Modeling the slow adoption of heat pumps in Germany with System Dynamics

Anna R. Siemer

System Dynamics Group, Department of Geography, University of Bergen, P.O. Box 7802, 5020 Bergen, Norway
Correspondence: anna.r.siemer@student.uib.no

International System Dynamics Conference 2024, Bergen, Norway, August 4–6.

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, heating, sustainability, innovation diffusion, energy efficiency

1. Introduction

Germany has set climate goals to protect the environment and adhere to the international Paris Agreement. This includes a reduction in emissions to minus 65% compared to 1990 until 2030, minus 88% until 2040 and becoming carbon neutral 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. One alternative way of heating is the use of heat pumps (HPs).

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), it uses a refrigerant to absorb the heat from outside, compresses it, and then releases it inside the home. 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. Combined with electricity generated from renewable sources this makes them especially environmentally friendly (Lowe, 2007).

Therefore, a fast replacement of fossil-based heating systems with heat pumps is a desirable scenario. However, the adoption of heat pumps in Germany is a slow process. Therefore, my research question is: *What factors contribute to the slow adoption of heat pumps in Germany, and what policy options can be identified to speed up the process?*

To answer this question a System Dynamics (SD) model has been developed, including different policy scenarios[1]. To develop the model, first, a literature review and an interview with an expert on heat pumps in Germany were conducted. SDs strength is the consideration of accumulation and delays and the use of feedback loops to explain behavior. 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,

[1] The model was originally developed and the paper is based on the master thesis Siemer (2024). A more detailed model description and full documentation is available there.

1969) and its various adaptions and extensions (Sultan et al., 1990). Therefore, it is well suited method to approach the given problem: the accumulation of a now unwanted heating system.

2. Historic Development

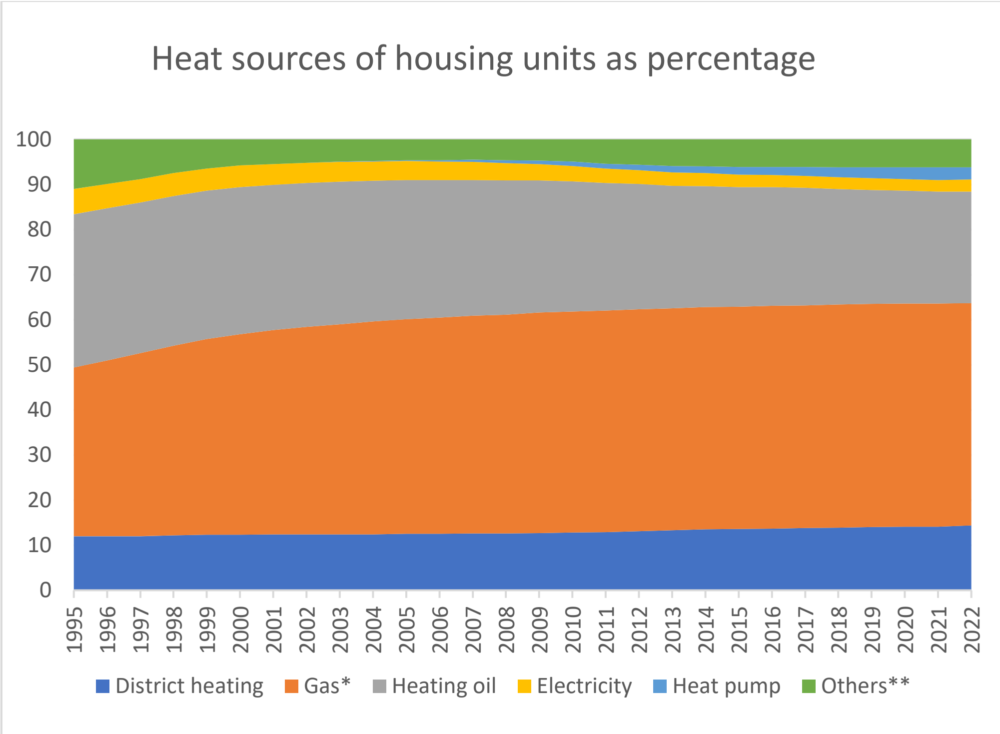


Figure 1 Heat sources of housing units in Germany in per cent. Own depiction based on data from BDEW (2023).

Figure 1[2] 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. 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). 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.

One of the reasons for the small percentage of HP-use is that per heat pump usually only one housing unit is supplied. In 2016 94% of HPs in residential buildings were installed in Single- and two-family homes (STFHs). Previously the ratio of Multifamily homes (MFHs) heated with HPs has been even lower (Born et al., 2017).

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.

Differentiated by installation in new and existing houses, as shown in Figure 3, 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 (Deutsche Energie-Agentur, 2023). 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

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

much more inconsistent compared to installations in new buildings; this includes sudden increases around 2006 and 2008, a slight drop afterward and stable, but low installation rates until 2016, and exponential growth afterward.

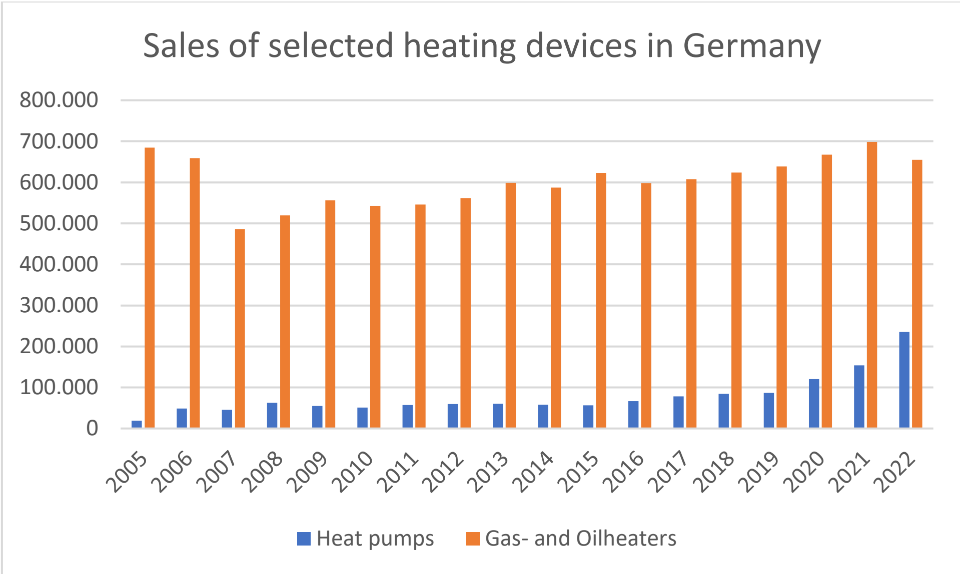


Figure 2 Total sales of selected heating devices in Germany. Own depiction based on data from Deutsche Energie-Agentur (2023).

