs a heat pump of about 10 kilowatts (Vattenfall, n.d.), the minimum refund is relevant.

The subsidy is introduced via a STEP function that starts in 2015.
The unit is € per house.
Maximum_capacity_per_hp_installer = 5
UNITS: heater/person/year
DOCUMENT: The maximum capacity per hp installer represents the maximum number of heat pumps one installer can install in a year. The number 5 is the result of calibration.

This number appears very small but is important to notice that it is an average value, that includes installers who do not install heat pumps at all because they specialize on other tasks. Additionally, usually installers work in teams to install heat pumps.

The unit is heater per person per year.
maximum_early_exchange_fraction = 0,15
UNITS: dmnl/year
DOCUMENT: This parameter represents the maximum fraction of fossil heater owners (STFH) each year that are considering scrapping their still-working fossil heater in the third part of its lifespan to install a heat-pump instead.

The unit is dimensionless per year.
maximum_price_per_installation = 5500
UNITS: €/heater
DOCUMENT: Maximum price per installation that has to be paid if the pressure is at the maximum (1). The parameter is an approximation based on data from Platt et al. (2010). The unit is Euro per heater.
mfh_aging_time_3 = 30
UNITS: years
mfh_aging_time_4 = 30
UNITS: years
mfh_buildings_with_district_heating = apartments_with_district_heating/housing_units_per_mfh
UNITS: house
DOCUMENT: Number of multi-family home buildings with district heating is calculated by dividing the apartments with district heating by the number of housing units per mfh. This is based on the simplification, that only mfh buildings have district heating and no stfh buildings. In reality, district heating is more prevalent in mfh buildings, but not exclusive to it. It is also calculated this way, since there is only data available on apartment level but not building level.

The unit is house.
mfh_demol_calibration = 0,2
UNITS: dmnl
mfh_demolition_fraction = 0,0006
UNITS: dmnl/year
DOCUMENT: Average estimated demolition fraction calculated from historic data from Destatis 2023.

The unit is dimensionless per year.
mfh_heater_sales_first_year = 100
UNITS: heater
mfh_new_construction_without_district_heating = mfh_new_constructions-mfh_new_constructions_with_district_heating
UNITS: house/year
DOCUMENT: Number of new mfh per year that are not heated with district heating, calculated by substracting the number of new mfh with distrcit heating from the total new mfh.

The units is house per year.
mfh_new_constructions_with_district_heating = (Rate_of_apartments_with_district_heating*(stfh_new_constructions*housing_units_per_stfh+mfh_new_constructions*housing_units_per_mfh)) /housing_units_per_mfh
UNITS: house/year
DOCUMENT: Number of multi-family buildings constructed per year that are heated with district heating is calculated by calculating the number of new apartments heated with district heating, based on the number of new apartments and the rate of apartments with district heating and dividing the result by the number of apartments per mfh. It is calculated this way due to the simplification, that all district heating occurs in mfh buildings, not stfh.

The unit is house per year.
minimum_price_per_installation = 1000
UNITS: €/heater
DOCUMENT: A minimum price was added to the model after extreme condition tests. It is an assumption and should reflect the price when the demand is at its lowest which reduces the price, however, it is supposed to be still high enough to cover work and material costs.

The unit is Euro per heater.
missing_heaters_in_mfh = MAX(0; necessary_heaters_in_mfh-existing_heaters_in_mfh)
UNITS: heater
DOCUMENT: Missing heaters are calculated by subtracting the number of existing heaters from the necessary heaters in mfh. Missing heaters represent the number of new heaters that are needed for all mfh to have sufficient heating units.

The unit is heaters.
missing_heaters_in_stfh = MAX(0; necessary_heaters_in_stfh-existing_heaters_in_stfh)
UNITS: heater
DOCUMENT: Missing heaters are calculated by subtracting the number of existing heaters from the necessary heaters. Missing heaters represent the number of new heaters that are needed for all stfh to have sufficient heating units.

