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The Impact of the Climate Action Programme 2030 and Federal State Measures on the Uptake of Renewable Heating Systems in Lower Saxony's Building Stock

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Abstract: A heating transition is urgently needed to fulfil the national CO_2 reduction targets in Germany. Thus, in 2019, there has been a strong policy push towards increasing the share of renewables in heating through the introduction of the Climate Action Programme 2030 and the reform of existing policies. In addition to the policy landscape on the national level, federal states have further leeway to implement policies; these options are currently largely unresearched. In order to fill this gap, we developed a System Dynamics Model for Lower Saxony to determine the effect of recent policy changes as well as additional regional subsidy schemes on the heating market. The results show that even though changes in subsidies can increase the renewable uptake considerably, the CO_{2e} and energy demand reduction targets are not met in any of the examined scenarios. Furthermore, the model shows that policy formulation must take the inertia of the sector into account and completely turn away from fossil fuels to reach the stipulated emission reductions.

Keywords: renewables; heating systems; Climate Action Program 2030; Lower Saxony; federal state; building stock

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1. Introduction

The building sector produces 14% of Germany's national greenhouse gas emissions and is therefore pivotal in reaching the country's climate targets [1]. In order to reach the targeted 40.3% CO_{2e} emission cut from 2014 to 2030, an increase in energy efficiency as well as the diffusion of renewable heating technologies are required [2]. Correspondingly, a 80% reduction of primary energy consumption by 2050 is postulated, which can only be reached by a reduction in energy demand of at least 35% and a share of renewable energy used for heating of at least 57% [3], therefore requiring a profound change of in energy demand and supply in the sector.

In 2019, there has been a strong policy push on the national level towards decarbonizing the building sector, mainly through the Climate Action Programme 2030 and a corresponding reform of the building sector's policy schemes. Up until this point, the main policies supporting the transition to a carbon-reduced building sector were the Energy Conservation Act (ENeG) [4], the Renewable Energies Heat Act (EEWärmeG) [5] and the Energy Saving Ordinance (ENeV) [6]. Those were replaced by the Building Energy Act (GEG) [7], which streamlined regulations and concurrently increased subsidies for renewable heating and building renovations. Most notably, a premium for exchanging oil boilers ('Ölheizung-Austauschprämie') was introduced, administered through the already existing Market Incentive Program (MAP), to accelerate the phase out of the technology [8]. In addition to these policy changes, the Climate Action Programme 2030 instituted a carbon price for the building sector, starting in 2021 [9,10].

In spite of these efforts, most estimates predict that the GHG reduction targets in the building sector will not be met, even though the gap is decreasing through the implemented reforms [2,11–14].

Developing effective policy programs is a challenging task, as the heating market is characterized by a lot of small decisions by mostly private actors with no central interfaces [15]. Therefore, policies mainly aim at reducing the investment barriers for individuals [16], whereby policy instruments are either non-financial, e.g., efficiency standards or renewable energy obligations, or financial, e.g., grants or levies [17]. The latter is the focus of this paper, in line with the current agenda set by the national government as well as the government of Lower Saxony, which both heavily favor financial incentives over regulatory instruments [9,18].

Research on fiscal policy instruments in the heating sector has established that subsidies are oftentimes necessary to make renewable technologies economically attractive [19]. The size of the subsidies is directly linked to its effect; the higher the subsidy, the higher the uptake of renewable heating systems [20,21]. Additionally, research largely recommends differentiating subsidies according to technologies, as the underlying economic conditions might differ [22].

External factors also influence the effectiveness of subsidies schemes to a considerable extent; most importantly, the fluctuations of oil and gas prices affect the decision-making behavior of consumers [17].

CO_2 levies are different, as they do not aim to lower investment barriers but to internalize environmental externalities and are hence considered to be more economically efficient [23]. However, research indicates that subsidies increase profitability of renewable energies to a larger extent than fossil fuel taxes [19].

Existing research is mainly focusing on examining policy options on the national e.g., [19,24] or international level e.g., [25]. However, in Germany, federal states ('Bundesländer') have considerable additional leeway in decarbonizing the building sector, as they can implement policy programs and regulations in addition to those of the federal government [26]. The state Baden-Wuerttemberg, for example, extended the federal requirements for a share in renewable energy in heating for new buildings also to the existing building stock [27]; North Rhine-Westphalia offers grants for renewable heating technologies in addition to those on the national level [28]. These policies can be closely tailored to regional conditions. Therefore, it is important to consider the role of the German federal states as political actors when looking at policy formulation in the building sector. Yet, policy programs of federal states in the building sector are rarely discussed in scientific literature, and if they are, it is mostly in a retroactive manner [29]. Thus, the opportunity is missed to explore policy options on a regional level in a more proactive way.

In order to close this gap, this paper analysis the effect of several policy options ex-ante, focusing on the federal state of Lower Saxony. The state's heating market is dominated by natural gas; about two thirds (66,3%) of residential buildings use gas as their energy carrier for heating, followed by oil (18,30%) [30]. Its gross electricity generation is already supplied by 86% renewable energies. However, the heating sector is still lagging behind, as just 7.2% of the gross final consumption used in heating are produced renewably [31] (in comparison to 14.4% nationwide [32]). The government of Lower Saxony has passed a Climate Protection Law in December 2020, which defines climate protection as an issue on the constitutional level. A corresponding strategy is currently under development [33]. A number of programs for renewable heating are already in place; mostly soft loans and grants specifically for low income housing [34]. Yet, the programs fall short of a comprehensive, strong push to jumpstart renewable heating uptake in the state [35].

The paper at hand adds to the existing research in two ways: First, it gathers further insight into the effects of the recent changes in policy on the uptake of renewable energy technologies in the heating market in Lower Saxony, focusing on the change in subsidy schemes and the introduction of the carbon price. Second, it gauges the effect of a possible additional subsidy program on a federal state level.

For this purpose, we developed a bottom-up system dynamics model, which considers the characteristics of Lower Saxony's heating technologies as well as of its building stock. The decision-making of the individual actor is modeled through an economic assessment that integrates psychological barriers through an implicit discount rate. Three policy scenarios are examined: The policy conditions before the legislative changes of 2019 (BAU-Scenario), the policy conditions under the Climate Action Programme 2030 ('Climate Package'), and a possible additional support program on the federal state level.

Results indicate that the Climate Action Programme 2030 will improve the uptake of renewable technologies considerably in comparison to the BAU scenario, which can mainly be attributed to the increase in subsidies of the MAP Program. The carbon price, however, was too small to change the decision-making behavior to a substantial extent. The energy and GHG reduction targets could not be met in any scenarios, due to the long investment cycles and the resulting inertia of the heating market that delay the impact of policy instruments. Therefore, the continued support of gas hybrid technologies through the MAP has to be called into question; a more radical turn towards renewable technology is needed. A subsidy program on the federal level can provide additional push, increasing the CO_2-reduction by an additional 4.2% until 2035.

2. Methodology: The SDA Model

The developed model is derived from Schmidt et al. [36] and has been implemented by the authors using Visual Basic in MS Excel. It is divided into a demand side, representing the building stock, and a supply side, representing the heating systems (see Figure 1). Two feedback loops can be identified on both sides: A feedback mechanism that maintains the status quo and a feedback mechanism which causes change. In terms of CO_2-emissions, this means positive feedback loops increase the resulting emissions, while negative loops diminish them. On the demand side, the loop towards renovation is driven by the aging process; a certain percentage of actors, determined by the refurbishment rate, decide to renovate. This is countered by the decision not to renovate, which results in the buildings remaining in the unrenovated stock. On the supply side, the change is driven by the need to replace the heating system. After assessing the profitability of the different heating systems, the actors either decide in favor of a renewable heating technology, thus reducing the stock of fossil heating systems, or the decision is made in favor of a fossil heating system, resulting in a positive feedback loop.

The basis mechanism of the model is a Coflow-structure, which depicts the heating systems together with their resource efficiency, energy demand and emissions on the supply side and the buildings with their energy consumption on the demand side. Figures 2 and 3 depict the basic mechanisms on either side which are applied to each building age group, for renovated and not renovated buildings and for those with access to a heating pump and without. There are 25 (one-family dwelling) or 30 (multi-family dwellings) initial stocks, that are structured according to the age of the heating system. Each year, the stock with the oldest heating system changes according to the rational choices implemented in the model through the feedback loops. The model is considering a timeframe from 2020 to 2035. The refurbishment always coincides with the exchange of the heating system. The efficiency of the heating system, the number of buildings changing their heating system and the emission factors of the electricity are adjusted exogenously, hence each year heating systems have different characteristics.