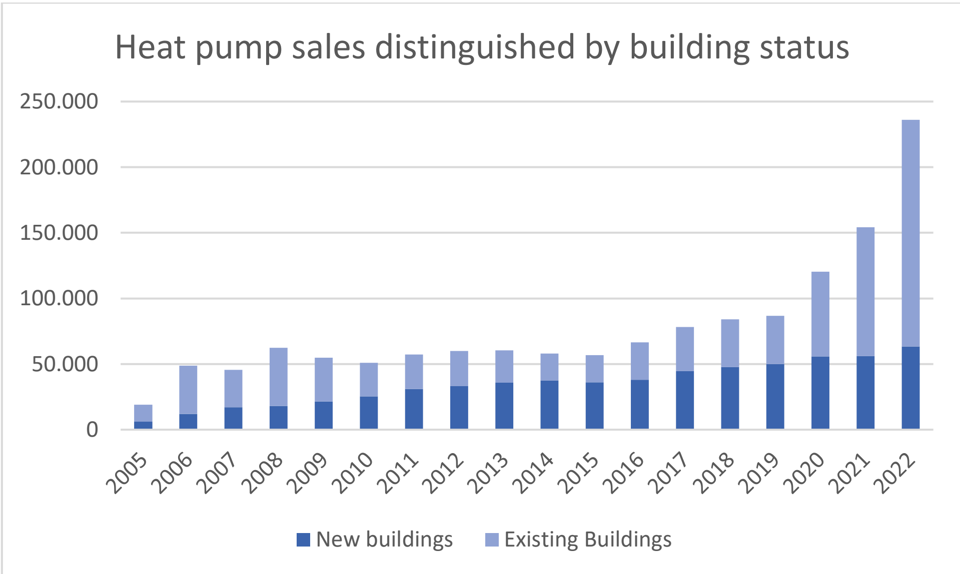


Figure 3 Heat pump sales differentiated by building type. Own depictions based on Deutsche Energie-Agentur(2023)

The steep increase in heat pump demand after 2019 led to a shortage in installation capacity, as well as device availability (Schieritz, 2023) despite the recent increase in workers in the field (Figure 4). Therefore, the uptick has the potential to be even more steep.

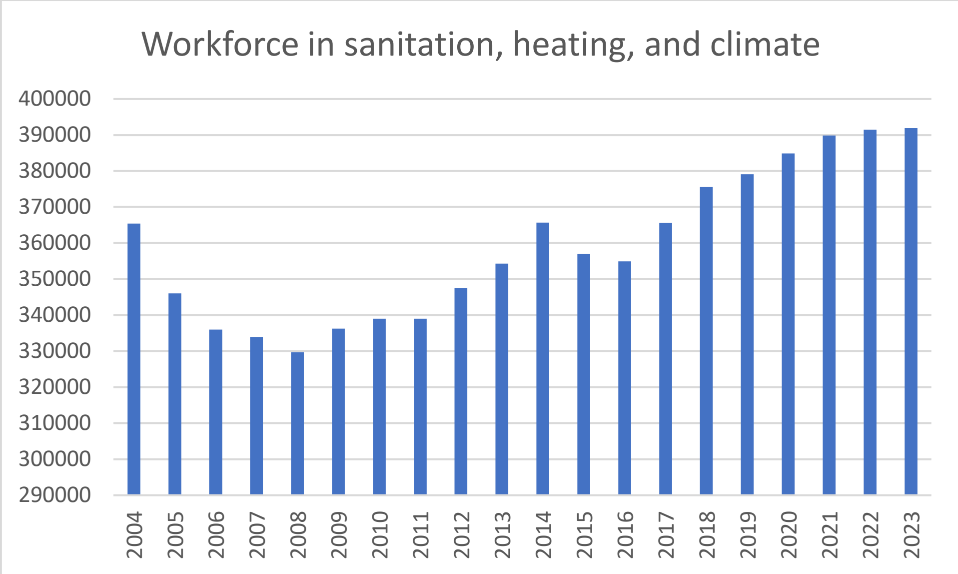


Figure 4 Number of employees in sanitation, heating, and climate. Own depiction based on Scholle (2024).

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 percent 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.

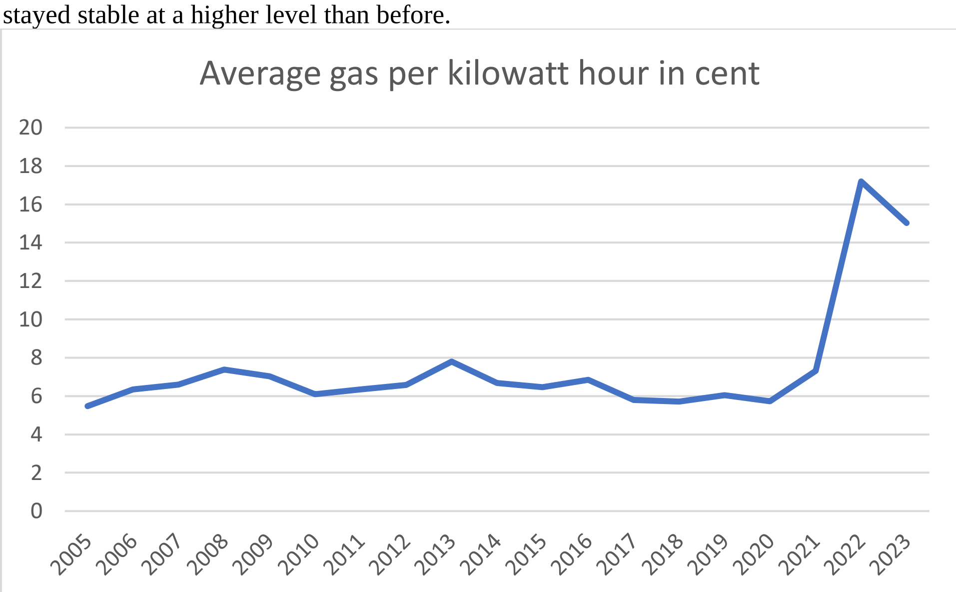


Figure 5 Development of gas price for end consumers. Own depiction based on Verivox (n.d.)

