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Abstract

To decrease emissions from residential buildings, Germany employs a number of policies like renewable energy requirements, subsidies, and CO_2 prices that incentivize heating decarbonization. This paper analyses policy-driven household decision-making with regard to decentralized heating technology investment and the resulting costs. We apply a building level mixed integer linear programming model that computes optimal energy investment and operation for decentralized building energy technologies in 770 archetype buildings that represent the German residential building stock. We find that under renewable energy requirements, subsidies, CO_2 prices, high medium-term gas prices, and moderately increasing electricity prices, it is optimal for many buildings to replace their fossil systems prematurely by electric heat pumps, achieving quick and substantial decarbonization. However, the costs for decentralized decarbonization differ greatly between buildings: Some buildings profit from the subsidies, while others face high burdens. Especially, single family homes with recently installed gas and oil systems and inhabitants of multifamily homes potentially face high expenditures for CO_2 prices. Policymakers should consider these dynamics when prioritizing buildings for district heating or hydrogen in the municipal heat planning processes and when designing CO_2 price revenue recycling mechanisms.

Keywords: emission reduction, building sector, building stock, household heating, CO_2 pricing, building policy, MILP, archetype buildings, subsidies, decentralized technologies

JEL classification: C53, C54, D15, D30, H20, Q48

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1. Introduction

As Germany aims to be climate neutral in 2045, special attention is paid to the residential heating sector. Today, the majority of the country's 20.8 million residential buildings are heated by fossil fuels such as natural gas and oil (Statistisches Bundesamt, 2024) and energy efficiency is low (Diefenbach et al., 2016). Consequently, the decarbonization of residential buildings requires large-scale investments into heating systems and building envelopes, which largely have to be mustered by private households.

To stimulate the transformation, Germany has a number of policy instruments in place that aim at influencing the economic decision-making of building owners. They include renewable energy requirements, subsidies for energy efficiency measures, heating system replacement and residential solar energy generation, for example by photovoltaic (PV), as well as CO_2 prices.

Building energy policy is subject to a public debate and most recently the legislative process around implementing a 65% renewable energy requirement for all new heating systems has sparked a public debate on costs and cost distribution of the transformation of the heating sector, with many doubting the ability of private households to raise the required capital and asking questions about distributional fairness (Pitel, 2023).

To contribute to the ongoing debate, this paper analyzes the cost of decentralized building energy technologies under building energy policy. We apply a building level heat and electricity supply optimization model to derive optimal energy investment and operation decisions for decentralized building energy technologies in 770 archetype buildings, which reflect the heterogeneity of the German building stock in terms of heating systems and their remaining lifetime as well as energy demand. We compare two scenarios: The *policy* scenario, which considers major policy elements such as renewable energy requirements, subsidies, and CO_2 prices and a *reference* scenario without policy intervention. Applying this model landscape allows us to calculate optimal investments in decentralized technologies, decarbonization, and costs across the German buildings stock. The results are used to discuss building energy policy beyond the decentralized options modelled in this paper, such as refurbishment, centralized solutions (e.g. district heating) as well socio-economic concerns such as building ownership structure and distribution effects.

We find that under high medium-term gas prices, moderately increasing electricity prices and the considered policy elements, electric heat pumps are the optimal decentralized technology and investment is often done prematurely, i.e. before the end of the existing heating technology's lifetime. This leads to quick decarbonization. However, the cost burden differs greatly between building types: Some households benefit greatly from the subsidies, while others face high cost burdens. For example, single family homes with recently added existing gas and oil systems do not have an incentive to invest early and face high expenditures for CO_2 prices. In multifamily homes, decentralized decarbonization leads to high capital costs for building owners and the owner-tenant dilemma may prohibit optimal decision-making. This may delay the phase-out of existing fossil technologies, which puts inhabitants of multifamily homes in danger of high CO_2 price burdens. The results can be used by policy-makers to prioritize buildings with high burdens for alternative decarbonization options such as district heating and hydrogen in the course of the ongoing municipal heat planning processes or for refurbishment. Additionally, the results can inform policy-makers, when designing CO_2 price revenue recycling mechanisms because they show that subsidies already lead to a certain unequal redistribution of costs.

The remainder of this paper is structured as follows: Section 2 gives an overview of the related literature and highlights the contribution of this paper. Section 3 describes the method, technology and building stock data, and analytical framework. Section 4 provides an overview of German building energy policy and introduces the scenarios. Section 5 presents the model results for each scenario and discusses the resulting costs and cost distribution. Section 6 discusses the results and reflects them beyond the chosen method. Section 7 concludes on the findings and gives an outlook on further research.