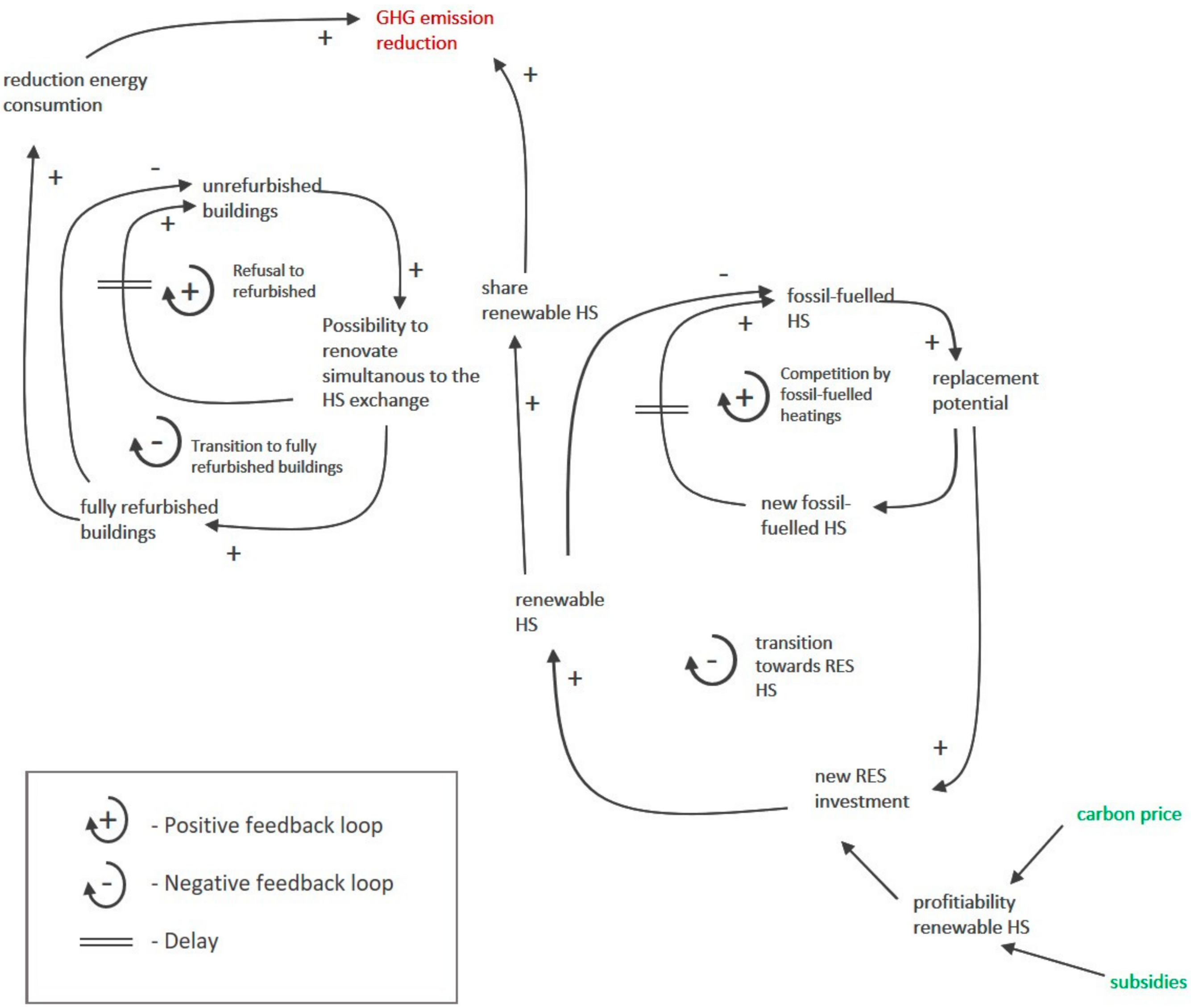

Figure 1. Causal-Loop Diagram of the model, derived from Schmidt et al. [36].

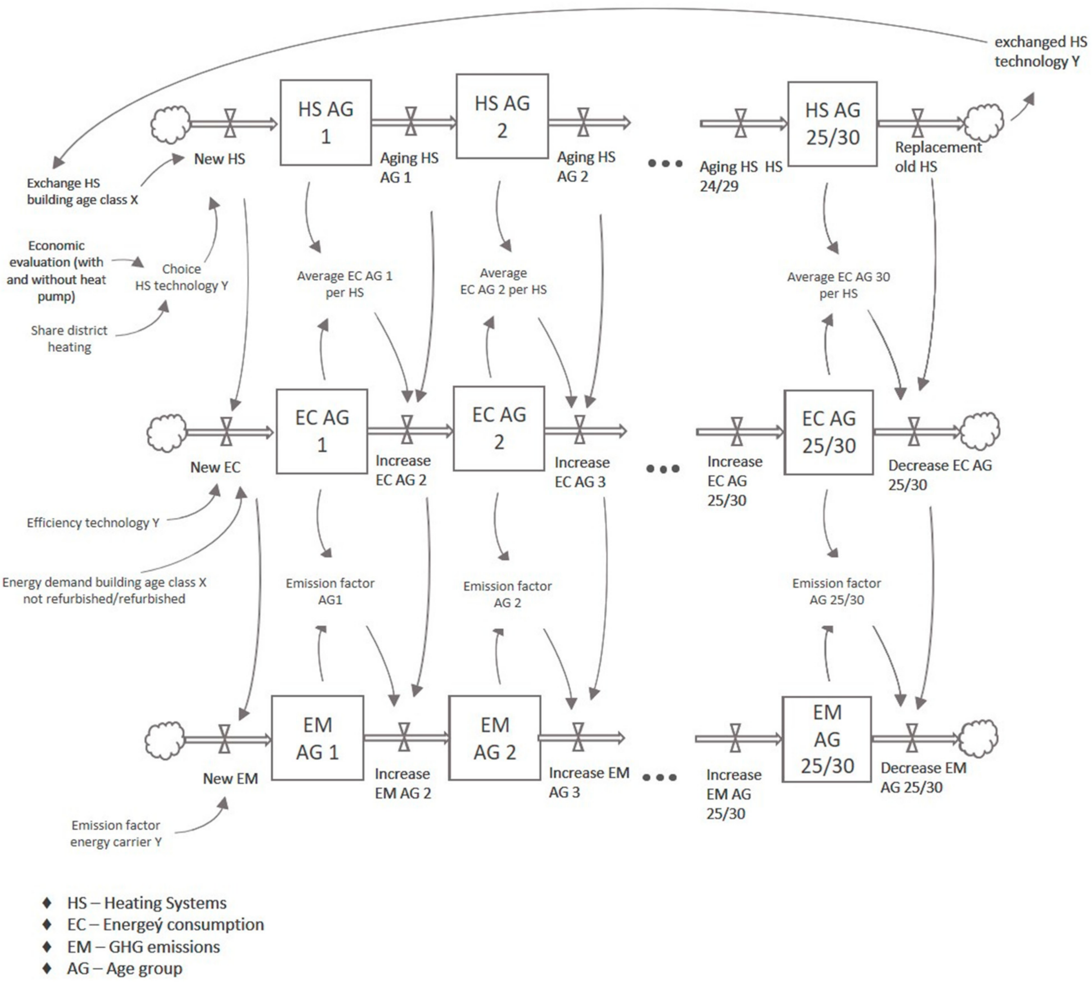

Figure 2. Aging chain co-flow structure of the supply side for building age class X and technology Y, derived from Schmidt et al. [36].

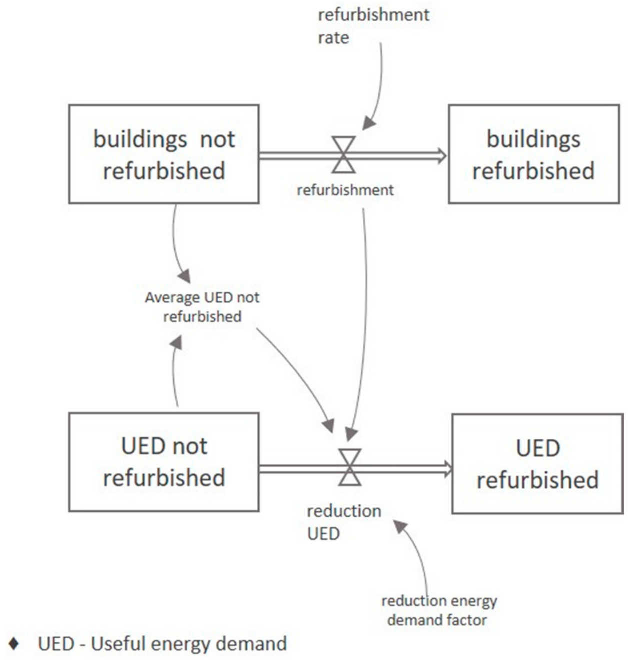

Figure 3. Aging chain co-flow structure of the demand side for building age class X and technology Y, derived from Schmidt et al. [36].

2.1. Model Assumptions

While economic considerations have largely been determined to be the most important factor when deciding for a new heating system [37–40], research has also shown that people do not always choose domestic appliances with the lowest life-cycle cost [17,41]. This phenomenon has been dubbed the 'energy efficiency gap' in economic literature and can be explained by barriers that impede actors to take an economically rational decision. According to Jaffe and Stavins [16], this can be caused by market failure, such as the lack of access to capital or the landlord–tenant dilemma [42]. The latter indicates that landlords are less likely than owners to improve the heating system of a house, as there is no monetary benefit for them [43]. It is included in the model by extending the lifespan of heating systems in multi-family homes, as 78% of their dwellings are leased out in Lower Saxony, in comparison to just 17% of single family dwellings [44]. Other explanations indicate that the energy efficiency gap can by caused by barriers that are not market failures, for example, a high implicit discount rate or the heterogeneity of actors [16]. The heterogeneity of actors influences the economic assessment [45] and is represented through the different building classes in our model, which vary in size and energy demand.