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 also play a major role. They 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.

3. Literature review

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.

3.1. Innovation Diffusion in System Dynamics

The basis for SD models on innovation diffusion is comparable to modeling 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). 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.

3.2. Motives for Energy-Efficient Renovations

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). 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 behavior. 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 criticized, 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).

3.3. Heat Pumps in MFHs

While the use of heat pumps in MFHs is technically feasible, it is not an established method and therefore lacks standardized 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 remodeling 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.

3.4. . 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).

4. 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 6 and described in the following paragraph. Not all identified feedback loops are included here, but only feedback loops that were relevant and feasible to model.

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 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.

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 demand are limiting factors for heat pump adoption and whatever is smaller, dominates the adoption rate.

R4 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.

R5 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 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.

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

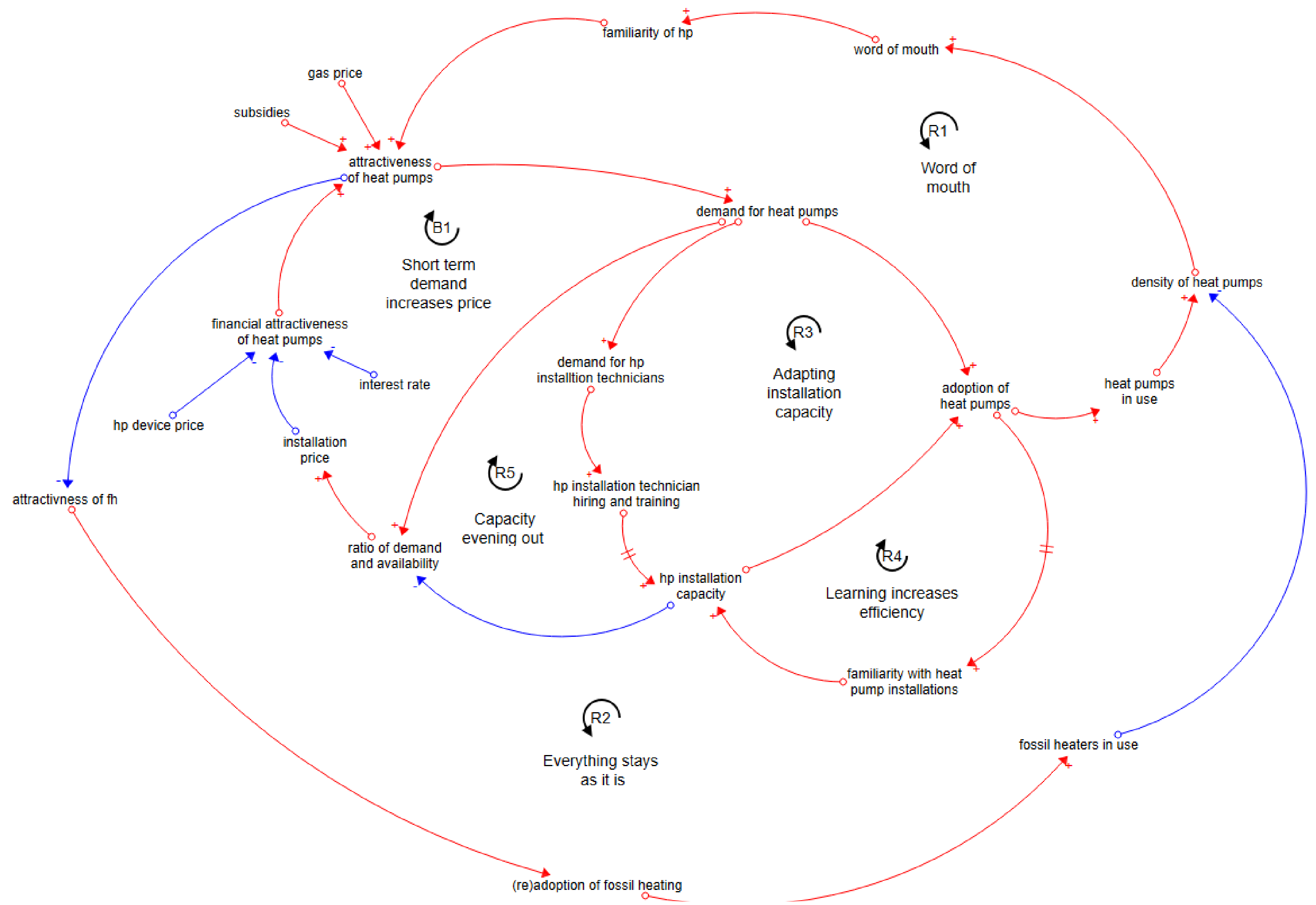


Figure 6 Causal Loop Diagram

5. Simulation Model

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 modeled separately. The model is divided into 5 sectors:

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

The first two sectors are structured very similarly: One aging chain for the building type is used to calculate the demand for heaters in old houses, while the exogenous inflow is used to calculate the demand for heaters in new houses. Additional two aging chains are modeled for the heaters, one for fossil heaters and one for heat pumps. Depending on the attractiveness value a probability is calculated to choose heat pumps or fossil heaters, that then feed into the aging chains. The existing heaters are used to calculate the density. Density, financial attractiveness, and gas price are weighted and used to calculate the attractiveness. Despite the same general structure, the attractiveness of HPs for STFH and MFH, and old and new houses, is calculated differently: a separate financial attractiveness and separate weights for the influences are used.

The sector installation capacity calculates the maximum number of installations possible per year depending on the installer that did additional schooling to do this and their experience. This maximum capacity and the demand calculated in the first two sectors than influence the financial attractiveness in sector 4, together with various exogenous variables and parameters, such as housing type and average income development.

5.1. Boundaries

The model depicts an exemplary town of 80.000 inhabitants based on average values in Germany or values of towns of a similar size. 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. For a better overview, boundaries are presented in Table 1.

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 Boundaries

6. 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.)