The unit is heaters.
necessary_heaters_in_mfh = (total_MFH-mfh_buildings_with_district_heating)*heater_per_mfh
UNITS: heater
DOCUMENT: Necessary heaters in mfh is the total number of heaters that are necessary to heat all mfh, depending on the total number of stfh and the heater per mfh. It represents the number of heaters that should be installed in mfh after accounting for buildings that are heated with district heating.

The unit is heater.
necessary_heaters_in_stfh = total_STFH*heater_per_stfh
UNITS: heater
DOCUMENT: Necessary heaters in stfh is the total number of heaters that are necessary to heat all stfh, depending on the total number of stfh and the heater per stfh. It represents the number of heaters that should be installed ins stfh, and does not account for whether they actually are or not.

The unit is heater.
new_hp_per_hp_installer = total_hp_installation_rate/hp_installers
UNITS: heater/person/year
new_mfh_per_year = IF TIME < 2024 THEN HIS_new_mfh_per_year ELSE future_new_mfh
UNITS: House/year
DOCUMENT: Number of new MFH built each year, based on historical data until 2023 and afterwards on scenarios. the unit is house per year.
new_mfh_scenario_1 = GRAPH(TIME)
Points: (2024,00, 15,000), (2024,525, 15,130), (2025,05, 15,250), (2025,575, 15,380), (2026,10, 15,500), (2026,625, 15,630), (2027,15, 15,750), (2027,675, 15,880), (2028,20, 16,000), (2028,725, 16,130), (2029,25, 16,250), (2029,775, 16,380), (2030,30, 16,500), (2030,825, 16,630), (2031,35, 16,750), (2031,875, 16,880), (2032,40, 17,000), (2032,925, 17,130), (2033,45, 17,250), (2033,975, 17,380), (2034,50, 17,500), (2035,025, 17,630), (2035,55, 17,750), (2036,075, 17,880), (2036,60, 18,000), (2037,125, 18,130), (2037,65, 18,250), (2038,175, 18,380), (2038,70, 18,500), (2039,225, 18,630), (2039,75, 18,750), (2040,275, 18,880), (2040,80, 19,000), (2041,325, 19,130), (2041,85, 19,250), (2042,375, 19,380), (2042,90, 19,500), (2043,425, 19,630), (2043,95, 19,750), (2044,475, 19,880), (2045,00, 20,000)
UNITS: House/year
new_mfh_scenario_2 = GRAPH(TIME)
Points: (2024,00, 15,000), (2024,525, 14,880), (2025,05, 14,750), (2025,575, 14,630), (2026,10, 14,500), (2026,625, 14,380), (2027,15, 14,250), (2027,675, 14,130), (2028,20, 14,000), (2028,725, 13,880), (2029,25, 13,750), (2029,775, 13,630), (2030,30, 13,500), (2030,825, 13,380), (2031,35, 13,250), (2031,875, 13,130), (2032,40, 13,000), (2032,925, 12,880), (2033,45, 12,750), (2033,975, 12,630), (2034,50, 12,500), (2035,025, 12,380), (2035,55, 12,250), (2036,075, 12,130), (2036,60, 12,000), (2037,125, 11,880), (2037,65, 11,750), (2038,175, 11,630), (2038,70, 11,500), (2039,225, 11,380), (2039,75, 11,250), (2040,275, 11,130), (2040,80,