2. Related literature and contribution

A vast body of literature is dedicated to model-based economic analysis of building energy policy in Germany. The literature is diverse both in research angles and methods. For example, many publications analyze the mitigation potential of different building energy policy measures. Commonly, two types of methods are applied to model building energy development: Heuristic methods or models with endogenous decision-making. Heuristic methods as applied in (e.g. Bürger et al., 2019; Olonscheck et al., 2011; Markewitz et al., 2016) extrapolate building stock development and resulting emissions based on projections for underlying factors, such as technology investment and refurbishment, i.e. using a top-down approach. In a bottom-up approach,Moritz et al. (2024) calculate LCOH of different heating options for different building and settlement types under different energy prices and search the solution space for efficient heating technologies.[1] However, part of German building energy policy is based on economic incentives such as technology-specific subsidies and taxes or CO_2 prices. These types of policies affect the economic decision-making of households without mandating specific technology options, and thus endogenous modelling of decision-making is a more suitable approach. Endogenous approaches to modelling energetic modernization and technology investment can be categorized into two groups: Approaches based on annual demands and technical approaches that model technology investment and operation in a higher temporal resolution. In the first category, discrete choice (e.g. Löffler/Dieckhöner and Hecking, 2014; Bauermann, 2016) and multinomial logit (e.g. Henkel, 2012) models are a common choice to model diffusion of main heating technologies under building energy policy. Additionally, Frondel and Schubert (2021) (in a partial equilibrium of the household sector) and Kirchner et al. (2019) (in a macro scale input-output model) use empirical price elasticities to model household behavior under CO_2 pricing. These models, which are based on annual demands, are computationally inexpensive. However, some building energy technologies, like solar technologies, heat pumps or storage systems have temporally variable characteristics. Additionally, demand varies over time. To consider the simultaneity of temporally variable components, researchers often opt for mixed integer linear problem (MILP) investment and operation models. These models minimize the cost of a building's energy supply under consideration of higher temporal resolutions. MILP models are computationally more expensive, which often limits the number of scenarios or considered buildings. Such a model is developed and applied to model the effect of CO_2 pricing on four exemplary households in Frings and Helgeson (2022). Kotzur et al. (2020) apply another model to 200 households representative of the German building stock, to estimate 2050 costs and grid loads. They

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[1] This forthcoming paper is co-authored by Berit Hanna Czock.

do not consider German building energy policy in their example scenario and do not distinguish between heating systems with different ages. In a similar approach, McKenna et al. (2017) analyze the impact of self-sufficiency requirements on electricity load profiles in the UK.

Building energy policy literature often analyzes resulting technology choices, energy demands, emissions, and costs. Some publications discuss the economic efficiency of policies by deriving abatement costs, i.e. costs per saved t of CO_2 (e.g. Löffler/Dieckhöner and Hecking, 2014; Bauermann, 2016; Hecking and Löffler/Dieckhöner, 2017). Instead of focusing on technology diffusion, Frondel and Schubert (2021) and Kirchner et al. (2019) discuss distributional effects of CO_2 prices against socioeconomic characteristics of the households and compare different revenue recycling mechanisms in Germany and Austria respectively. Rausch et al. (2011) carry out a similar analysis for the US, however, in their general-equilibrium model households consume fuels at fixed amounts. In a top-down approach, Schaffrin (2013) perform a regression of income and types of climate policies on household utility costs across a sample from 18 European countries and 14 years. While socioeconomic factors are well represented, the literature on distributional effects lacks detailed representation of household decision-making. Consequently, the resulting energy demands, emissions, and costs are less robust compared to literature with endogenous decision-making.

The paper at hand adds to the existing literature by developing a model for cost and cost distribution of decentralized heating decarbonization under incentive based building energy policy in Germany. To do so, we employ a high-resolution consumer decision-making MILP model (Frings and Helgeson, 2022) to a set of archetype buildings that is representative of the German building stock, including existing heating systems and their remaining lifetime. By comparison with a reference scenario, which allows us to quantify anyway costs, we determine the additional costs and burdens associated with policy-driven investment in decentralized heating systems. We then use the results to discuss distribution effects induced by building energy policy in Germany. Doing so, even though we do not take socio-economic parameters into account, we bridge the gap between detailed technical and economic modelling of household decision-making under incentive-based policy and the discussion of distribution effects.

3. Modelling residential buildings

The paper at hand examines optimal investment decisions in decentralized energy technologies and subsequent costs and burdens of archetype buildings of the German residential building stock from 2020 until 2045 under building energy policy. The technology development and operation for each building is modelled applying a building optimization model, which is presented in Section 3.1. Section 3.2 describes the representation of the German residential building stock in terms of archetype buildings, and Section 3.4 elaborates on the considered technology options. Section 3.5 concludes the model description with a summary.

3.1. Consumer technology investment and operation model

The model for "Consumer Management of Decentralized Options" (COMODO) was introduced by Frings and Helgeson (2022). COMODO is a MILP cost minimizing model for the energy supply of a specific consumer or consumer group. Consumers are predefined in terms of their annual space heating, hot water, and electricity (non-heating purposes) demands. Given the annual demands, the model optimizes investment into decentralized energy technologies for space heat, hot water, and residential electricity generation as well as their operation. The cost minimisation considers technology investment costs, fixed operation and maintenance costs (FOM) and fuel costs. Investment costs are modelled as piece-wise linear cost functions in order to account for non-linear scale effects in costs. The model allows to optimize the consumer choice over the span of multiple years, considering an hourly resolution of demand schedules and technology operation. A detailed model description, including an overview of the technology catalog considered in this paper, is presented in Appendix A.

3.2. Archetype buildings for the existing building stock

We define a set of archetype buildings that are representative of the German building stock. The archetype buildings are defined by a number of attributes that reflect the input requirements of the COMODO model. Table 1 lists the attributes and sets them in relation to the underlying building and household characteristics. Based on these attributes, we derive 770 archetype buildings that are representative of the existing building stock.