The structural validity is most important for model validation, 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. Afterward, the sensitivity analysis and the reference mode replication were conducted.

6.1. Model testing

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 modeling 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.

The **parameter confirmation** has been validated in the model documentation. It is available as part of the model or in Siemer (2024). 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.

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.

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.

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.

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 Overview results sensitiviyt 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 behavior. 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).

6.2. 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, and yearly fossil heater sales for old houses. The behavior replication showed to be very good for heat pumps and fossil heaters in new houses, while there are moderate deviations for the other indicators.

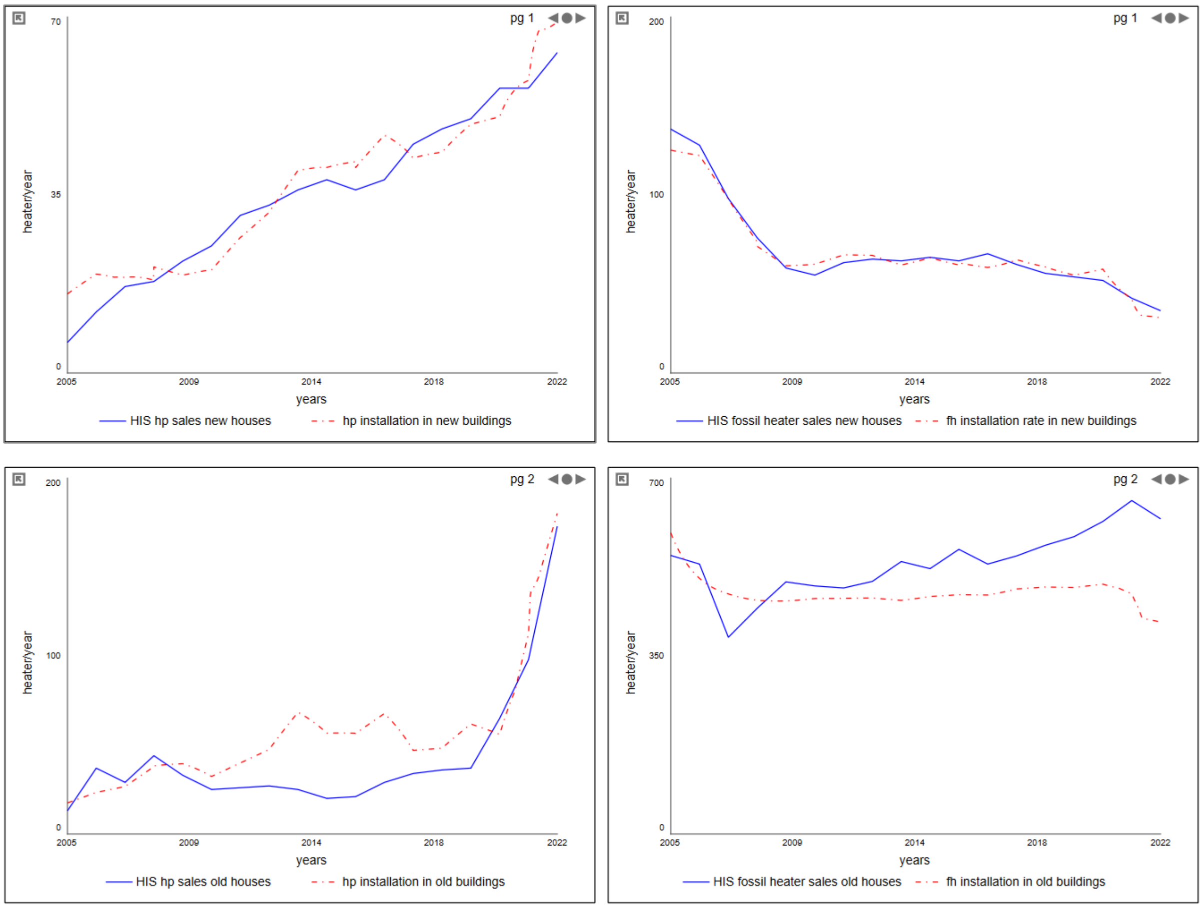


Figure 7 Behaviour replication for heater installations in new and old buildings.

Part of the difference in fit between new houses and old houses (Figure 7) 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 test of behavioral 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, 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.

7. Analysis

This section addresses the simulation of the model beyond 2023 and discusses the endogenous and exogenous influences on the system. For so far historical data-driven variables different scenarios for the future have been created. 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.

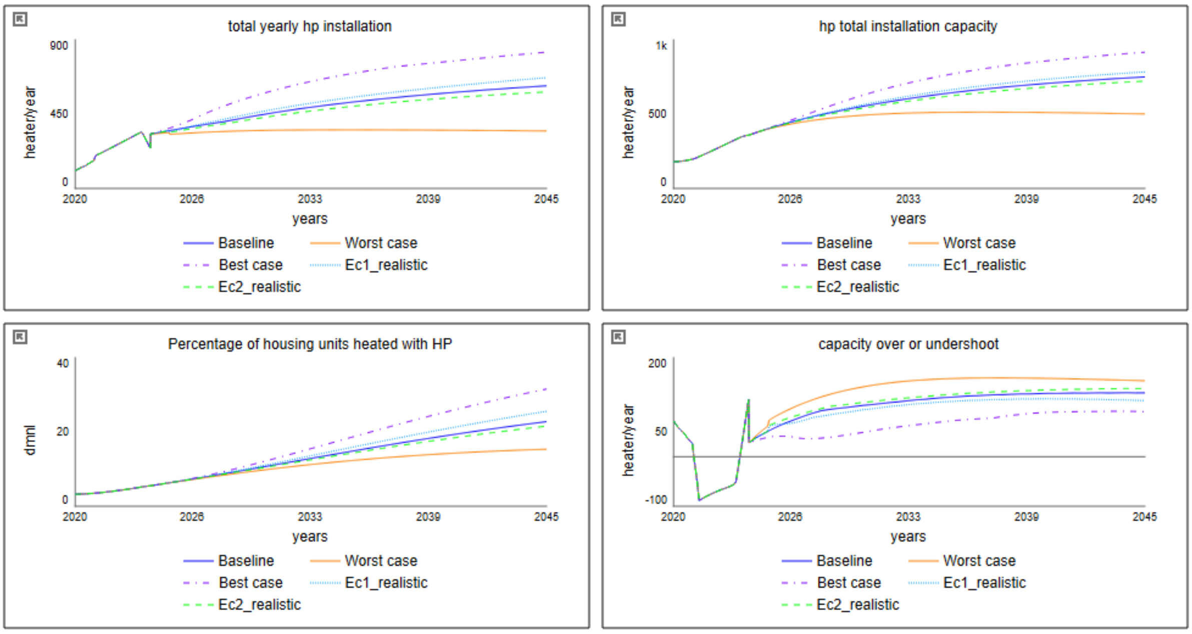


Figure 8 KPIs development for different scenarios.