The implicit discount rate is included in the model and is used to reflect some barriers of rational decision making. Firstly, it represents the time preference of actors, who weigh immediate expenses higher than long term savings, thus most of the time disfavoring renewable technologies, which tend to have higher upfront costs and lower running expenses than fossil fuel-based systems [36]. Secondly, it accounts for risk aversity, i.e., the desire to avoid the risk of fluctuating energy prices. Lastly, it depicts reference-dependent preferences, as the loss of investment capital is weighted higher than savings through lower energy costs [42]. Additionally, the preference to stay with the current technology, the 'Status-Quo-Bias' [42] is modeled by the means of a nuanced cost structure, which distinguishes actors that had a gas boiler and those who had an oil boiler before exchanging their heating system, making it cheaper to continue choosing the same technology option [46].

Regulatory restrictions are included in the model through restricting the actors' choice options. Oil boilers are forbidden by the year of 2026, as by the Climate Action Programme 2030, so they are no options for actors; low temperature boilers are excluded completely, as they are an outdated technology, and their distribution is heavily restricted [47]. Furthermore, the access to geothermal heating is limited by regulations as well as geological conditions [48], which is why just a share of actors can choose it as their heating system.

2.2. Building Stock

The building stock is based on data from the 2011 micro census and, for the following years until 2017, the online database of the State Statistical Office of Lower Saxony [49,50]. In accordance with the available information, a classification into 8 building age classes was made and split into single and multi-family houses. The ratio of single and multi-family houses was determined by grouping houses with 1 or 2 apartments and houses with 3 or more apartments for all available building age classes [49] (p. 8). It is assumed that each house has one central heating system. The demolition rate was not included in the model, as it amounts to 0.1% p.a. (one-family dwellings) and 0.2% p.a. (multi-family dwellings) nationwide and is thus negligible [2].

The useful energy consumption of the buildings was sourced from the housing typology developed by the Institute for Housing and Environment [51].

The refurbishment rate is modeled by means of three elements: the energy coefficients of the renovated houses, the share of already renovated housing in Lower Saxony and the refurbishment rate. The energy demand of renovated houses in this model can be considered to represent 'complete renovated' houses by the categorization of the Institute for Economic Ecological Research, as they encompass four different renovation measures [52]. The same categorization has been applied to the data base 'Wohnen und Sanieren-Wohngebäude-Statistiken 2002 bis heute', which quantifies the share of completely refurbished buildings in Lower Saxony at 5.2% [34]. Hence, this share is modeled with the 'renovated' energy coefficients. This approximation, however, does not consider partly refurbished housing due to the lack of data availability.

The exact yearly refurbishment rate for complete renovations is extremely difficult to ascertain [53]. In order to develop an estimate, the total share of fully refurbished houses was divided by the amount of years that complete refurbishment has been common practice in Germany. The starting point is the Heat Insulation Ordinance (Wärmeschutzverordnung) from 1977 [51]; the most recent recorded additions to the building stock are from the year 2018. Consequently, we estimate the refurbishment rate for complete renovation to be at 0.13% of the total building stock each year. This roughly corresponds to the findings of the European Commission, which estimate the average 'deep' renovation rate for Germany in the years from 2012 to 2016 to be at 0.1% [54].

2.3. Heating Systems

The heating systems represented in the model are gas condensing boilers (with and without solar thermal collectors for water heating), oil condensing boilers (with and without solar thermal collectors), air heat pumps (with and without solar PV), pellet boilers (with and without solar thermal collectors) and geothermal heat pumps. The access to the latter is restricted, as there are geological and regulatory requirements that impede the installation for the majority of houses. Faulstich and collegues [48] estimate the potential of geothermal heating in the settlement area of Lower Saxony at 13%. Hence, in the model, only 13% of actors are able to choose this technology.

Furthermore, low-temperature gas and oil boilers as well as district heating systems are included in the existing building stock but are no option for the actors. They are an outdated technology which is largely forbidden in the European Union [47], thus their use will continuously decline in the upcoming decades. The share of district heating is held constant at 4.2%, as it is a separate decision-making area, depending on local regulations [55].

In the initial building stock, the share of each of the technologies as well as their age distribution are based on data of the Federal Association of the German Energy and Water Industries (BDEW) for Lower Saxony [30]. When pre-processing the data, central and individual heating systems of the same type were grouped together, and the share of 'not assignablel' heating systems was factored out. The remaining technologies represent 95% of heating systems in Lower Saxony. The age groups are available in 5-year intervals; in order to estimate an initial stock for each year, a homogeneous distribution in all intervals was assumed.

The assumed maximum age in the beginning of the simulation is 30 years, in accordance with ENeV regulations [6]. In order to account for the landlord-tenant dilemma, the boilers in single family houses are assumed to be exchanged quicker than in multi-family homes, thus lasting only 25 years. Therefore, the oldest and second oldest stock of heating systems are exchanged simultaneously in the first 5 years of the simulation.

2.4. Energy Consumption, Efficiency and Emissions

The energy consumption and CO_{2e}-emissions were calculated according to the polluters-pay-principle and thus include electricity for heat pumps and energy used for district heating. In order to convert the useful energy consumption of the buildings into the final energy demand of each technology, a final energy expenditure factor was used [2], the exception being the heat pumps and PV combination. For those systems, the achieved degree of self-sufficiency was taken from Tjaden and colleagues [56]. The primary energy consumption was calculated with the primary energy factors of DIN V 18599 (2011) [46]. The emission factors for each energy carrier were mainly taken from data of the German Energy Agency (dena) [2]. Nevertheless, there were two notable exceptions: first, as the data from the dena [2] only included data for biomass generally and not specifically for pellets, the emission factor of the latter was taken from Corradini and colleagues [57].

Second, as the carbon emissions of electricity fluctuate depending on the electricity mix, the emission factors for the modeled period were extrapolated via a trend line based on the emission factors of the years from 1990 to 2018 [58].

2.5. Economic Evaluation for Decision-Making

The economic assessment is the heart of the model, as the examined policy instruments come to play here. According to VDI 2067 Blatt 1 [59], economic evaluation of heating systems can be split in three components: (upfront) investment costs, fuel costs and operational costs.

Thus, net present value (NPV) is calculated as follows (based on Schmidt et al. [36]):

$$\mathrm{NPV} = \mathrm{IC} * \mathrm{CD} + \mathrm{IP} * \mathrm{CD} + \frac{(\mathrm{FK}+\mathrm{OC})}{(1+\mathrm{i})} + \frac{(\mathrm{FK}+\mathrm{OC})}{(1+\mathrm{i})^2} + \frac{(\mathrm{FK}+\mathrm{OC})}{(1+\mathrm{i})^3} + \ldots + \frac{(\mathrm{FK}+\mathrm{OC})}{(1+\mathrm{i})^{20}} \tag{1}$$

where IC = Investment costs (including subsidies), IP = (where applicable) investment costs PV or solar thermal water heating, FK = Fuel costs, OC = Operation costs, CD = Factor of cost development and i = implicit discount rate

2.6. Investment Costs

Investment costs were determined by technology specific cost functions that are dependent on the size of the dwelling, which is in line with relevant scientific findings [60,61] (see Appendix A). Hinz [61] determined that the relationship of the variables can be described with a negative potential function. Thus, this functional form was chosen and specified with data points from Hinz [61] and from the BDEW [46] for all technologies. The latter data set offers a crucial advantage: it includes different sets of data that depend on the technology of the previous heating system, slightly favoring the repetition of the previous choice. Based on this data, distinct cost functions could be established for households that initially had a gas heating system and those that had an oil heating system. Due to the lack of availability of data for the other depicted technologies, those houses that initially had another heating system were calculated as if they had gas before.

As a reduction of investment costs over time through economies of scale and technological progress can be expected, the predicted cost development of Hecking et al. [2] was included in investment costs through the integration of a cost factor. This factor is changing for each year of the simulation and is determined by the factor of the previous year minus the average change in costs per year [2]. Furthermore, the assessed grant schemes are included in the investment cost. However, it is assumed that the investment costs are paid upfront, thus soft loan schemes were excluded from the model.

2.7. Fuel Costs

Fuel costs are calculated by multiplying the price of the fuel with the final energy consumption, which is determined by the useful energy demand of the house and the final energy expenditure factor of the specific technology [2].

Hence, it is calculated according to the equation:

$$\text{Fuel costs} = \mathrm{UE} * \mathrm{Eff} * (\mathrm{Pr} + \mathrm{CP}) \tag{2}$$

where UE = Final energy consumption, Eff = Final energy expenditure factor, Pr = Price fuel and CP = Carbon Price

For forecasting the commodity prices in the modelled timeframe, it was assumed that the prices increased similar to previous years, which is a common assumption in economic literature [57]. Consequently, the previous price development was adjusted for inflation and extrapolated with a linear trendline. Furthermore, it is presumed that in the moment of deciding for a heating system, actors consider the prices at that point in time to stay the same in the future, as empirical literature establishes that they operate under a no-change forecast [62].