11,000), (2041,325, 10,880), (2041,85, 10,750), (2042,375, 10,630), (2042,90, 10,500), (2043,425, 10,380), (2043,95, 10,250), (2044,475, 10,130), (2045,00, 10,000)
UNITS: House/year
new_stfh_per_year = IF TIME < 2024 THEN HIS_new_stfh_per_year ELSE future_new_stfh
UNITS: House/year
DOCUMENT: Number of new STFH built each year, based on historical data until 2023 and afterwards on scenarios.
new_stfh_scenario_1 = GRAPH(TIME)
Points: (2024,00, 89,00), (2024,525, 89,28), (2025,05, 89,55), (2025,575, 89,83), (2026,10, 90,10), (2026,625, 90,38), (2027,15, 90,65), (2027,675, 90,93), (2028,20, 91,20), (2028,725, 91,48), (2029,25, 91,75), (2029,775, 92,03), (2030,30, 92,30), (2030,825, 92,58), (2031,35, 92,85), (2031,875, 93,13), (2032,40, 93,40), (2032,925, 93,68), (2033,45, 93,95), (2033,975, 94,23), (2034,50, 94,50), (2035,025, 94,78), (2035,55, 95,05), (2036,075, 95,33), (2036,60, 95,60), (2037,125, 95,88), (2037,65, 96,15), (2038,175, 96,43), (2038,70, 96,70), (2039,225, 96,98), (2039,75, 97,25), (2040,275, 97,53), (2040,80, 97,80), (2041,325, 98,08), (2041,85, 98,35), (2042,375, 98,63), (2042,90, 98,90), (2043,425, 99,18), (2043,95, 99,45), (2044,475, 99,73), (2045,00, 100,00)
UNITS: house/year
new_stfh_scenario_2 = GRAPH(TIME)
Points: (2024,00, 89,000), (2024,525, 88,780), (2025,05, 88,550), (2025,575, 88,330), (2026,10, 88,100), (2026,625, 87,880), (2027,15, 87,650), (2027,675, 87,430), (2028,20, 87,200), (2028,725, 86,980), (2029,25, 86,750), (2029,775, 86,530), (2030,30, 86,300), (2030,825, 86,080), (2031,35, 85,850), (2031,875, 85,630), (2032,40, 85,400), (2032,925, 85,180), (2033,45, 84,950), (2033,975, 84,730), (2034,50, 84,500), (2035,025, 84,280), (2035,55, 84,050), (2036,075, 83,830), (2036,60, 83,600), (2037,125, 83,380), (2037,65, 83,150), (2038,175, 82,930), (2038,70, 82,700), (2039,225, 82,480), (2039,75, 82,250), (2040,275, 82,030), (2040,80, 81,800), (2041,325, 81,580), (2041,85, 81,350), (2042,375, 81,130), (2042,90, 80,900), (2043,425, 80,680), (2043,95, 80,450), (2044,475, 80,220), (2045,00, 80,000)
UNITS: house/year
normal_skill_gain = 0,13
UNITS: dmnl/year
DOCUMENT: Normale skill gain represents the gain of skill depending on the effect of hp installations. The number is result of calibration. The unit is dimensionless per year.
"percentage_houses_0-30" = ("STFH_0-30"+"MFH_0-30") /total_residential_buildings
UNITS: dmnl
"percentage_houses_31-60" = ("STFH_31-60"+"MFH_31-60") /total_residential_buildings
UNITS: dmnl
percentage_houses_above_61 = (STFH_above_61+MFH_above_61) /total_residential_buildings
UNITS: dmnl
percentage_of_buildings_heated_with_HP = PERCENT(Total_HP/(Total_FH+Total_HP+district_heating_connections))
UNITS: dmnl
Percentage_of_housing_units_heated_with_HP = PERCENT(housing_units_heated_by_heat_pumps/total_housing_units)
UNITS: dmnl
DOCUMENT: The percentage of housing units heated with heat pumps is important because it is needed for comparison with the reference mode. This variable is influenced by the number of heat pumps in MFHs and STFHs and also shows the ratio of heat pumps used in different building types.
percentage_of_HP = PERCENT(Total_HP/(Total_HP+Total_FH))
UNITS: dmnl
percentage_of_hp_in_MFH = PERCENT(HP_MFH_total/(HP_MFH_total+FH_MFH_total+district_heating_connections))
UNITS: dmnl
percentage_of_hp_in_STFH = PERCENT(HP_STFH_total/(HP_STFH_total+FH_STFH_total))
UNITS: dmnl
percentage_of_hp_installation_in_old_buildings = PERCENT(hp_installation_in_old_buildings/(hp_installation_in_old_buildings+fh_installation_in_old_buildings))
UNITS: dmnl
percentage_of_hp_installations_in_stfh = PERCENT(hp_installation_rate_in_stfh/(hp_installation_rate_in_stfh+total_fh_installation_in_stfh))
UNITS: dmnl