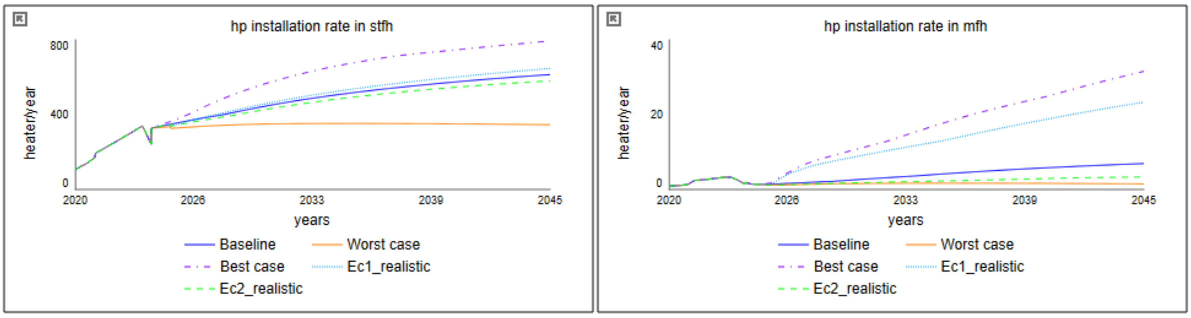


Figure 9 Differnece for STFH and MFH HP installation for different scenarios.

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 9.

8. Policies

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.

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.

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.

8.1. 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 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.

As can be seen in Figure 10 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.

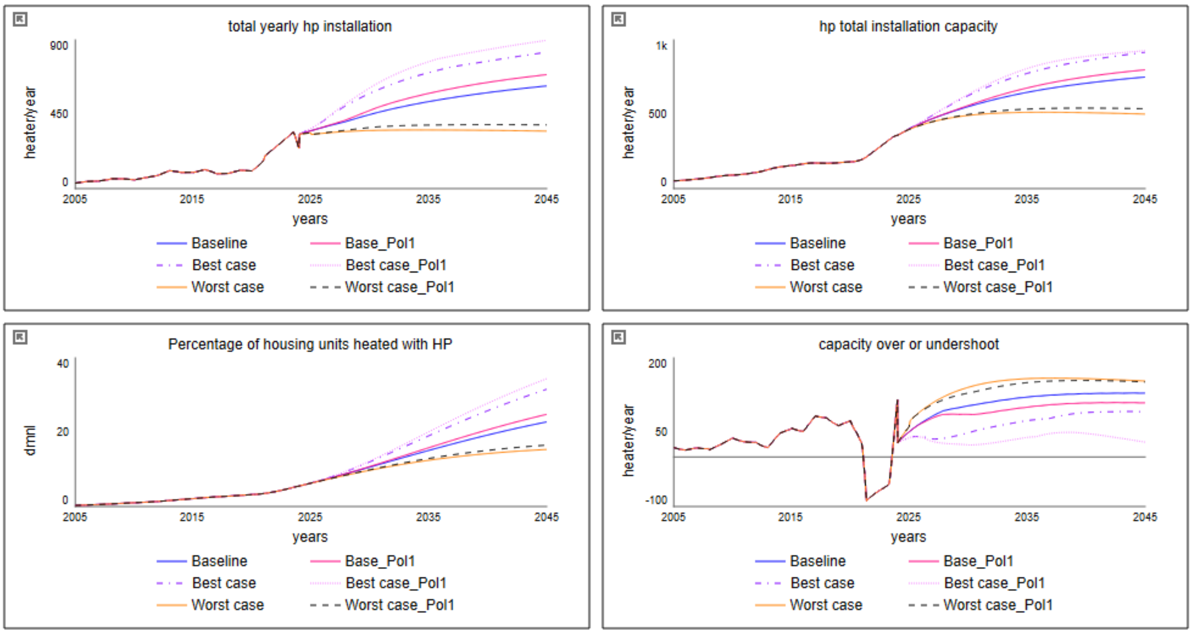


Figure 10 The influence of reducing heaters' lifespan under different circumstances.

8.2. 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 subsidizing energy-efficient renovations.