Pellet prices were taken from the Centralen Agrarrohstoff Marketing und Energienetzwerk e.V. (CARMEN) [63], starting in 2002. Natural gas, light heating oil and electricity prices were gathered from data from the German Federal Ministry for Economic Affairs and Energy (BMWi), starting in 1992 [64]. The electricity supply for heat pumps has a discounted tariff, which was taken from a publication of the Federal Association of the German Heating Industry and the Federal Association of Heat Pumps [65]. However, when the heat pump is connected to a PV system, it has to be connected to the electricity circuit of the house, thus the regular electricity tariff applies [56], which was also taken from the dataset of the BMWi [64].

The fuel price also includes the carbon price, which was estimated by multiplying the average CO_2-emissions of each energy carrier per kWh and kilogram with the carbon price per kilogram.

2.8. Operational Costs

The operational costs consist of maintenance costs, chimney sweeper fees, insurance and, in the case of multi-family homes, the heating cost accounting. As with the investment costs, technology specific linear cost functions were determined which depend on the size of the respective building. They were specified with data from the BDEW [46].

For future fuel and operational costs, a discount rate applies (see Section 2.1), which is exponential and thus reduces the weight of costs the farther in the future the arise. The estimation of the implicit discount rate for energy-using consumer goods is difficult as it varies depending on a variety of factors, such as the perceived trade-off between investment and expected fuel and operation costs. In the paper at hand, the discount rate for heating systems and renovations from the Price-Induced Market Equilibrium System (PRIMES) is used, which is based on an extensive literature review [66]. It is set at 12% (i in Equation (1)).

2.9. Modelled Scenarios

The aim of the scenario conceptualization was to make different policy scenarios comparable. Thus, the market development is held constant, meaning that the same price, investment cost and efficiency trajectories are utilized in all scenarios. In order to achieve a conservative estimate, the default option (‘Basisförderung’) is always chosen by the actors, i.e., special schemes for very innovative technologies are excluded. The modelled scenarios are: The BAU-scenario, including the policies in place before 2020, the ‘Climate Package’-scenario, containing the Climate Action Programme 2030 with the corresponding amendment of the MAP, and the ‘Additional Incentive Program’—scenario, considering a subsidy scheme in the regional level supplementary to the national policy framework.

The policies modeled in the BAU-scenario are part of the MAP, which is administered through the Federal Office of Economics and Export Control (BAFA), or the KfW promotional programs for buildings. The supporting schemes of the two agencies are mutually exclusive [67], thus the most financially beneficial scheme is chosen for each technology: The MAP (lump sum) payments for renewable technologies and the KfW Program 430 for the exchange to an oil or gas heating as an individual measure [68].

The basis of the second scenario is the Climate Action Programme 2030, which was passed in the fall of 2019, in concert with the amendment of the MAP. The KfW programs are not applicable anymore, as the BAFA has taken over the responsibility of most support schemes for heating systems with the start of the year 2020 [69]. Germane for the second scenario are the carbon price, starting in 2021; the MAP grants, which have been changed to proportional payments; the prohibition of oil boilers, starting in 2026, and the increase in technological requirements for solar thermal collectors. It is important to note that while traditional oil and gas systems are phased out, gas hybrid systems are now added to the MAP scheme (for details, see Appendix B).

For the last scenario, a possible grant scheme in addition to the already existing MAP is examined, which was developed under the objective of providing a strong policy push towards the ambitious aims of Lower Saxony's Climate protection law.

The proposed program is based on two considerations in regard to the focus of the program and it's fit with already existing policies. Firstly, in order to reach emission reduction goals, the use of gas for heating should be phased out as soon as possible, therefore gas hybrid should not receive additional support. Additionally, PV systems are not supported through grants by the federal government, hence financing substantial grants through state funding alone might strain the budget too much. Therefore, the focus of the scheme should lie on the support of air and geothermal heat pumps as well as pellet heating. Secondly, results of the second scenario show that the oil boiler exchange premium is already very effective. Starting from 2021, actors who had an oil boiler before decide mostly for a renewable technology afterwards. Consequently, no additional support for those type of dwellings is needed. The additional grant therefore applies in the case that a gas boiler is exchanged, to encourage a switch to a renewable technology.

In order to specify the exact amount of additional support, different support schemes were modeled. The starting point was a grant of 45% of investment costs for pellet systems, heating pumps and hybrid heating systems that consist of just renewable energy technologies. This grant constitutes a 10% increase to the regular scheme and corresponds to the 'oil boiler exchange premium'. Different schemes were tested, oscillating around the starting point by 5%.

3. Results

3.1. Sensitivity Analysis

For a deeper understanding of the model's functioning, the influence of the central model parameters, namely fuel prices, the implicit discount rate and the comprehensive refurbishment rate, was assessed through a one-at-a-time sensitivity analysis. The focal output parameter was the achieved emission reduction until 2035; the baseline scenario in this case is the 'Climate Package scenario'. The results can be found in Appendix C. Overall, the achieved emission reductions ranged from 22.63% to 35.96% percent in the tested scenarios, indicating that the leeway of each parameters is limited due to the inertia of the market. Selected parameters are furthermore shown in Figure 4.

The results for the fuel prices confirm that the price development of fossil fuels has the highest influence on the achieved emission reduction, as they cause a higher standard deviation in the output (s = 2.89%) in comparison to pellet (s = 2.02%) or electricity price changes (s = 0.79%). They are therefore crucial for the effectiveness of subsidies, as has been noted in scientific literature before [19,70].

The results of the carbon price indicate that small increments of 10 to 20 €/t or even a price trajectory that culminates in 137 €/t in the year 2035 as proposed by Wagner et al. [71] do not lead to a meaningful decrease in emissions, the latter only increasing the reduction by 2.25%. However, an extremely high price of 150 €/t that comes into effect immediately increases the emission reduction to 35.96%; about three times more than the Wagner et al. trajectory.

The specification of the implicit discount rate comes with a great amount of uncertainty, as empirical studies have led to a variety of results [72]. However, the extent to which actors incorporate future energy costs into their considerations has a comparatively large influence on the achieved emission reductions, as a discount rate of 36% leads to a considerably lower emission reduction of just 22.63%, in comparison to 28.65% of the Climate Package scenario.

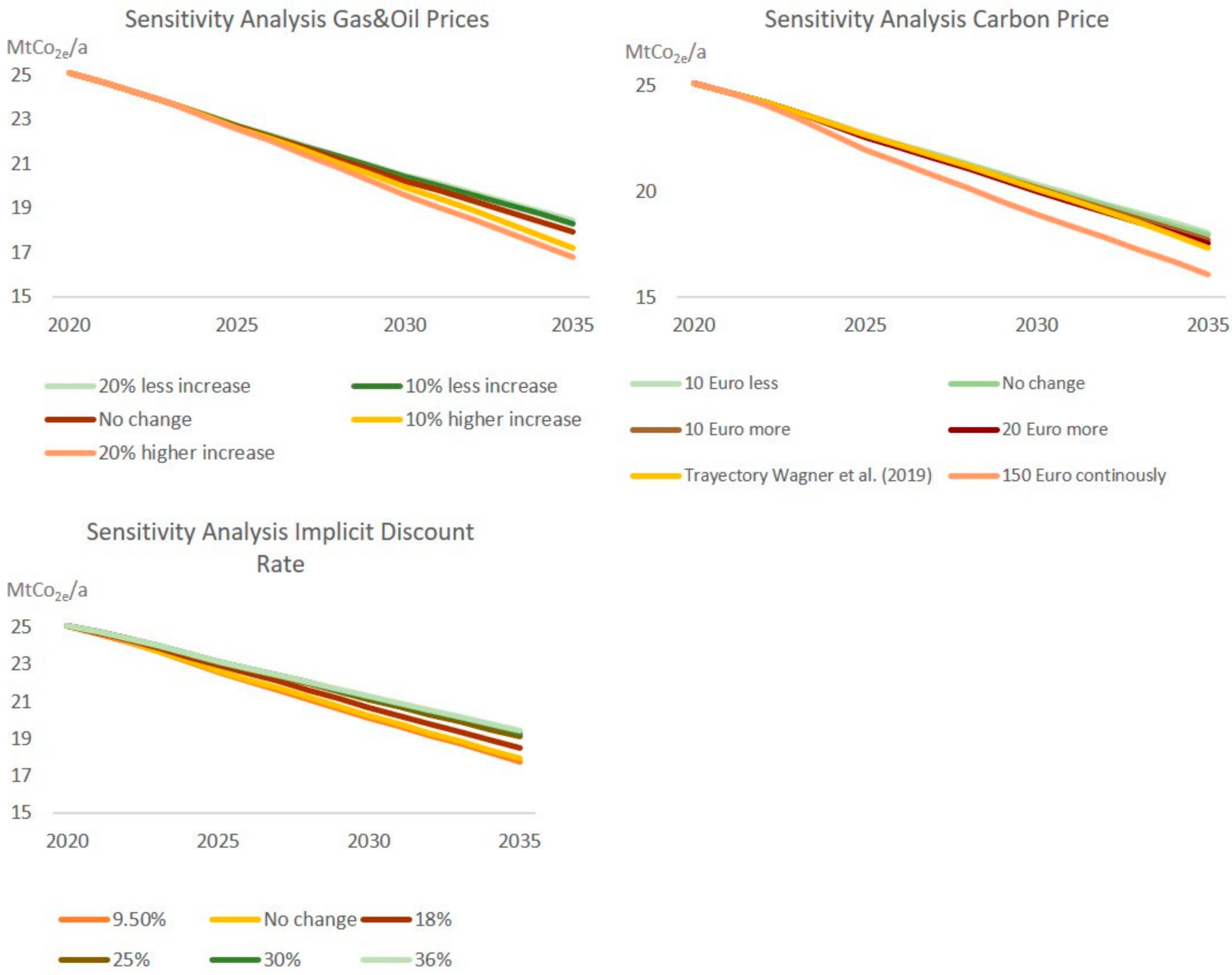

Figure 4. Results of the sensitivity analysis for Oil and Gas prices, carbon price and the implicit discount rate.