percentage_of_hp_installtion_in_new_buildings = PERCENT(hp_installation_in_new_buildings/(hp_installation_in_new_buildings+fh_installation_rate_in_new_buildings))
UNITS: dmnl
Percentage_of_installers_with_hp_training = PERCENT(hp_installers/installers_total)
UNITS: dmnl
DOCUMENT: Percentage of installers that know how to install heat pumps.
percentage_of_total_yearly_hp_installations = PERCENT(total_yearly_hp_installation/(total_yearly_hp_installation+total_yearly_fh_installation))
UNITS: dmnl
price_attract_hp_new_stfh = MIN(1; income_to_price_relation_hp_new_stfh//income_to_price_relation_gas_heater)
UNITS: dmnl
DOCUMENT: The price attractiveness for heat pumps in new STFH is calculated by dividing the 'income to price relation hp new stfh' by the 'income to price relation gas heater' and using a MAX function. The max function stops the value from going beyond 1. The higher the value, the higher the attractiveness, a value of 1 means that a heat pump has the same or better relation to income than a gas heater.

The variable only changes up until the point were heat pumps are as affordable as gas heaters, since they are cheaper in operation it is assumed that at this point the maximum attractiveness is reached.

The unit is dimensionless.
price_attract_hp_old_stfh = MIN(1; income_to_price_relation_hp_old_stfh//income_to_price_relation_gas_heater)
UNITS: dmnl
DOCUMENT: The price attractiveness for heat pumps in old STFH is calculated by dividing the 'income to price relation hp old stfh' by the 'income to price relation gas heater' and using a MAX function. The max function stops the value from going beyond 1. The higher the value, the higher the attractiveness, a value of 1 means that a heat pump has the same or better relation to income than a gas heater.

The variable only changes up until the point were heat pumps are as affordable as gas heaters, since they are cheaper in operation it is assumed that at this point the maximum attractiveness is reached.

The unit is dimensionless.
price_attractiveness_new_mfh = IF TIME > 2025 AND SWITCH_subsidies = 1 THEN MIN(1; gas_heater_for_mfh/total_hp_price_new_mfh) ELSE MIN(1; gas_heater_for_mfh/after_subsidies_hp_costs_new_mfh)
UNITS: dmnl
DOCUMENT: The price attractiveness for heat pumps in new MFH is calculated by dividing the 'after subsidies hp costs new mfh' by 'gas heater for mfh' and using a MAX function. The max function stops the value from going beyond 1. The higher the value, the higher the attractiveness, a value of 1 means that the heat pump has the same costs as a gas heater.

The variable only changes up until the point were heat pumps are as affordable as gas heaters, since they are cheaper in operation it is assumed that at this point the maximum attractiveness is reached. In contrast to the price attractiveness for STFH, costs are compared directly and not in relation to income, since the owners of MHFs are often landlords or developers.

Depending on the chosen scenario after 2024 either the costs with or without subsidies are considered.

The unit is dimensionless.
price_attractiveness_old_mfh = MIN(1; gas_heater_for_mfh/hp_device_plus_renovation_mfh)
UNITS: dmnl
DOCUMENT: The price attractiveness for heat pumps in old MFH is calculated by dividing the 'hp device plus renovation mfh' by 'gas heater for mfh' and using a MAX function. The max function stops the value from going beyond 1. The higher the value, the higher the attractiveness, a value of 1 means that the heat pump has the same costs as a gas heater.

The variable only changes up until the point were heat pumps are as affordable as gas heaters, since they are cheaper in operation it is assumed that at this point the maximum attractiveness is reached. In contrast to the price attractiveness for STFH, costs are compared directly and not in relation to income, since the owners of MHFs are often landlords or developers.

The unit is dimensionless.
probabilty_hp_new_mfh = GRAPH(attractiveness_of_hp_in_new_mfh)
Points: (0,0000, 0,000), (0,0800, 0,01263), (0,1600, 0,04341), (0,2400, 0,1165), (0,3200, 0,2676), (0,4000, 0,500), (0,4800, 0,7324), (0,5600, 0,8835), (0,6400, 0,9566), (0,7200, 0,9874), (0,8000, 1,000)
UNITS: dmnl
DOCUMENT: The probability of choosing a heat pump is based on the attractiveness of heat pumps (for that specific building type). The attractiveness is translated into a probability via a graphical function. The graphical function is an S-curve that goes from 0 to 1. 1 representing 100% probability of choosing heat pumps. The curve reaches 1 at an attractiveness of 0,8. This is based on the assumption that full attractiveness cannot realistically be reached, the exact number is based on hand calibration. The shape is based on an assumption.