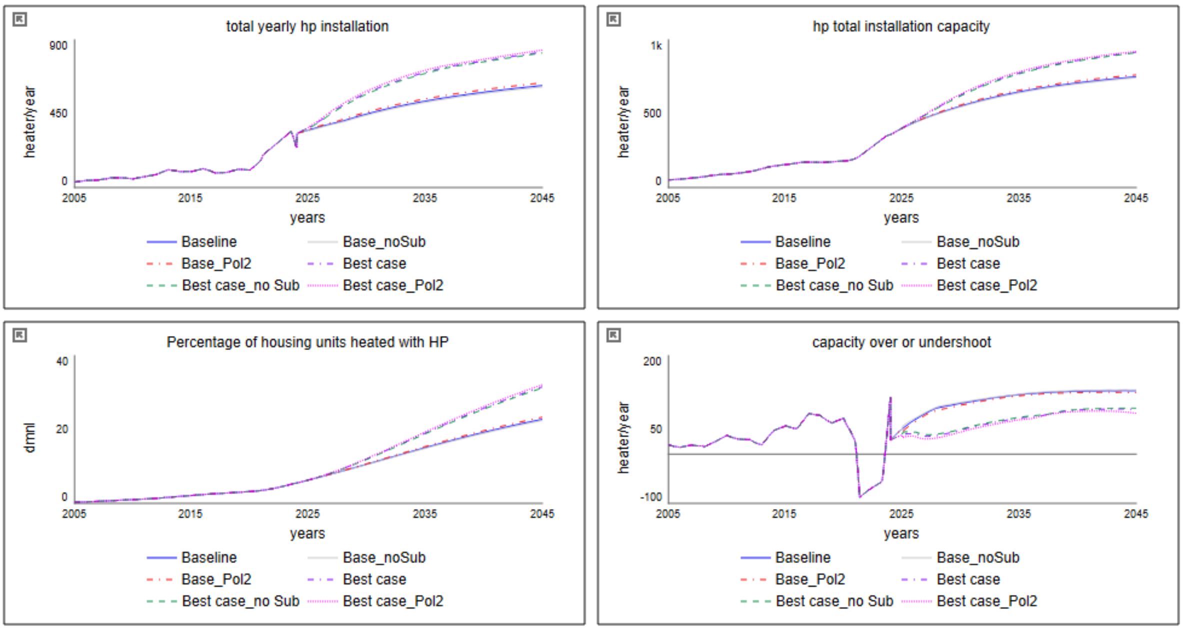


Figure 11 Influence of subsidies for best-case and baseline scenario.

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.

8.3. 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, conceptualized 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 analyzed additional scenarios with varying gas price developments.

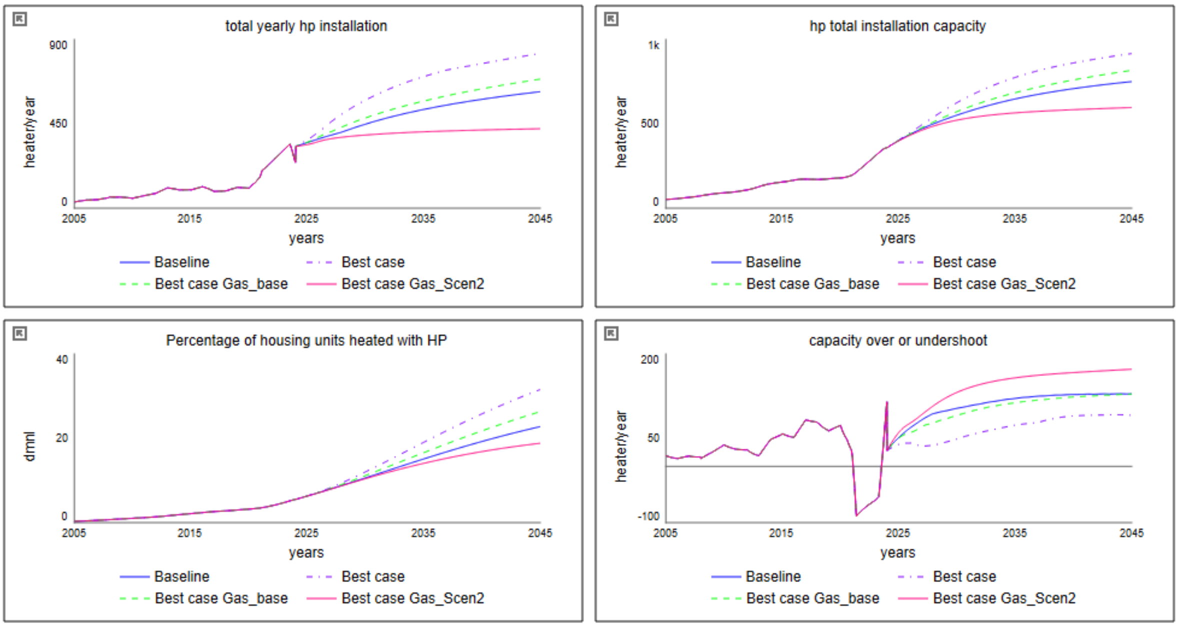


Figure 12 Influence of gas price on best-case scenario.

No matter the other circumstances, 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.

9. 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.

9.1. Answers to the research questions

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.

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.

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.

9.2. 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.

9.3. 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.

References

Achtnicht, M. (2011). Do environmental benefits matter? Evidence from a choice experiment among house owners in Germany. *Ecological Economics*, *70*(11), 2191–2200. https://doi.org/10.1016/j.ecolecon.2011.06.026

Bass, F. M. (1969). A New Product Growth for Model Consumer Durables. *Management Science*, *15*(5), 215–227.

BDEW. (2023). *Beheizungsstruktur des Wohnungsbestandes in Deutschland* [dataset]. https://www.bdew.de/service/daten-und-grafiken/beheizungsstruktur-wohnungsbestand/

BMWK-Bundesministerium für Wirtschaft und Klimaschutz. (n.d.). *Deutsche Klimaschutzpolitik*. Retrieved 11 December 2023, from https://www.bmwk.de/Redaktion/DE/Artikel/Industrie/klimaschutz-deutsche-klimaschutzpolitik.html

Born, H., Schimpf-Willenbrink, S., Lange, H., Bussmann, G., & Bracke, R. (2017). *2. Aktualisierung der Studie Analyse des deutschen Wärmepumpenmarktes 2017 Bestandsaufnahmen und Trends*. https://www.ieg.fraunhofer.de/content/dam/ieg/deutsch/dokumente/ver%C3%B6ffentlichungen/Analyse%20des%20deutschen%20W%C3%A4rmepumpenmarktes%202017.pdf

Deutsche Energie-Agentur. (2023). *DENA--GEBÄUDEREPORT 2024. Zahlen, Daten, Fakten zum Klimaschutz im Gebäudebestand.*

Erhebung des Schornsteinfegerverbands 2022. (2022). Bundesverband des Schronsteingeferhandwerks. https://www.schornsteinfeger.de/erhebungen.aspx

Expert Interview (Siemer, Interviewer). (2024, February 16). [Personal communication].

Friege, J., & Chappin, E. (2014). Modelling decisions on energy-efficient renovations: A review. *Renewable and Sustainable Energy Reviews*, *39*, 196–208. https://doi.org/10.1016/j.rser.2014.07.091

Giddens, A. (1984). *The Constitution of Society: Outline of the Theory of Structuration*. University of California Press.