	Characteristics
Heat demand - space heating [kWh/a]	Form: Total floor area; number of floors; floor height Envelope: Exterior walls; insulation
Heat demand - water heating [kWh/a]	Operation: Occupancy
Electricity demand [kWh/a]	Operation: Occupancy; lightning; appliances
Technology endowment	System: Installed systems and age; installed infrastructure
Usable roof area [m^2]	Form: Roof area; shading; orientation
Demand profiles	Operation: Occupancy; schedules; location

Table 1: Considered attributes and corresponding building and household characteristics based on Corgnati et al. (2013)

The definition of archetype buildings is based on a comprehensive building database developed in Scharf et al. (2021).[2] The building stock database from Scharf et al. (2021) is based on the data set provided by Heitkoetter et al. (2020), who utilised a special evaluation of the German census data. The database from Scharf et al. (2021) consists of 2574 representative buildings and their assumed occurrence to approximate the German building and technology stock of the year 2019. As the optimization problem described in Appendix A is computationally demanding, there is a need to reduce the number of representative buildings.[3] Figure 1 illustrates the steps for determining 770 archetype buildings[4] that represent the building stock of the year 2019.

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[2] The work was also co-authored by one of the authors of this paper as part of the *Erdgas Bridge* research project supported by the German Federal Ministry for Economic Affairs and Energy.

[3] The number of 770 representative buildings represents a trade-off between maintaining model accuracy and managing computational resources. On the hardware used for this study (AMD EPYC 7763 64-Core Processor CPU @2.44GHz, 64GB RAM), the optimization problem took an average of around 5 minutes per household, totaling approximately 60 CPU hours per optimization run with 770 representative buildings.

[4] In their definition of reference buildings Corgnati et al. (2013) distinguish between *example buildings* based on experts' assumptions, *real buildings*, and *theoretical buildings* based on statistical data. Our archetype buildings can be classified as *theoretical buildings* as they are not derived from a database of real buildings, but are created synthetically from statistical data of the building stock.

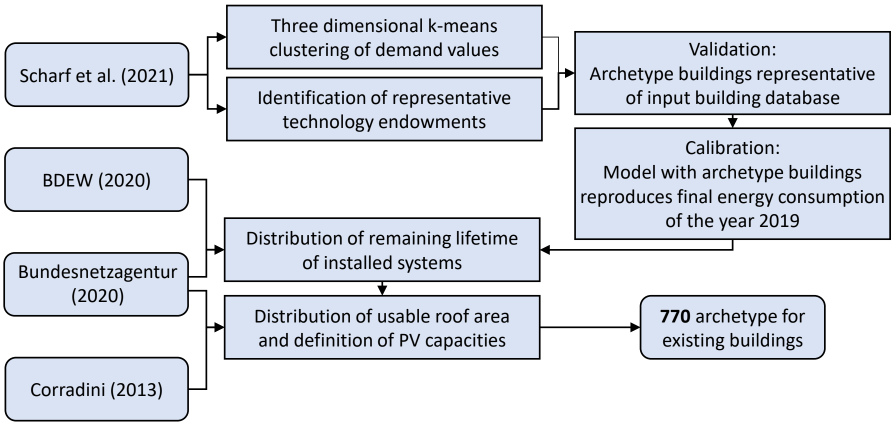

Figure 1: Building aggregation approach

This approach results in three building categories: SFH, small MFH, and large MFH. SFH contain one unit, which corresponds to one household. Small MFH contain 2.77 residential units/households on average, and large MFH contain 13.81 residential units/households on average.

Step 1: Demand clustering.

Within these building categories, we differentiate between different demand levels. Each building is defined by three annual demand values: space heating, hot water heating, and electricity not used for heating purposes. Using a three-dimensional k-means clustering approach, we identify 13 representative combinations of the three dimensions of demand for the existing building stock.[5] Energetic refurbishment over time is not modelled, as we focus solely on the investment decisions regarding energy technologies.

Step 2: Technology endowment.

Based on the database from Scharf et al. (2021), we identify 66 representative combinations of technology endowments and the representative demand combinations. Each of the technology combinations is defined by a *heating type*, a *heating system*, a *hot water technology*, and the category of *PV system*. For example, the most common technology combination in the database is a central

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[5] Figure D.6 in Appendix D.1 shows the graphical representation of the clustering results. Figure D.7 in Appendix D.1 shows that by using these 13 demand combinations, we can closely reproduce the demand distribution from Scharf et al. (2021).

heating system (supplying both, space heating and hot water heating) fuelled with oil and without a PV system. A special case results from the endowment of buildings with existing biomass heating, district heating, liquid gas heating and coal heating, which we subsume in the category *others*. These buildings are assumed to stick with their heating technology and are thus only optimized in terms of meeting their electricity demand and, if they do not have central heating, their heat demand for water heating. To derive the number of occurrences for each of the combinations, firstly, the share of each technology endowment within each of the 13 identified building types is determined. This reproduces the contributions of the individual technologies to the provision of the three demand variables based on the underlying database. Secondly, the final share of each technology endowment is adjusted to reproduce the final energy consumption of German residential buildings in 2019 based on AGEB (2021).[6]

Step 3: Heating system age.