The unit is dimensionless.
probabilty_hp_new_stfh = GRAPH(attractiveness_of_hp_in_new_stfh)
Points: (0,0000, 0,000), (0,0800, 0,02248), (0,1600, 0,06725), (0,2400, 0,1536), (0,3200, 0,3005), (0,4000, 0,500), (0,4800, 0,6995), (0,5600, 0,8464), (0,6400, 0,9327), (0,7200, 0,9775), (0,8000, 1,000)
UNITS: dmnl
DOCUMENT: The probability of choosing a heat pump is based on the attractiveness of heat pumps (for that specific building type). The attractiveness is translated into a probability via a graphical function. The graphical function is an S-curve that goes from 0 to 1. 1 representing 100% probability of choosing heat pumps. The curve reaches 1 at an attractiveness of 0,8. This is based on the assumption that full attractiveness cannot realistically be reached, the exact number is based on hand calibration. The shape is based on an assumption.

The unit is dimensionless.
probabilty_hp_old_mfh = GRAPH(attractiveness_of_hp_in_existing_mfh)
Points: (0,1500, 0,000), (0,2150, 0,02996), (0,2800, 0,08349), (0,3450, 0,1758), (0,4100, 0,3182), (0,4750, 0,500), (0,5400, 0,6818), (0,6050, 0,8242), (0,6700, 0,9165), (0,7350, 0,970), (0,8000, 1,000)
UNITS: dmnl
DOCUMENT: The probability of choosing a heat pump is based on the attractiveness of heat pumps (for that specific building type). The attractiveness is translated into a probability via a graphical function. The graphical function is an S-curve that goes from 0 to 1. 1 representing 100% probability of choosing heat pumps. The curve curve start increasing at 0,15 and reaches 1 at an attractiveness of 0,8. This is based on the assumption that full attractiveness cannot realistically be reached, the exact number is based on hand calibration. Additionally, due to the early adopters stage MFH are in, it is assumed that MFH owners shy away from heat pumps until they reach a higher attractiveness level. The shape is based on an assumption.

The unit is dimensionless.
probabilty_hp_old_stfh = GRAPH(attractiveness_of_hp_in_existing_stfh)
Points: (0,0000, 0,000), (0,0800, 0,02478), (0,1600, 0,07238), (0,2400, 0,1608), (0,3200, 0,3064), (0,4000, 0,500), (0,4800, 0,6936), (0,5600, 0,8392), (0,6400, 0,9276), (0,7200, 0,9752), (0,8000, 1,000)
UNITS: dmnl
DOCUMENT: The probability of choosing a heat pump is based on the attractiveness of heat pumps (for that specific building type). The attractiveness is translated into a probability via a graphical function. The graphical function is an S-curve that goes from 0 to 1. 1 representing 100% probability of choosing heat pumps. The curve reaches 1 at an attractiveness of 0,8. This is based on the assumption that full attractiveness cannot realistically be reached, the exact number is based on hand calibration. The shape is based on an assumption.

The unit is dimensionless.
Rate_of_apartments_with_district_heating = 0,13
UNITS: dmnl
DOCUMENT: rate of apartments that are heated using heat pumps. Based on historical data. Assumption is that the number does not increase (despite slight increase from 2005 to 2022)

In this model it is assumed that
rate_of_fh_age_one = 0,33
UNITS: dmnl
rate_of_fh_age_one_1 = 0,33
UNITS: dmnl
rate_of_fh_age_three = (1-rate_of_fh_age_one)*fh_age_relative_distribution