Guzzo, D., Walrave, B., Videira, N., Oliveira, I. C., & Pigosso, D. C. A. (2024). Towards a systemic view on rebound effects: Modelling the feedback loops of rebound mechanisms. *Ecological Economics*, *217*, 108050. https://doi.org/10.1016/j.ecolecon.2023.108050

Hofe, M. vom. (2018). *Energetische Sanierung von Einfamilienhäusern: Drei Essays über Motive, Entscheidungsprozesse und Aktivierungsmöglichkeiten im Kontext von Privateigentum*. https://doi.org/10.17877/DE290R-19110

Keith, D. R., Struben, J. J. R., & Naumov, S. (2020). The Diffusion of Alternative Fuel Vehicles: A Generalised Model and Future Research Agenda. *Journal of Simulation*, *14*(4), 260–277. https://doi.org/10.1080/17477778.2019.1708219

Kunde, J. (2021, May 31). *Wie alt darf Ihre Heizungsanlage sein?* https://www.heizung.de/ratgeber/diverses/wie-alt-darf-ihre-heizungsanlage-sein.html

Lowe, R. (2007). Technical options and strategies for decarbonizing UK housing. *Building Research & Information*, *35*(4), 412–425. https://doi.org/10.1080/09613210701238268

Meade, N., & Islam, T. (2006). Modelling and forecasting the diffusion of innovation – A 25-year review. *International Journal of Forecasting*, *22*(3), 519–545. https://doi.org/10.1016/j.ijforecast.2006.01.005

Miara, M. (2022). *Heat Pumps in Multi-Family Buildings for Space Heating and Domestic Hot Water (DHW)* (HPT-AN50-SUM; Technology Collaboration Programme on Heat Pumping Technologies). heat Pump Centre.

Preisbremsen für Strom und Gas | Bundesregierung. (2024, January 1). Die Bundesregierung informiert | Startseite. https://www.bundesregierung.de/breg-de/schwerpunkte/entlastung-fuer-deutschland/strompreisbremse-2125002

Schieritz, M. (2023, April 10). Wärmepumpe: 'Wir haben nicht genug Geräte'. *Die Zeit*. https://www.zeit.de/2023/14/waermepumpe-kosten-wartezeiten-einbau-knappheit

Siemer, A. R. (2024). *Heat Pump Adoption in Germany: A Model-based Study of the Influences on the Diffusion of Innovation in Space Heating [* [Manuscript submitted for publication, Master Thesis].

Sterman, J. D. (2000). *Business dynamics: Systems thinking and modeling for a complex world* (International student edition). Irwin, McGraw-Hill.

Sultan, F., Farley, J. U., & Lehmann, D. R. (1990). A Meta-Analysis of Applications of Diffusion Models. *Journal of Marketing Research*, *27*(1), 70–77. https://doi.org/10.2307/3172552

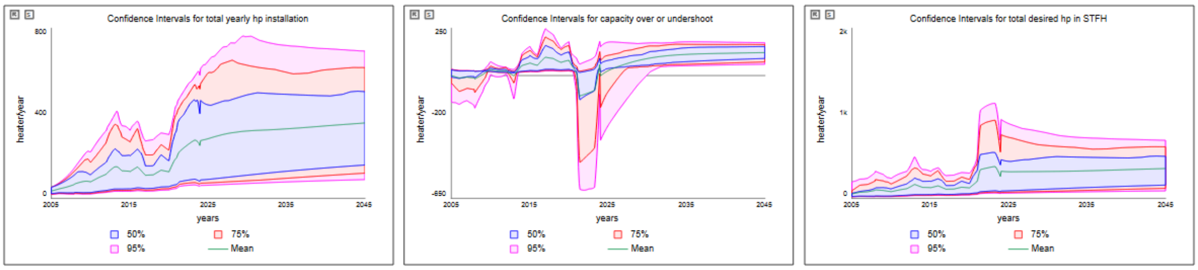
Verivox. (n.d.). *Verbraucherpreisindex Gas: Preisentwicklung für Haushaltskunden*. Retrieved 8 November 2023, from https://www.verivox.de/gas/verbraucherpreisindex/

Wilke, S. (2023, March 3). *Energieverbrauch privater Haushalte* [Text]. Umweltbundesamt; Umweltbundesamt. https://www.umweltbundesamt.de/daten/private-haushalte-konsum/wohnen/energieverbrauch-privater-haushalte

World Bank Group. (2019). *State and Trends of Carbon Pricing 2019*. World Bank. http://hdl.handle.net/10986/31755

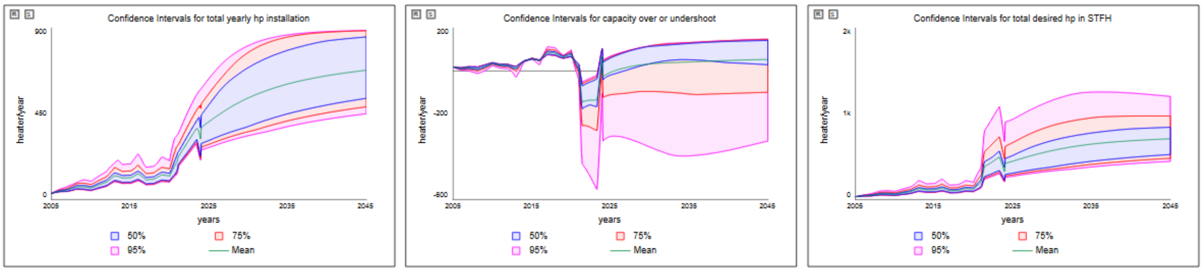
10. Appendix A Sensitivity analysis

Imp density old stfh & distr imp old stfh



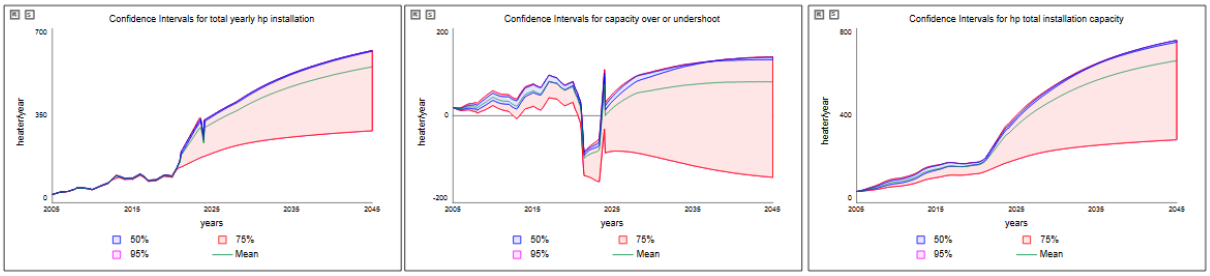
Combined testing for both values between 0 and 1. The model reacts appropriately sensitive to changes.