For the pre-existing heating system endowments, i.e., systems already existing in the building stock in 2019, we assume a finite lifetime of 30 years. Based on this assumption and the distribution of the heating systems' age in 2019 from BDEW (2020), we define the year for latest heating system replacement, thus adding another dimension to the definition of the archetype buildings.

Step 4: PV capacities and solar potential.

Scharf et al. (2021) provide the number of installed PV systems in each building type: 1.2 million in SFH, 266,000 in small MFH, and 54,000 in large MFH. In Bundesnetzagentur (2023), the German transmission grid operators publish an inventory of registered renewable power plants including existing PV systems and their installed capacity and year of construction. We assume that the smallest PV installations in the inventory are installed on SFH, followed by small MFH and large MFH. Based on this we estimate the average size of installed PV systems in SFH to be 7 kW, in small MFH to be 16 kW, and in large MFH to be 25 kW. The total installed capacity on existing residential buildings following this approach amounts to 14.2 GW.

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[6] In the course of the calibration, it was also determined what proportion of the demand of the archetype buildings is provided by wood-fired secondary heating systems. Based on FNR (2019) and Döring et al. (2020), we estimate the useful energy provided by wood-fired secondary heating to be 33 TWh in 2019. Based on Döring et al. (2020), we assume that this useful energy demand is distributed across approximately 6 million buildings.

Additionally, buildings with an existing PV system are defined in terms of the construction year of the PV system. We utilize data on the year of construction of existing plants in Germany, separated into SFH and MFH. According to the year of construction of the systems, households receive different feed-in tariffs. The assumptions on construction year distributions are shown in Appendix D.2. We assume a technical lifetime and corresponding funding period of 20 years.

The building-specific potential for new solar installations is calculated based on Corradini (2013) who estimates available rooftop space for solar (thermal) installations on residential buildings in a bottom-up analysis. We estimate the total net available rooftop area of the building stock for SFH at 438 km^2, for small MFH at 137 km^2, and for large MFH at 85 km^2. With regard to building type-specific potential, not all buildings are considered to be suitable for PV installations. By assuming that rooftops must be able to harbor the building type specific calculated average installed capacity for installed PV systems, we estimate that 57% of SFH, 38% of small MFH, and 18% of large MFH have the potential to install PV systems.[7]

The differentiation according to the demand, technology endowment, installed systems' remaining lifetime, and the solar potential results in 770 archetype buildings for the existing building stock. Besides the specific characteristics, each building is defined by the absolute number of occurrences to be representative of the building stock in the year 2019. A complete list of the archetype buildings is included in Appendix D.4.[8]

3.3. Existing systems

While the type and age of the existing heating system for each archetype building is obtained from the data, the actual installed capacity was determined using COMODO and reflects cost minimal investment. The technical and economic assumptions used to optimize the initial capacity are shown in Appendix C.2. One exception to this method is the design of existing PV systems, which is described in 3.2. It should be noted that the investment costs of existing technologies are assumed as sunk and cannot be recovered. Thus, replacing existing systems before the end of their lifetime will not recover investment costs, but FOM costs do not have to be paid any longer.

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[7] A more detailed description of the underlying assumptions and estimates can be found in Appendix D.3.

[8] 110 of the 770 representative buildings are assigned the technology endowment *others*, i.e. technologies that are not endogenously modelled. 40 are assigned the technology endowment *night storage heater*.

3.4. Technology options

Generally, households can invest into the decentralized technologies presented in Appendix A. The technology catalog includes electric and gas heat pumps, boiler technologies and a multitude of additional technologies such as flow heaters, solar thermal systems, storage systems and PV. As we model the costs and cost distribution associated with decentralized building decarbonization, technology options such as hydrogen and district heating, which require additional infrastructure and thus decision-making on a centralized level, are excluded from the initial analysis. Additionally, we exclude biomass (pellet) heating, due to the potentially limited availability of biofuels in the future[9]. Within the technology catalog, specific investment options depend on the building type. We distinguish between buildings that have centralized supply, i.e. SFH and MFH with a single system supplying all residential units, and split supply in MFH with single-story heating. We assume that buildings cannot change the nature of their heating circuit systems. Thus, buildings with existing centralized systems reinvest in centralized heating systems when replacing their existing system. Centralization of the heating supply in buildings with single-story heating is not considered in the endogenous decision-making. Thus, for buildings with existing single-story heating, technology options are limited to single-story systems supplying each unit individually. We assume that these buildings cannot install large thermal storage capacities used for heating due to space restrictions. However, they can install small-scale thermal storage for hot water buffering. Similarly, these buildings can only install solar thermal for hot water generation but not for space heating. This is due to the fact that all MFH have water pipes and they are often at a central location. Thus, solar thermal for hot water supply can be added relatively easily. Contrarily, the centralized heating circuit needed for solar thermal heating is missing. Next to centralization on the buildings scale, we distinguish between central and decentral supply of hot water. If buildings have central supply, i.e. the boiler provides both, hot water and space heating, typically a thermal storage system is needed in order to allow buffering. Buildings can choose between central or decentral supply of hot water in the course of the endogenous decision-making and can opt for separate hot water heating using typical single-story systems such as flow heaters. Finally, we

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[9] c.f. Hennenberg and Böttcher (2023) who highlight the trade-off between harvesting wood for biomass heating and the potential for natural sinks needed to achieve carbon neutrality in 2045.

assume that buildings with existing night storage heaters and *other* technologies continue to rely on their technologies. To take into account the different flow temperatures in the building stock, we also distinguish between buildings with high and low flow temperatures. The latter can invest in more efficient heat pump technologies than the former.[10] Finally, as described in Section 3.2 not all buildings have the option to invest in a PV system.