The refurbishment rate for complete renovations does have a very small impact on the emission reduction. Even quintupling the rate only leads to an additional increment in reduction of 0.63%.

3.2. Potential Subsidy Schemes for Lower Saxony

Different subsidy rates have been tested (see Section 2.9). The resulting CO_{2e}-emission trajectories are depicted in Figure 5. The graph illustrates that starting from an additional support of 7.5% of investment costs, a considerably higher emission reduction can be achieved in comparison to lower subsidy levels, undercutting yearly emissions of 17 $MtCO_{2e}$ by the end of the simulated time span. Thereafter, raising the subsidies even higher decreases the CO_{2e}-Reduction per invested Euro.

Therefore, in order to not burden the state budget further, the proposed grant is set at 7.5%, meaning a total of 42.5% of investment costs is covered.

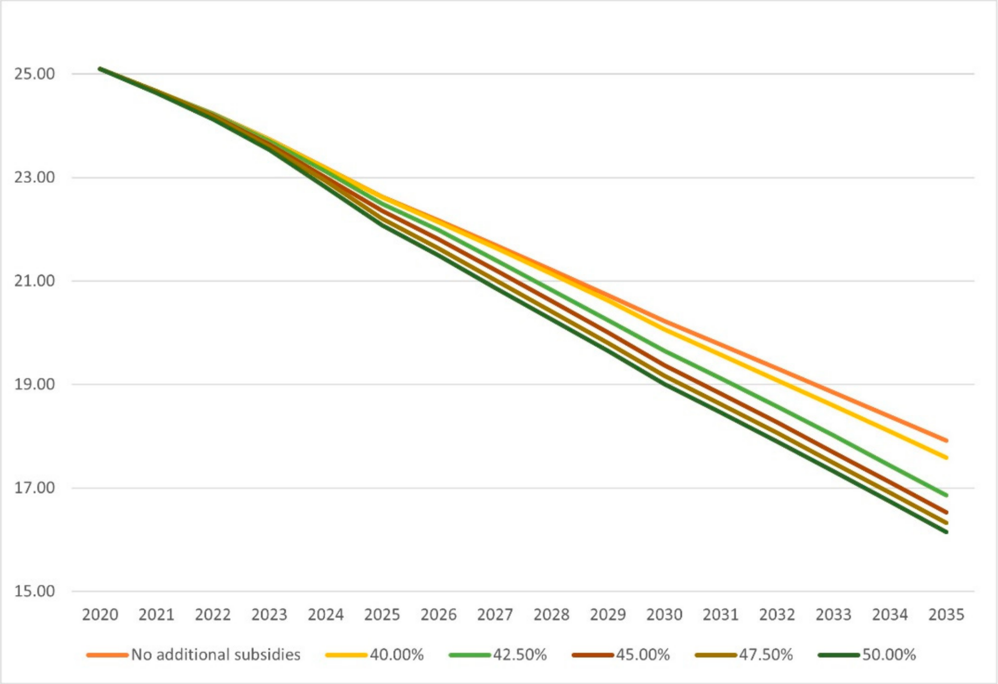

Figure 5. GHG emissions under different state subsidy schemes for Lower Saxony.

3.3. *Primary Energy Consumption, Final Energy Consumption and CO_{2e}-Emissions*

In the following subchapter, the energy consumption and emissions of the scenarios are presented and compared (see Figure 6). In order to obtain an indication of federal government's targets in Lower Saxony, the BAU-scenario's final energy and primary energy consumption were estimated for the baseline year 2008 and the energy consumption and emission trajectories of the scenarios were extrapolated to the year 2050, both by means of a linear trend line. Following the same procedure, carbon emissions were estimated for the year 2030, in order to compare them with the target year 2030.

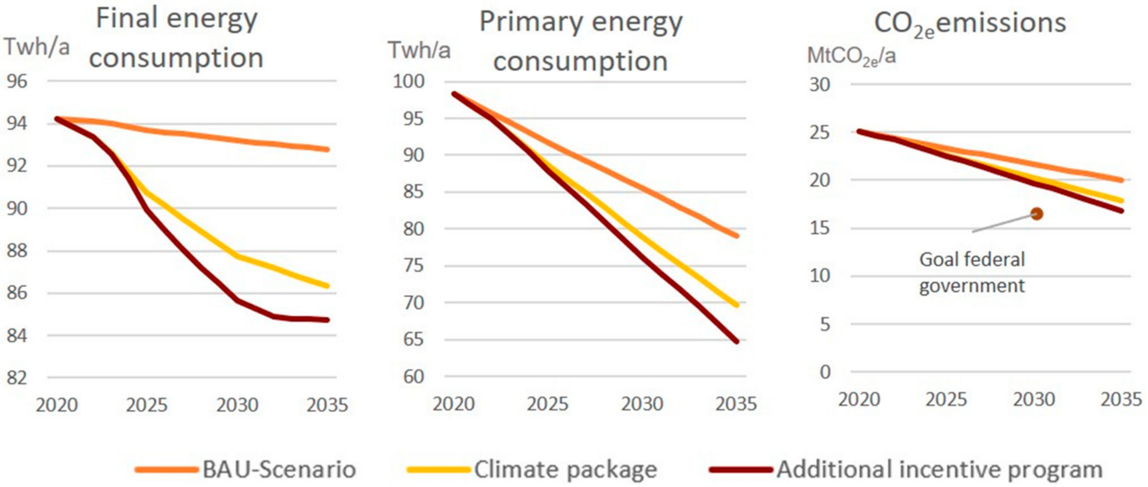

Figure 6. Primary energy consumption, final energy consumption and CO_{2e}-Emissions in the scenarios over the simulated period.

The final energy consumption of the model is estimated to be 94.32 Twh. Unfortunately, there is no official data on the final energy consumption of the private building stock in Lower Saxony available. However, the 'Report of Energy Transition 2019′ for Lower Saxony discloses the total final energy consumption for buildings, including consumption by companies, to be at 127.77 Twh, thus to be approximately 35% higher [73].

Final energy consumption decreases in all scenarios, albeit to different extents; while it is only marginally reduced in the reference scenario, it decreases by a tenth in the 'Additional Incentive Program' scenario (see Table 1). Looking at the total trajectory, it becomes clear that in the scenarios with higher subsidies, the final energy consumption decreased to a substantially larger degree than in the BAU scenario. From 2030 onwards, the curve flattens, indicating a loss of momentum in the reduction of energy consumption. The extrapolation to the year 2050 indicates that the target corridor of the Energy Efficiency Strategy for Buildings, which lies between 36 and 54% final energy reduction [3], cannot be achieved in any scenario.

Table 1. Scenario results for final energy consumption, primary energy consumption and GHG emissions.

	Final Energy Consumption		**Primary Energy Consumption**		**CO_{2e} Emissions**	
	Change over the Simulated Timeframe (2020–2035)	**Extrapolation to 2050 (Baseline Year: 2008)**	**Change over the Simulated Timeframe (2020–2035)**	**Extrapolation to 2050 (Baseline Year: 2008)**	**Change over the Simulated Timeframe (2020–2035)**	**Change until 2030 (Baseline Year: 2014)**
BAU- Scenario	−1.53%	−4.43%	−19.61%	−46.75%	−20.37%	−21.08%
Climate Package Scenario	−8.33%	−18.72%	−29.21%	−63.14%	−28.65%	−26.34%
'Additional incentive program' Scenario	−10.07%	−23.78%	34.11%	−71.27%	−32.85%	−28.43%

The primary energy consumption falls in all scenarios throughout the whole simulated period. However, the extrapolations show that all policy mechanisms fall short of reaching the reductions target postulated by the Energy Efficiency Strategy for Buildings of 80% by 2050. The 'Additional Incentive Program' scenario achieves the biggest reduction, closing the gap to 9%.

When looking at the emission development, it becomes apparent that a reduction is achieved in all scenarios, albeit to varying degrees. The Climate Package Scenario achieves an additional 8.28% emission reduction in comparison to the BAU scenario; the additional support program of Lower Saxony further reduces emissions by 4.2%.

Nevertheless, the target set in the Climate Action Plan 2050 of a CO_{2e} reduction of 40.3% by 2030 cannot be met in any scenario.

3.4. Distribution of Technologies

In the following subchapter, the overall development of the distribution of technologies is presented (see Figure 7 and Appendix D).