UNITS: dmnl
rate_of_fh_age_three_1 = (1-rate_of_fh_age_one_1)*relative_distribution_1
UNITS: dmnl
rate_of_fh_age_two = (1-rate_of_fh_age_one)*(1-fh_age_relative_distribution)
UNITS: dmnl
rate_of_fh_age_two_1 = (1-rate_of_fh_age_one_1)*(1-relative_distribution_1)
UNITS: dmnl
real_gas_heater_price_stfh = gas_heater_price_2020*CPI*heater_per_stfh
UNITS: €/house
real_heat_pump_device_price_mfh = IF TIME >2025 AND SWITCH_HP_price = 1 THEN heat_pump_device_price_mfh*CPI ELSE heat_pump_device_price_mfh
UNITS: €/heater
DOCUMENT: The heat pump device either as it is in the parameter, or if the Switch HP price is activated (=1) and it is after 2025 multiplied by the CPI.

The price is Euro per heater.
real_heat_pump_device_price_stfh = IF TIME >2025 AND SWITCH_HP_price = 1 THEN heat_pump_device_price_stfh*CPI ELSE heat_pump_device_price_stfh
UNITS: €/heater
DOCUMENT: The heat pump device either as it is in the parameter, or if the Switch HP price is activated (=1) and it is after 2025 multiplied by the CPI.

The price is Euro per heater.
real_minimum_price_per_installation = minimum_price_per_installation*CPI
UNITS: €/heater
DOCUMENT: Minimum price per installation after considering the CPI.

The unit is Euro per Heater.
real_normal_price_per_installation = maximum_price_per_installation*CPI
UNITS: €/heater
DOCUMENT: Maximum price per installation after considering the CPI.

The unit is Euro per Heater.
relative_distribution_1 = 0,5
UNITS: dmnl
renovation_costs_mfh = IF SWITCH_subsidies AND TIME > 2025 THEN average_renovation_costs*CPI*additional_effort_renovation_mfh - 0,1*average_renovation_costs*CPI*additional_effort_renovation_mfh ELSE average_renovation_costs*CPI*additional_effort_renovation_mfh
UNITS: €/house
DOCUMENT: The renovation costs for MFH are calculated by multiplying the average renovation costs with the additional effort of renovation for mfh. and CPI
If Policy 2 is activated (Switch subsidies = 2) the renovation costs are reduced by 10%.

The unit is € per house.
renovation_price_stfh = IF SWITCH_subsidies AND TIME > 2025 THEN average_renovation_costs*CPI-0,1*average_renovation_costs*CPI ELSE average_renovation_costs*CPI
UNITS: €/house
DOCUMENT: The renovation costs for STFH are based on the average renovation costs and CPI.
If Policy 2 is activated (Switch subsidies = 2) the renovation costs are reduced by 10%.

The unit is € per house.
request_ratio_to_pressure_translation = GRAPH(installer_capacity_to_request_ratio)
Points: (0,000, 0,000), (0,200, 0,100), (0,400, 0,200), (0,600, 0,300), (0,800, 0,400), (1,000, 0,500), (1,200, 0,600), (1,400, 0,700), (1,600, 0,800), (1,800, 0,900), (2,000, 1,000)
UNITS: dmnl
DOCUMENT: The request ratio to pressure translation is a graphical function and can vary between 0 and 1, it becomes higher the higher the ratio of request to available capacity is and reaches its maximum of 1 if there are two times as many requests for hp installations as there is capacity.
The unit is dimensionless.

scrapping_heaters = fh_scrapping_through_demolition_1 + fh_scrapping_through_demolition_2 + fh_scrapping_through_demolition_3 + hp_scrapping_through_demolition_1 + hp_scrapping_through_demolition_2
UNITS: heater/year
skill_loss_over_time = 3,5
UNITS: Years
DOCUMENT: Parameter represents the average time it takes to forget acquired skill about heat pump installation. The number is an assumption. The unit is year.
stfh_aging_time_1 = 30
UNITS: years
stfh_aging_time_2 = 30
UNITS: years
stfh_demol_calibration = 0,2
UNITS: dmnl
stfh_demolition_fraction = 0,0003
UNITS: dmnl/year
DOCUMENT: The parameter is an approximation based on data from Destatis 2023.