3.5. Application of COMODO to the archetype buildings

COMODO is applied to each archetype building individually and optimizes its decentralized energy provision by minimizing total costs (which include investment, FOM and energy costs). The optimization spans the years 2020-2045 and considers steps of five years, taking into account the technology endowment of 2019 or the year of construction in the case of new buildings. For the case of SFH, which contain one residential unit, optimization takes the perspective of a household. For MFH with centralized heating, we optimize from a building point of view, summing up all residential units within a MFH. For buildings with single-story heating, we optimize from a residential unit point of view, which we assume to correspond to a household. However, in both cases we assume that all residential units in a MFH have the same characteristics. It has to be noted that the majority of inhabitants in MFH are renters and thus they do not have control of investment decisions. This is discussed in detail in Section 6.1.

4. Building energy policy

This section introduces building energy policy in Germany (4.1) and the scenario approach used to quantify its cost effects (4.2).

4.1. Current legislation

German building energy policy comprises different elements such as renewable energy requirements for new and replacement heating systems, lump-sum investment subsidies for investments and feed-in tariffs for PV and CHP as well as CO_2 prices. Together, these elements create a complex

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[10] We assign low flow temperatures to buildings with comparably low specific heat demands. The number of existing buildings with low flow temperatures in our model corresponds approximately to the new constructions of the last 20 years.

incentive structure that influences decision-making for building energy investment. Generally, according to the *Law on building energy* (German abbreviation: GEG), new heating systems have to achieve a minimum renewable share of 65% starting January 1^{st} 2024. Electrical heating systems, for example, with heat pumps or direct electric heaters, hybrid heating systems, and biomass heating with wood pellets or similar, are defined as renewable. For the time being, the renewable requirement holds for newly built buildings. For existing buildings, the starting date is linked to the *Law on heat planning and decarbonization of heating networks* (German abbreviation: WPG). The WPG obliges the federal states to ensure the finalization of heating plans (district heating and hydrogen) by June 30^{th} 2026 for municipal areas with over 100,000 inhabitants and by June 30^{th} 2028 for municipal areas with less than 100,000 residents.[11] Until the region's heat planning has been finalised, building owners are not bound by the 65% requirement set in the law. In these cases, investment in a conventional gas heating system is still permitted after an obligatory consultation. Nevertheless, if a gas system is installed between January 1^{st} 2024 and the publication of the municipal heat plans, it is required to operate with 15% climate-neutral gas, for example from biomass or hydrogen, starting in 2029. This share of renewables rises to 30% by 2035 and to 60% by 2040. Another exemption from the 65% renewable requirement is granted for MFH with single-story heating. If one of the single-story boilers fails and has to be replaced, a decision on whether heating is to be centralized must be made within five years. Implementation of the central heating system must then be completed within another eight years. If single-story heating is maintained, all new boilers in the building must achieve the 65% requirement five years after the failure of the first boiler. There are exceptions and hardship provisions for all parts of the law.

The 65% renewable requirement is flanked by the federal investment subsidy program as per the *Guideline for federal funding for efficient buildings - Individual measures* (German abbreviation: BEG EM). Homeowners receive onetime investment subsidies of 30%. Additional subsidies are grated to lower-income households (additional 30%) if the heating systems are exchanged prematurely (additional 20% for exchange until 2028)[12] or if a heat pump is installed that uses a natural

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[11] Furthermore, the WPG defines the target to provide 30% of every heating network with heat from renewable energies or unavoidable waste heat by 2030 and 80% by 2040.

[12] This additional subsidy amounts to 20% until 2028, after which it will decrease by 3%-points every two years

refrigerant or ground, water, or waste water as a heat source (additional 5%). Households can use a combination of bonuses. However, the full subsidies may not exceed 70% of the costs. Also, lump sum subsidies of up to 20% are granted for efficiency gaining measures such as refurbishment. This incentive scheme is flanked by low-interest loans for investments in specific heating technologies, building envelope refurbishment, and further efficiency measures provided by the semi-state owned KfW bank. Next to such lump sum incentives, residential electricity generation technologies are subsidized through feed-in tariffs and energy-based remunerations for self-consumption. Feed-in tariffs for residential PV systems stem from the general German RES support scheme (*Law on the expansion of renewable energies*, German abbreviation: EEG). Feed-in tariffs incentivize homeowners to install rooftop PV panels and feed (excess) electricity into the grid. By creating investment incentives for electricity generation via PV, the respective policies also influence the opportunity cost regarding electrical technologies combined with PV, for example, electric heating or electric storage technologies.