The results show overall that gas technologies will play a crucial role in all scenarios, although to different degrees. Moreover, renewable technologies only notably increase in the Climate Package and Additional Incentive Scenario.

In the reference scenario, there share of gas condensing boilers almost doubled from 36.71% to 68.45% in 2035; the total percentage of gas systems at the end of the time frame amounted to 81.20%. The only renewable technology gaining traction are pellet systems with solar thermal collectors, which grew from 0 to 4.46%, due to the demand of multi-family homes. For those dwellings, running costs are more important than investment costs for bigger houses. Pellet systems are therefore more economically attractive, as has already been indicated by literature [74], because pellets are consistently cheaper than other fuels [46]. Additionally, operational costs decline with increasing size of the house for pellet systems [46], which also makes them even more economically viable for bigger houses.

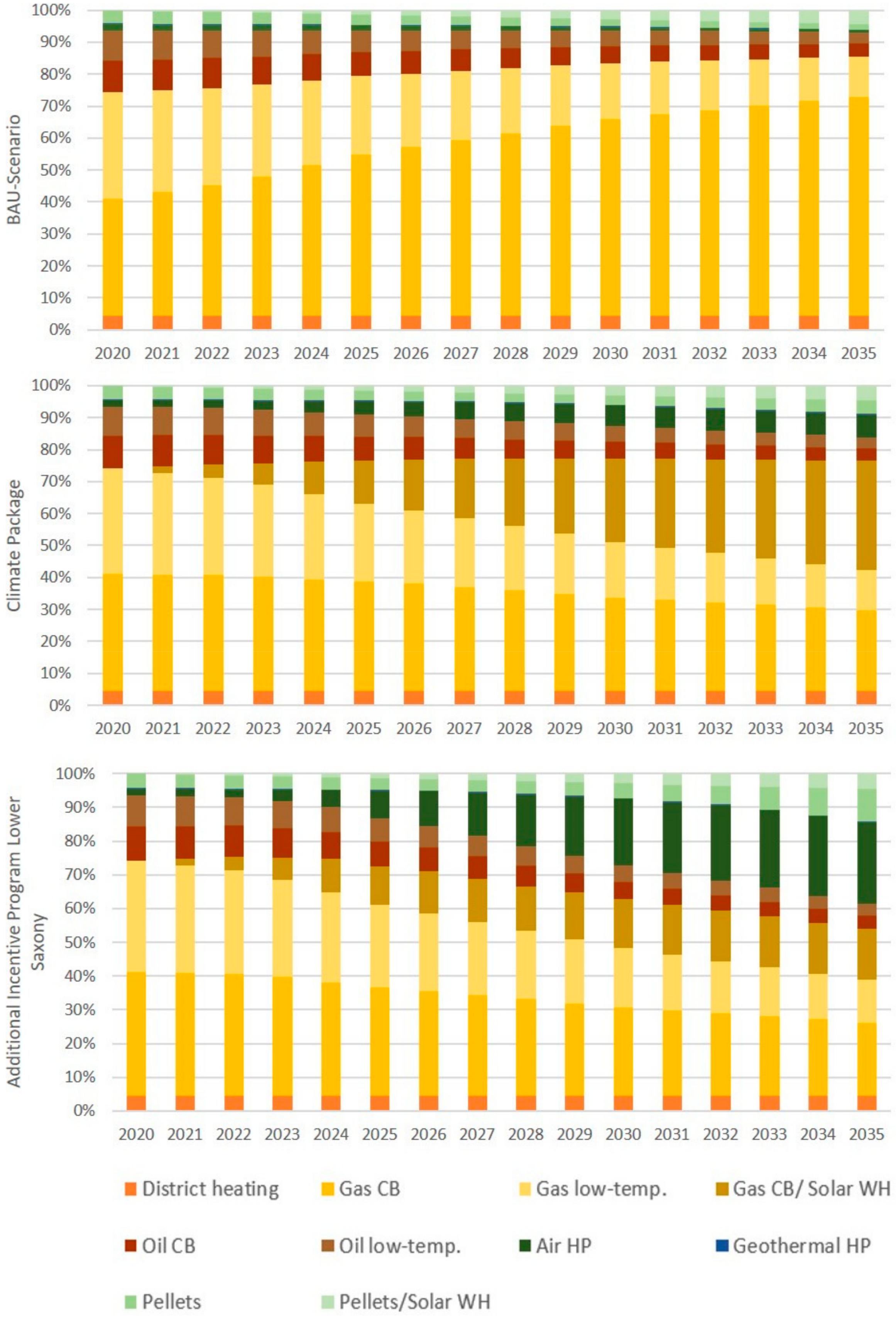

Figure 7. Distribution of heating systems in the building stock in the modelled period (Heating technologies that were not present in the building stock and have not been chosen by the actors in the modelled period were excluded from the figure).

The share of gas technologies grew in the 'Climate Scenario' as well, to 72.09% at the end of the simulation. This was mostly due to a rise in installations of gas hybrid technologies with solar thermal panels, which constitute 34.04% of heating systems by 2035. Purely renewable technologies also increase, though to a lesser extent; especially the shares of air heat pumps (from 2.10 to 7.16%) and pellet technologies with solar thermal collectors (from 0 to 4.44%) expand. The share of regular pellet boilers decreases at first; however, this trend turns around in the beginning of the 2030s. Overall, its percentage slightly increases from 4.1% to 4.42%.

The last scenario is the only one in which renewable technologies gain significant momentum; especially the amount of air heat pumps increases considerably. In 2035, 24.34% of households own the technology, mostly due to an increased demand of single-family homes. Pure pellet systems, like in the scenario before, decrease slightly at first but amount to 9.75% at the end of the simulation. Similarly, the share of pellet systems with solar thermal increases from 0% to 4.44%.

Nevertheless, the last scenario is also characterized through a high share of gas technologies (49.57%), albeit considerably lower than in the other two scenarios. Like in the 'Climate Package Scenario', the share of pure gas technologies falls, from 31.71 to 21.82%, and the share of gas boilers with solar thermal support increases, although to merely 15.10%.

Generally, oil boilers with solar thermal collectors, heat pumps with PV and geothermal heat pumps are not chosen in any of the scenarios. In spite of the subsidies, they stay economically unattractive. Similarly, the share of oil boilers decreases in all scenarios; the reference scenario is the only one this technology is chosen. As was determined through model specification beforehand, the share of low-temperature gas and oil boilers fell throughout the simulation, from 42.23 to 16.50%. This illustrates the inertia of the market that has been noted in literature before [15].

4. Discussion and Conclusions

4.1. General Discussion

The results show a reduction in energy consumption and emissions in Lower Saxony in all scenarios, albeit to a varying extent. However, the GHG emission reduction targets of the German government are not met in any of the scenarios. The Climate Action Programme represents an improvement over the previous policy scheme, which would not have enabled a move away from traditional heating systems and would have missed the CO_2-reduction target for 2030 by 19.22%. Under the current policy scheme, achieved emission reductions are higher, but still fall short of the targets by about 13.96%. This roughly corresponds to studies commissioned by the BMU and the BMWi [12,13], which predict a gap of 8% and 4%, respectively Due due to different model assumptions, exact values are not directly comparableOne possible explanation is the continued support for gas hybrid technologies, which—combined with the inertia of the sector-impede a more radical cut in emissions. In the model, one-family-homes, which have a greater potential for change due to the higher frequency of heating system exchange, continue to choose gas hybrid options due to the monetary support. Another explanation could be the model's restrictive assumptions regarding the renovation rate; more optimistic premises could have led to more favorable results. Moreover, the model shows that an additional subsidy program in Lower Saxony could further increase the achieved emission reduction and closes the gap down to 11.87%. This shows, however, that additional policy measures would be needed to close the remaining emission gap completely. Specifically, regulatory instruments or information campaigns could aim at lowering the energy demand of buildings further in order to achieve the required emission reduction.

The comparison with the reference scenario shows that the improvement brought about by the Climate Action Programme can be attributed primarily to the increased subsidies of the amended MAP, which causes a significant change in the decision-making behavior of the actors due to the increased profitability of renewable energy sources.

In contrast, sensitivity analysis demonstrate that different CO_2 prices only cause a small change in emission reduction; in comparison, regular fluctuation in fossil fuel energy prices brings about larger effects. This coincides with the findings of Hast and colleagues [19], who also found that increasing subsidies increases the financial attractiveness of renewable technologies to a greater extent than increasing the price of fuels. A possible explanation could be the fact that the carbon price, as it is currently planned, leads only to a small addition fossil fuel costs and therefore fails to meaningfully impact decision-making behavior. The achieved emission reductions remain more or less constant if the price scheme is varied, the only exception being a -politically unfeasible- scenario of 150 €/tCO_{2e}, starting in the year 2021.

Most of the results correspond with existing literature. A comparison of the scenarios reveals that in the foreseeable future, in most cases substantial subsidies are necessary to make renewable technologies financially attractive [19,75]. Some technologies, such as geothermal heat pumps, might always need subsidies due to the oftentimes prohibitively high cost of drilling [15]. Furthermore, the analysis confirms the notion that change in the heating sector happens very slowly [15], which is illustrated by the fact that ever though low-temperature boilers are not an option for actors in the model, the still constitute 16,53% of heating systems by 2035, down from a share of 42.35% in 2020.