The unit is dimensionless per year.
stfh_heater_sales_first_year = 500
UNITS: heater
SWITCH_apprentices = 1
UNITS: dmnl
SWITCH_capacity = 1
UNITS: dmnl
DOCUMENT: The Switch capacity was created for testing the influence of the capacity of installers on the model. When the Switch is activated (=1) the capacity limits the number of installations. If it is not activated the desired hp installations will all be conducted without limitation, but the capacity still influences other areas such as costs of installation.

The unit is dimensionless.
SWITCH_economy = 1
UNITS: dmnl
DOCUMENT: The switch summaries different future developments to 3 coherent scenarios:

0 = Baseline
1= Strong economy
2= Weak economy
SWITCH_gas_scenario = 1
UNITS: dmnl
SWITCH_heater_lifetime = 0
UNITS: dmnl
DOCUMENT: Heater lifetime:

0= BAU: Stays the same as 2024
1 = Policy 1: Heater lifetime decreases after 2025
SWITCH_HP_price = 0
UNITS: dmnl
DOCUMENT: Controls scenarios for the future HP device price

0 = Stable at 12500 € per heater for stfh and 30.000€ per heater for mfh.
1 = Increases according to CPI.
The unit is dimensionless.
SWITCH_subsidies = 2
UNITS: dmnl
DOCUMENT: Subsidies:

0 =BAU: Subsidies continue
1 =Test: Subsidies are decontinued
2 =Policy2: Additional subsidies for renovation
time_to_install = 1

UNITS: year
DOCUMENT: The installation time is assumed to be one year for simplification reasons.
time_to_register_pressure = 1
UNITS: year
DOCUMENT: Time to register pressure represents an information delay that is assumed since a change takes time to be noticed. This delay could be caused due to the fragmentation of the market into many small workshops. The number is an assumption. The unit is year.
total_desired_hp = desired_hp_in_existing_buildings_per_year+desired_hp_in_new_buildings+desired_early_exchange_stfh
UNITS: heater/year
DOCUMENT: Total number of desired hp installations, including all building types and early exchanges. The unit is heater per year.
total_desired_hp_in_MFH = desired_hp_in_new_mfh+desired_hp_in_existing_mfh_per_year
UNITS: heater/year
total_desired_hp_in_STFH = desired_hp_in_new_stfh+desired_early_exchange_stfh+desired_hp_in_existing_stfh_per_year
UNITS: heater/year
total_existing_heaters = Total_HP+Total_FH
UNITS: heater
Total_FH = FH_STFH_total+FH_MFH_total
UNITS: heater
DOCUMENT: Total number of fossil heaters (gas and oil) currently in use in MFH and STFH. Calculated by totalling the fossil heater in MFH and STFH.

The unit is heater.
total_fh_installation_in_mfh = desired_fh_in_new_mfh+desired_fh_in_existing_mfh
UNITS: heater/year
DOCUMENT: Total number of fh installations per year in mfh.
total_fh_installation_in_stfh = desired_fh_in_new_stfh+desired_fh_in_existing_stfh
UNITS: heater/year
DOCUMENT: Total number of fh installations per year in stfh.
total_fh_installation_rate = fh_installation_rate_stfh+fh_installation_rate_mfh
UNITS: heater/year
total_heaters_in_mfh = HP_MFH_total+FH_MFH_total+district_heating_connections
UNITS: heater
total_heaters_in_stfh = HP_STFH_total+FH_STFH_total
UNITS: heater
"total_houses_0-30" = "MFH_0-30"+"STFH_0-30"
UNITS: house
"total_houses_31-60" = "STFH_31-60"+"MFH_31-60"
UNITS: house
total_houses_above_61 = MFH_above_61+STFH_above_61
UNITS: house
total_housing_units = housing_units_in_stfh+housing_units_in_mfh
UNITS: housing unit
DOCUMENT: Sums up all housing units in stfh and mfh (apartments and housing units per stfh). It is used to calculate the percentage of housing units heated by heat pumps.

The unit is housing unit.
Total_HP = HP_STFH_total+HP_MFH_total
UNITS: heater
DOCUMENT: Total number of heat pumps currently in use in MFH and STFH. Calculated by totalling the heat pumps in MFH and STFH.