In addition to the technology-specific funding, the *Law on National Certificate Trading for Fuel Emissions* (German abbreviation: BEHG) implements a national CO_2 price for the sectors not included in the existing European emission certificate trading scheme (EU-ETS). Under this scheme, consumers from the transport, building, and non-EU-ETS industry sectors are charged per t of CO_2 emitted from fuel combustion. CO_2 prices target any kind of behavior leading to CO_2 emissions and therefore create an incentive for decreasing energy consumption as well as switching fuels, i.e. replacement of heating systems. CO_2 prices have long been discussed as an effective method to incentivize CO_2 abatement. Weitzman (1974) argues that compared to direct quantity control, CO_2 prices can be a suitable instrument for inducing abatement when regulating many independent units, as those being able to reduce emissions at lower costs are "screened out" first. In the German case, CO_2 prices are set to increase from 25 EUR/tCO_2 in 2021 to 45 EUR/tCO_2 in 2025.[13] After 2025, prices will emerge from a market for CO_2 certificates.

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thereafter, i.e., from January 1^{st} 2029 it will be 17% (2031 14%; 2033 11% and 2035 8%). The bonus will no longer apply after 2036.

[13] The CO_2 price for 2025 was increased to 55 EUR/tCO during the publication process of this paper. The impact of this change is discussed in Section 6.

4.2. Scenario design

To estimate the future technology costs associated with building energy policy, we set up two scenarios: The *reference* scenario computes the optimal investment and operational decisions of the archetype buildings in a business-as-usual scenario undistorted by building energy policy. The *policy* scenario considers major elements from German building energy policy and their incentives with regard to decentralized building energy technologies. The scenarios can be compared to derived additional decarbonization and costs incurred by the policies, thus allowing to count out anyway costs.

4.2.1. Reference and Baseline Economic Assumptions

Economic decision-making regarding energy technologies is influenced by fixed costs and operation costs and their relation, which in turn depend on building specific demands. Fixed costs consist of fixed operation costs and capital costs, i.e. the annualized value of technology-specific investment costs given the lifetime.[14] All assumptions on economic parameters are made in real terms and reflect 2020 levels. The assumptions on fixed operation and investment costs are described in detail in Frings and Helgeson (2022) and in Appendix C. Operation costs in the *reference* scenario are defined by fuel costs, i.e. the end-user prices for oil, electricity, and gas. Fuel prices are assumed exogenously. For oil and natural gas, the assumptions on wholesale prices are based on the German Federal Environment Agency's projections report 2023 (Mendelevitch et al., 2022). To compute end-user prices, taxes, fees, and other surcharges for gas are held constant at 2020 levels.

Electricity prices, too, are end-user prices including wholesale prices, taxes, fees, and surcharges. The electricity price path is therefore constructed from assumptions on the individual components. We assume that taxes and fees (excluding grid fees) remain constant in absolute numbers. For the grid fees we assume an increase of 19% by 2030 (vs. 2018), 27% by 2040, and 33% by 2050, following Mendelevitch et al. (2022). We account for the termination of the EEG surcharge at the end of 2023. To ensure consistency between price assumptions for different energy carriers, wholesale prices are based on electricity market modeling that is consistent with current climate targets for

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[14] Costs are discounted with an interest rate of 1.6%, which corresponds to a long-term average of borrowing cost, as derived based on European Central Bank (2021)

the electricity system. To this end, the energy system model used in (EWI, 2021), was expanded to include the current climate change legislation and updated with the fuel price projections described earlier and used in this paper.[15] A special case is given for electricity consumed by heat pumps, which historically have received a reduced electricity tariff. Analogously, we assume that heat pumps are offered tariffs at 90% of the general end-consumer electricity price.

All end-consumer fuel price assumptions are summarized in Table 2.

	2020	2025	2030	2035	2040	2045
Oil	5.1	6.9	5.8	5.8	5.7	5.7
Gas	6.5	10.8	7.4	7.3	7.1	7.0
Electricity	32.2	30.5	26.6	28.4	28.9	30.0

Table 2: End-consumer fuel price development (ct/kWh)

We assume that the electricity fed into the grid from PV systems is compensated either according to a technology-specific market value of electricity or based on existing feed-in tariff commitments. The market value is calculated as the product of the wholesale price and technology specific value factor. Both assumptions are presented in Table E.18 in Appendix E.1. For existing PV systems, a continuation of eligibility for already established feed-in subsidies is assumed until their end of life (20 years). In Appendix D.2, the assumed feed-in tariffs are shown depending on the age of the systems, based on historical legislation.

4.2.2. Policy scenario

In the *policy* scenario, buildings have to fulfil the renewable requirement of 65% from 2025 on. An additional equation in the model ensures that for new investments, the heat generated over one year, i.e. space heating and heat for domestic hot water, from renewable sources (including electricity) must be greater than 65% of the total heat generated in the year. This assumption neglects the linkage between the individual (GEG) and municipal heat planning (WPG), which is discussed in Section 6.

Analogously to current German policies, when investing, buildings receive two types of subsidies that essentially decrease investment costs for the subsidized technologies: Lump sum investment

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[15] The approach and underlying assumptions are described in more detail in Appendix E.1.

subsidies as granted per the BEG EM and feed-in tariffs or remunerations for electricity generated from PV systems. We assume lump sum subsidies of 30%, which reflects the basic support for renewable technology investments according to the BEG EM. Further subsidies considered by the BEG EM are not part of this study, as they were still under debate during the time of writing and likely largely based on socio-economic factors.