The results also indicate that gas technology will play a pivotal role in Lower Saxony's heating market in the next 15 years, as they constitute at least half of the heating technologies in all scenarios. Oil boilers, however, strongly decline and are not financially attractive in any scenario. This is due to the low efficiency and the resulting higher fuel costs of the systems.

Another crucial factor influencing the emission reduction is the chosen implicit discount rate. The sensitivity analysis shows that, particularly if the discount rate is higher than 12%, emission reductions are greatly slowed down. Consequently, it is of critical relevance to what extent actors devalue future energy costs, i.e., to what extent their risk aversion, their reference point-like preference and their time preference influence their decision-making behavior [42].

4.2. Policy Recommendations

Overall, the results demonstrate that due to the inertia of the sector, the effect of policy instruments is deferred. Hence, two aspects should be considered in policy formulation. First, the continued support for gas hybrid technologies has to be called into question, as the emissions of gas -even though it is less CO_{2e}-intensive than oil- put the target out of reach. Therefore, policy makers should aim to increase the speed with which the energy carrier is phased out and discontinue its support through subsidies. Secondly, policy should aim at speeding up the exchange of heating systems as a short-term measure in order to facilitate the necessary shift in the sector. Possible measures could include lowering the age of the mandatory replacement of heating boilers from 30 to 25 or policies aimed at raising public awareness, as the exchange of fossil fuel heating systems for renewable ones is not established in the general public as an action to fight climate change [76].

Furthermore, the promotion of heat pumps in combination with PV systems is a blind spot of the MAP funding program, as it only applies to thermal solar systems [77]. The subsidy actually foreseen via the Energy Feed Act expires in 2021, after which self-consumption is the most economical option for homeowners [78]. In addition, when the heat pump is coupled to a PV system, a heat pump electricity tariff can no longer be claimed for technical reasons [56]. Consequently, the economic efficiency of the combination is conceivably unfavorable, which is why it was not chosen by any actor in the model. Therefore, an additional subsidy specifically for PV systems that supply electricity for the operation of heat pumps is advisable.

Lower Saxony could take a pioneering position in terms of the heat transition and come closer to achieving the goals set out in the Lower Saxony Climate Protection Law [33].

A state subsidy specifically for purely renewable technologies can achieve a significant additional CO_{2e}-reduction of 4.2% by 2035, with 7.5% additional subsidies to the investment costs. In doing so, it optimizes the impact of the Climate Action Program 2030 by shifting the funding focus away from gas technologies. Such a funding program could be incorporated into the comprehensive package of measures currently being developed as part of the Climate Protection Law [33]. Like existing subsidy loans, it could be administered through the development bank of the state of Lower Saxony (NBank) [79].

The system dynamics modelling approach shown in this paper has some limitations. First, rational choice assumption, which actors' behavior is modeled after, are a strong simplification of reality. Even though some barriers have been included through the implicit discount rate, some factors are not represented in the model, such as a restricted access to capital, environmental preferences or neighborhood effects [80]. Consequently, the mapped decision context loses complexity due to these simplifications. However, research shows that economics factors are pivotal in the decision for a heating system [39,40,81]. Second, the -in most parts- simplified data base further limits the results. In general, detailed building data are only available to a very limited extent, and detailed registers on the energy performance of buildings are not available [11,53]. This is particularly noticeable at the state level. For example, it was not possible to gather information on the energy coefficient of each building class specifically for Lower Saxony, thus the climatic conditions of the state could not be taken into account. Lastly, this work focusses on energy and emission reductions as central parameter for the evaluation of policy measures. Additional sustainability concerns, such as land-use conflict for the production of biomass, should be included in the policy making process.

The model-based analysis of this paper creates an approach upon which future research can build: System Dynamics modeling is suitable for mapping the multi-layered mechanisms of the building market; the bottom-up perspective captures the complexity of the initial situation. Future work should take additional factors into account; for instance, regulatory policy instruments could be included through a change in expected costs [16]. Furthermore, incentives which more strongly encourage reduction in energy consumption through behavioral change [82], such as information campaigns or training, could be included. Those could be incorporated through additional feedback loops on the demand side.

Moreover, as climate change is likely to bring about an increased demand of cooling in Germany [83], the decision for or against air conditioning systems could be incorporated into the model to further refine it.

Overall, this work provides a solid basis to examine the policy options available to states in order to advance the heating transition on all possible levels. The evaluation can provide detailed insights into the extent to which state governments can expand upon federal policy schemes in the building sector.

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Appendix A. Cost Functions

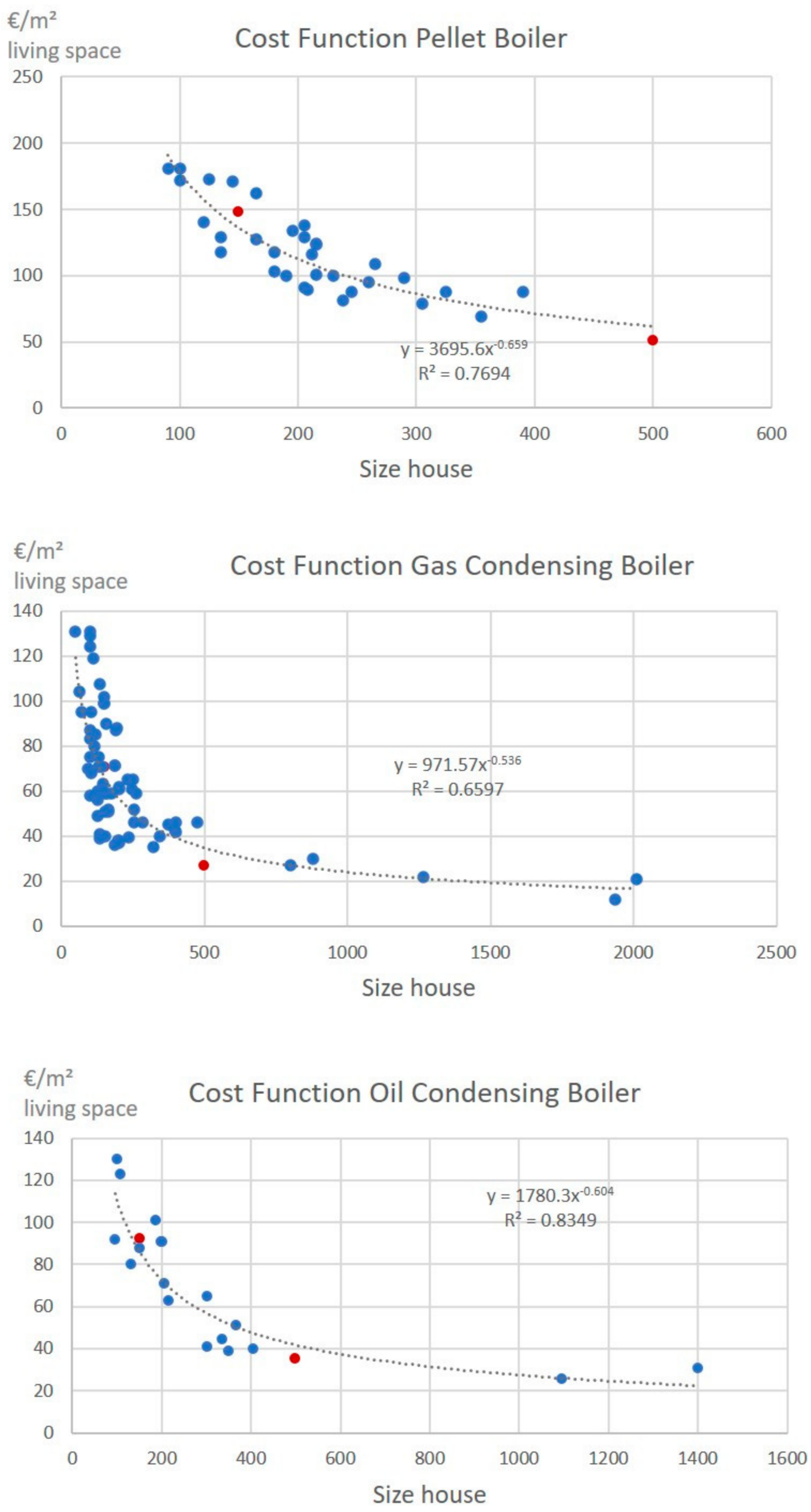

Figure A1. Calibrated cost functions for some heating systems with data from [61] (p. 51) and [46] (marked dark red).

Appendix B. Details of the First Two Modeled Scenarios BAU-Scenario

- MAP subsidies that apply for renewable heating systems, i.e., heat pumps, thermal solar collectors and pellet systems. For small houses, they are lump sump payments that differ depending on the technology. However, when the boilers or solar thermal collectors cross specific size related thresholds, the payments are dependent on either heating load or square footage in the case of solar thermal collectors. Therefore, the heating load was calculated through the useful energy consumption and full heating hours [84]. The square footage of the thermal collector had to be estimated using a formula by Acker [85] through the average amount of people living in the house.
- The KfW-Program promotes individual measures, like the exchange of a heating system, with a grant of 10% of the investment costs. In the model, the program applies to gas and oil heating systems, including those which are combined solar thermal collectors.