The unit is heater.
total_hp_installation_rate = total_hp_installation_rate_stfh+new_hp_mfh
UNITS: heater/year
DOCUMENT: Summarizes all HP installations per year in STFH and MFH.

The unit is heater per year.

total_hp_installation_rate_stfh = hp_installation_rate_new_stfh+hp_installation_rate_old_stfh_without_early_exch+early_exchange_stfh
UNITS: heater/year
DOCUMENT: Total number of yearly HP installations, including the installation in new buildings, the regular installations in old buildings and the early exchange in old buildings.

The unit is heater per year.
total_hp_price_new_mfh = (real_heat_pump_device_price_mfh+installation_price_new_mfh)*heater_per_mfh
UNITS: €/house
DOCUMENT: The cost for one installed hp in a new mfh, it consist of the installation costs and the price for the device multiplied by the number of heaters needed per mfh.

The unit is Euro per house.
total_hp_price_new_stfh = (installation_price_new_construction_stfh+real_heat_pump_device_price_stfh)*heater_per_stfh
UNITS: €/house
DOCUMENT: The cost for one installed hp in a new stfh, it consist of the installation costs and the price for the device multiplied by the number of heaters needed per stfh.

The unit is Euro per house.
total_hp_price_old_mfh = (real_heat_pump_device_price_mfh+installation_price_existing_mfh)*heater_per_mfh
UNITS: €/house
DOCUMENT: The cost for one installed hp in an old mfh, it consist of the installation costs and the price for the device multiplied by the number of heaters needed per mfh.

The unit is Euro per house.
total_hp_price_old_stfh = (installation_price_existing_stfh+real_heat_pump_device_price_stfh)*heater_per_stfh
UNITS: €/house
DOCUMENT: The cost for one installed hp in a old stfh, it consist of the installation costs and the price for the device multiplied by the number of heaters needed per stfh.

The unit is Euro per house.
total_MFH = "MFH_0-30" + "MFH_31-60" + MFH_above_61
UNITS: house
total_mfh_with_heating = district_heating_connections+total_heaters_in_mfh
UNITS: heater
total_residential_buildings = total_STFH+total_MFH
UNITS: house
total_STFH = "STFH_0-30" + "STFH_31-60" + STFH_above_61
UNITS: house
DOCUMENT: Sum of STFHs of all ages (summary of the three stocks containing STFHs).

the unit is house.
total_yearly_fh_installation = fh_installation_rate_in_new_buildings+fh_installation_in_old_buildings
UNITS: heater/year
total_yearly_heater_installation = total_yearly_hp_installation+total_yearly_fh_installation
UNITS: heater/year
DOCUMENT: Total number of yearly heater installations, all heaters and all building types.
total_yearly_hp_installation = hp_installation_in_new_buildings+hp_installation_in_old_buildings
UNITS: heater/year
trending_time = 10
UNITS: year
unskilled_labour_share = 0,15
UNITS: dmnl
DOCUMENT: To keep a reasonable ratio between skilled and unskilled workers it is assumed that the hiring is in a ratio ('unskilled labour share') to the training of employees. The variable represents the ratio. The exact ratio is an assumption.

The unit is dimensionless.
willingness_for_further_training = 0,3

UNITS: dmnl/year
DOCUMENT: It represents the ratio of installers without training for HP installation that is willing to consider training when customers request HP installations. The number is an assumption.

The unit is dimensionless per year.
working_life_1 = duration_working_life/2
UNITS: years
DOCUMENT: The first half of the working life, is calculated by dividing 'duration working life' by two.

The unit is years.
working_life_2 = duration_working_life/2
UNITS: years
DOCUMENT: The second half of the working life, is calculated by dividing 'duration working life' by two.

The unit is years.
yearly_mfh_demolition = total_MFH*mfh_demolition_fraction
UNITS: house/year
DOCUMENT: The yearly demolition rate is calculated by multiplying the total number MFHs by the mfh demolition fraction.

The unit is house per year.
yearly_stfh_demolition = total_STFH*stfh_demolition_fraction
UNITS: house/year
DOCUMENT: The yearly demolition rate is calculated by multiplying the total number STFHs by the stfh demolition fraction.

The unit is house per year.