Electricity generation from newly installed PV panels is subsidized via fixed feed-in tariffs. Based on Art. 49, EEG we assume feed-in tariffs to decline by 1% per month, reaching 6.2 ct/kWh and 5.4 ct/kWh for SFH and MFH, respectively, for systems installed in 2025 and 3.4 ct/kWh and 2.9 ct/kWh for systems installed in 2030. In our model, consumers can choose between the fixed feed-in tariff and the market value-based remuneration, as in *reference* scenario. As the feed-in tariff declines, choosing the feed-in tariff is economical only for systems installed before 2030.

CO_2 prices increase operation costs of fossil-fired technologies proportionally to the fuel-specific emission factor and the efficiency of the systems. By increasing costs associated with fossil-fired technologies, CO_2 prices decrease the relative cost of low emission technologies. According to the sectoral balancing of emissions applied in German energy policy, electricity has an emission factor of zero, as the emissions are accounted for in the electricity sector. According to the BEHG, the price for CO_2 to increase is set to increase from 24 EUR/tCO_2 in 2021 to 38 EUR/tCO_2 in 2025 (25 EUR/tCO and 45 EUR/tCO respectively in nominal terms). After 2025, when prices will emerge from a market for CO_2 certificates, based on Mendelevitch et al. (2022) we assume an increase to 196 EUR/tCO_2 until 2045.

5. Results

This chapter presents the model results. Section 5.1 gives an overview of the results on investment decisions and decarbonization. Section 5.2 presents the resulting costs and cost distribution across the building types.

5.1. Investments and emissions

The following gives an overview of the results regarding investment decisions and decarbonization in the *reference* and *policy* scenarios, and compares the CO_2 emissions between the scenarios. In addition to the summary given in the following, the results are presented in more detail in Appendix F.

5.1.1. Reference scenario

In the *reference* scenario, there are no subsidies or CO_2 prices that alter the economics of the technology options[16] and thus investment decisions are solely driven by energy prices and investment and FOM costs.

Figure 2 summarizes the investment decisions into main technologies as well as additional systems and investment timing. The color code gives the fuel type of the main technology. While green indicates an electric heat pump, red stands for gas -fueled heating systems, and gray means oil heating. If only parts of the buildings in a category decide for a fuel switch, the color is mixed by the weighted number of buildings (see the list of archetype buildings in Appendix D.4) using the corresponding main heating technology.

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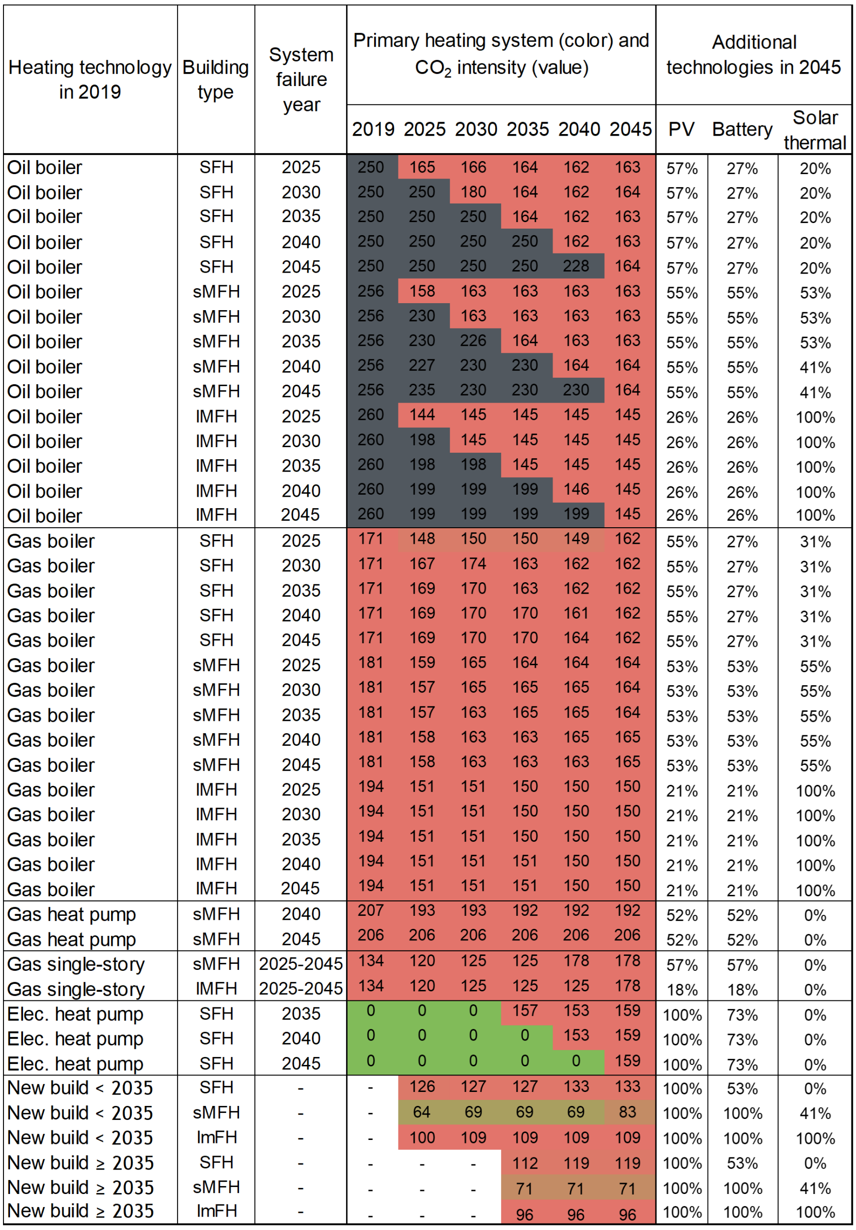
[16] Except for historical PV feed-in tariffs which are assumed to be continued until the failure of the existing PV system.