'Climate Package Scenario'

- The newly introduced carbon price for the building sector, which are introduced in 2021 and increase gradually until 2025. For the year 2026, a range between 55 and 65 Euros per tonne of CO_{2e} is intended which was simplified by the arithmetic mean, 60 Euros. This was further used for the remaining time frame of the model, since predictions are bound to a great amount of uncertainty. It is furthermore assumed that the consumer bears the complete costs.
- The MAP grants, which have been restructured and simplified. The most crucial alteration has been the shift from lump sum payments to grants that cover a specific percentage of the investment costs. They apply to all renewable heating systems as well has gas hybrid systems. If it is an oil boiler that is replaced, the covered percentage increases considerably, serving as the stipulated proposed 'oil boiler exchange premium' [77].
- The ban on oil boilers as of 2026. From this date on, oil heating technologies is no longer an option in the model.
- The increase in requirements for solar thermal collectors. They have to cover at least 25% of the heating load to receive the support under the amendment [77], which is roughly double in comparison to the scenario before. The investment costs were adjusted accordingly by including an adjustment factor of 1,5, derived from the real life calculations of Schmitz [86].

Appendix C. Results Sensitivity Analysis

Change in Price Progression	**Achieved Emission Reduction 2020–2035**		
	Oil and Gas	**Pellet Prices**	**Electricity Prices**
20% less increase	−26.48%	−32.11%	−30.37%
10% less increase	−27.09%	−30.40%	−28.53%
'Climate Package Scenario'	−28.65%	−28.65%	−28.65%
10% more increase	−31.49%	−27.57%	−28.61%
20% more increase	−33.22%	−27.36%	−28.61%

CO_2-Prices	**Achieved Emission Reduction (2020–2035)**
10 €/t lower	−28.14%
'Climate Package Scenario'	−28.65%
10 €/t higher	−29.36%
20 €/t higher	−30.14%
Trajectory of Wagner et al.	−30.90%
150 €/t from the starting point	−35.96%

Comprehensive Refurbishment Rate	**Achieved Emission Reduction (2020–2035)**
0%	−28.54%
'Climate Package Scenario'	−28.65%
0.33%	−28.86%
0.53%	−29.07%
0.73%	−29.28%

Implicit Discount Rate	**Achieved Emission Reduction (2020–2035)**
9.5%	−29.25%
'Climate Package Scenario'	−28.65%
18%	−26.45%
25%	−23.97%
30%	−23.10%
36%	−22.63%

Appendix D. Share of Technologies in the Different Scenarios

Table A1. Share of technologies BAU Scenario.

	2020	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**	**2031**	**2032**	**2033**	**2034**	**2035**
District heating	4.42%	4.42%	4.42%	4.42%	4.42%	4.42%	4.42%	4.42%	4.42%	4.42%	4.42%	4.42%	4.42%	4.42%	4.42%	4.42%
Gas CB	36.71%	38.71%	40.75%	43.50%	46.98%	50.46%	52.70%	54.93%	57.16%	59.39%	61.63%	62.99%	64.36%	65.72%	67.09%	68.45%
Gas low.-temp.	33.10%	31.78%	30.47%	28.74%	26.61%	24.48%	23.06%	21.64%	20.22%	18.80%	17.38%	16.43%	15.49%	14.54%	13.60%	12.66%
Oil CB	10.13%	9.78%	9.39%	8.88%	8.24%	7.60%	7.18%	6.76%	6.33%	5.90%	5.47%	5.19%	4.90%	4.61%	4.32%	4.04%
Oil low.-temp.	9.13%	8.77%	8.41%	7.93%	7.34%	6.75%	6.36%	5.97%	5.58%	5.19%	4.79%	4.53%	4.27%	4.01%	3.75%	3.49%
Air HP	2.10%	2.02%	1.94%	1.83%	1.69%	1.56%	1.47%	1.38%	1.28%	1.19%	1.10%	1.04%	0.98%	0.92%	0.86%	0.80%
Geothermal HP	0.31%	0.30%	0.29%	0.27%	0.25%	0.23%	0.22%	0.20%	0.19%	0.18%	0.16%	0.16%	0.15%	0.14%	0.13%	0.12%
Pellets	4.10%	3.94%	3.78%	3.56%	3.30%	3.03%	2.86%	2.68%	2.51%	2.33%	2.15%	2.04%	1.92%	1.80%	1.69%	1.57%
Pellets/ solar WH	0.00%	0.29%	0.57%	0.87%	1.17%	1.47%	1.76%	2.04%	2.32%	2.60%	2.89%	3.20%	3.52%	3.83%	4.14%	4.46%

Table A2. Share of technologies “Climate Package” Scenario.

	2020	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**	**2031**	**2032**	**2033**	**2034**	**2035**
District heating	4.42%	4.42%	4.42%	4.42%	4.42%	4.42%	4.42%	4.42%	4.42%	4.42%	4.42%	4.42%	4.42%	4.42%	4.42%	4.42%
Gas CB	36.71%	36.54%	36.34%	35.79%	34.98%	34.17%	33.59%	32.57%	31.48%	30.39%	29.29%	28.53%	27.74%	26.96%	26.18%	25.40%
Gas low-temp.	33.10%	31.78%	30.47%	28.74%	26.61%	24.48%	23.06%	21.64%	20.22%	18.80%	17.38%	16.43%	15.49%	14.54%	13.60%	12.66%
Gas CB/ Solar WH	0.00%	2.08%	4.08%	6.71%	10.15%	13.59%	15.82%	18.40%	20.99%	23.59%	26.15%	27.73%	29.34%	30.94%	32.49%	34.04%
Oil CB	10.13%	9.73%	9.33%	8.80%	8.14%	7.49%	7.06%	6.62%	6.19%	5.75%	5.32%	5.03%	4.74%	4.45%	4.16%	3.87%
Oil low-temp.	9.13%	8.77%	8.41%	7.93%	7.34%	6.75%	6.36%	5.97%	5.58%	5.19%	4.79%	4.53%	4.27%	4.01%	3.75%	3.49%
Air HP	2.10%	2.14%	2.28%	2.84%	3.55%	4.26%	4.71%	5.23%	5.70%	6.15%	6.61%	6.73%	6.84%	6.95%	7.06%	7.16%
Geothermal HP	0.31%	0.30%	0.29%	0.27%	0.25%	0.23%	0.22%	0.20%	0.19%	0.18%	0.16%	0.16%	0.15%	0.14%	0.13%	0.12%
Pellets	4.10%	3.94%	3.79%	3.60%	3.36%	3.13%	3.01%	2.90%	2.90%	2.90%	2.97%	3.23%	3.49%	3.76%	4.08%	4.42%
Pellets/Solar WH	0.00%	0.31%	0.60%	0.90%	1.20%	1.50%	1.78%	2.06%	2.35%	2.63%	2.92%	3.22%	3.53%	3.83%	4.13%	4.44%

Table A3. Share of technologies in the ‘Additional Incentive Programme Lower Saxony’-Scenario.

	2020	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**	**2031**	**2032**	**2033**	**2034**	**2035**
District heating	4.42%	4.42%	4.42%	4.42%	4.42%	4.42%	4.42%	4.42%	4.42%	4.42%	4.42%	4.42%	4.42%	4.42%	4.42%	4.42%
Gas CB	36.71%	36.54%	36.34%	35.25%	33.76%	32.12%	31.00%	29.85%	28.70%	27.54%	26.39%	25.48%	24.56%	23.65%	22.73%	21.82%
Gas low-temp.	33.10%	31.78%	30.47%	28.74%	26.61%	24.48%	23.06%	21.64%	20.22%	18.80%	17.38%	16.43%	15.49%	14.54%	13.60%	12.66%
Gas CB/ Solar WH	0.00%	2.08%	4.07%	6.66%	9.92%	11.52%	12.54%	12.95%	13.31%	13.94%	14.49%	14.68%	14.86%	15.04%	15.04%	15.10%
Oil CB	10.13%	9.73%	9.33%	8.80%	8.14%	7.49%	7.06%	6.62%	6.19%	5.75%	5.32%	5.03%	4.74%	4.45%	4.16%	3.87%
Oil low-temp.	9.13%	8.77%	8.41%	7.93%	7.34%	6.75%	6.36%	5.97%	5.58%	5.19%	4.79%	4.53%	4.27%	4.01%	3.75%	3.49%
Air HP	2.10%	2.14%	2.28%	3.38%	4.93%	8.28%	10.43%	12.95%	15.41%	17.60%	19.79%	21.11%	22.44%	23.09%	23.75%	24.34%
Geothermal HP	0.31%	0.30%	0.29%	0.27%	0.25%	0.23%	0.22%	0.20%	0.19%	0.18%	0.16%	0.16%	0.15%	0.14%	0.13%	0.12%
Pellets	4.10%	3.94%	3.80%	3.65%	3.44%	3.22%	3.15%	3.35%	3.65%	3.96%	4.34%	4.95%	5.55%	6.83%	8.28%	9.75%
Pellets/Solar WH	0.00%	0.31%	0.60%	0.90%	1.20%	1.50%	1.78%	2.06%	2.35%	2.64%	2.92%	3.23%	3.53%	3.83%	4.14%	4.44%

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