FH total lifetime stfh



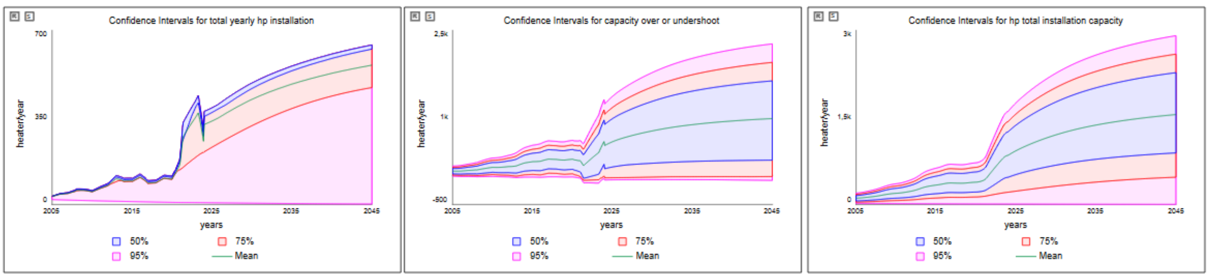
Tested for values between 10 and 50 years, original parameter value is 33 years. The model reacts appropriately sensitive to changes.

Willingness for further training



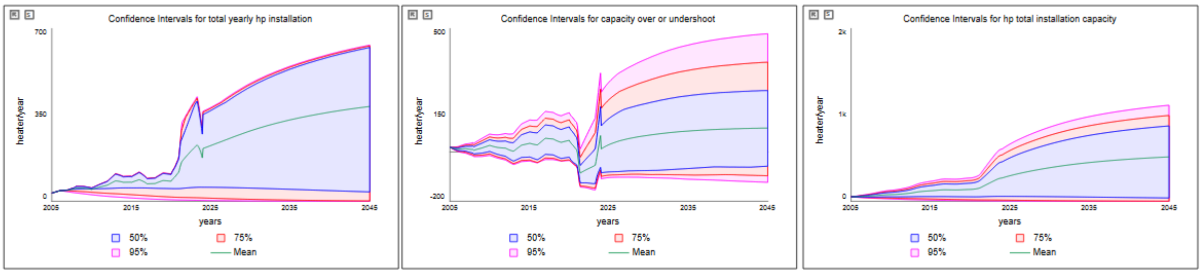
Tested for values between 0 and 1, the original parameter value is 0,15. The model reacts appropriately sensitive to changes.

Maximum capacity per hp installer



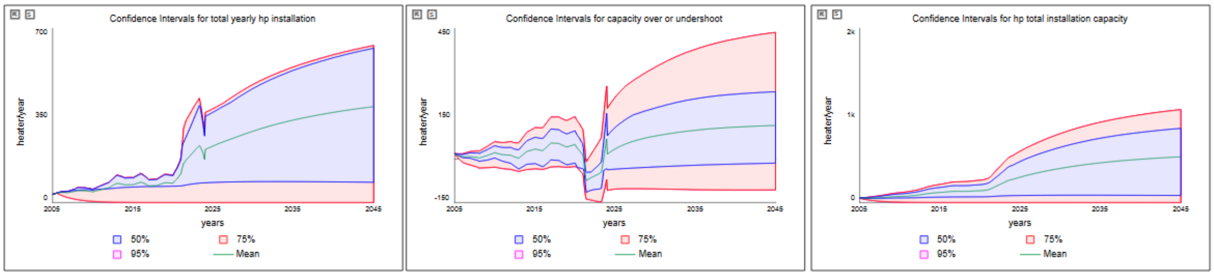
Tested for values between 1 and 20, the original parameter value is 5. Changes have the potential to stop a successful diffusion from happening.

Normal skill gain



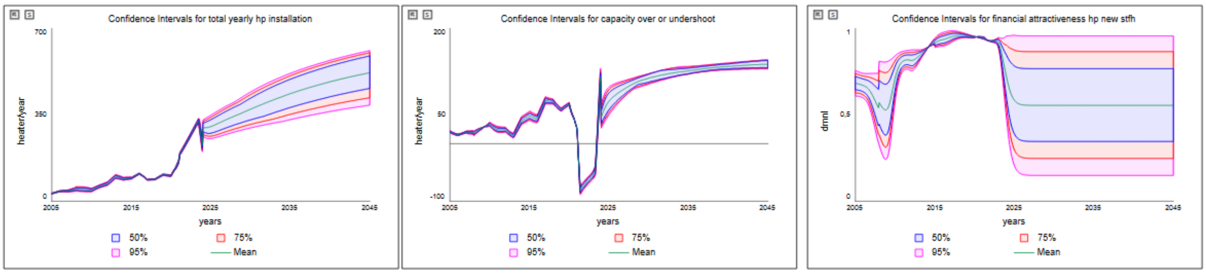
Tested for values between 0,01 and 0,1. Changes have the potential to stop a successful diffusion from happening.

Skill loss over time



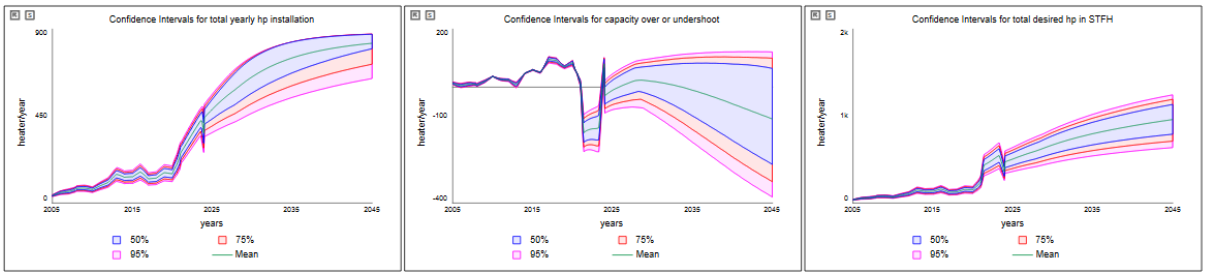
Tested values between 1 and 5. Changes have the potential to stop a successful diffusion from happening.

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.