Heading technology in 2019	Building type	System failure year	Primary heating system (color) and CO_2 intensity (value)						Additional technologies in 2045		
			2019	2025	2030	2035	2040	2045	PV	Battery	Solar thermal
Oil boiler	SFH	2025	250	165	166	164	162	163	57%	27%	20%
Oil boiler	SFH	2030	250	250	180	164	162	164	57%	27%	20%
Oil boiler	SFH	2035	250	250	250	164	162	163	57%	27%	20%
Oil boiler	SFH	2040	250	250	250	250	162	163	57%	27%	20%
Oil boiler	SFH	2045	250	250	250	250	228	164	57%	27%	20%
Oil boiler	sMFH	2025	256	158	163	163	163	163	55%	55%	53%
Oil boiler	sMFH	2030	256	230	163	163	163	163	55%	55%	53%
Oil boiler	sMFH	2035	256	230	226	164	163	163	55%	55%	53%
Oil boiler	sMFH	2040	256	227	230	230	164	164	55%	55%	41%
Oil boiler	sMFH	2045	256	235	230	230	230	164	55%	55%	41%
Oil boiler	lMFH	2025	260	144	145	145	145	145	26%	26%	100%
Oil boiler	lMFH	2030	260	198	145	145	145	145	26%	26%	100%
Oil boiler	lMFH	2035	260	198	198	145	145	145	26%	26%	100%
Oil boiler	lMFH	2040	260	199	199	199	146	145	26%	26%	100%
Oil boiler	lMFH	2045	260	199	199	199	199	145	26%	26%	100%
Gas boiler	SFH	2025	171	148	150	150	149	162	55%	27%	31%
Gas boiler	SFH	2030	171	167	174	163	162	162	55%	27%	31%
Gas boiler	SFH	2035	171	169	170	163	162	162	55%	27%	31%
Gas boiler	SFH	2040	171	169	170	170	161	162	55%	27%	31%
Gas boiler	SFH	2045	171	169	170	170	164	162	55%	27%	31%
Gas boiler	sMFH	2025	181	159	165	164	164	164	53%	53%	55%
Gas boiler	sMFH	2030	181	157	165	165	165	164	53%	53%	55%
Gas boiler	sMFH	2035	181	157	163	165	165	164	53%	53%	55%
Gas boiler	sMFH	2040	181	158	163	163	165	165	53%	53%	55%
Gas boiler	sMFH	2045	181	158	163	163	163	165	53%	53%	55%
Gas boiler	lMFH	2025	194	151	151	150	150	150	21%	21%	100%
Gas boiler	lMFH	2030	194	151	151	150	150	150	21%	21%	100%
Gas boiler	lMFH	2035	194	151	151	150	150	150	21%	21%	100%
Gas boiler	lMFH	2040	194	151	151	151	150	150	21%	21%	100%
Gas boiler	lMFH	2045	194	151	151	151	150	150	21%	21%	100%
Gas heat pump	sMFH	2040	207	193	193	192	192	192	52%	52%	0%
Gas heat pump	sMFH	2045	206	206	206	206	206	206	52%	52%	0%
Gas single-story	sMFH	2025-2045	134	120	125	125	178	178	57%	57%	0%
Gas single-story	lMFH	2025-2045	134	120	125	125	125	178	18%	18%	0%
Elec. heat pump	SFH	2035	0	0	0	157	153	159	100%	73%	0%
Elec. heat pump	SFH	2040	0	0	0	0	153	159	100%	73%	0%
Elec. heat pump	SFH	2045	0	0	0	0	0	159	100%	73%	0%
New build < 2035	SFH	-	-	126	127	127	133	133	100%	53%	0%
New build < 2035	sMFH	-	-	64	69	69	69	83	100%	100%	41%
New build < 2035	lmFH	-	-	100	109	109	109	109	100%	100%	100%
New build ≥ 2035	SFH	-	-	-	-	112	119	119	100%	53%	0%
New build ≥ 2035	sMFH	-	-	-	-	71	71	71	100%	100%	41%
New build ≥ 2035	lmFH	-	-	-	-	96	96	96	100%	100%	100%

Figure 2: Investment, CO_2 footprint and timing in the *reference* scenario

Note: Colors indicate whether gas systems (red), oil systems (gray) or electric heat pumps (green) are installed by buildings in a category and in a year. Colors are mixed according to the weighted number of buildings using the corresponding technology, if choices within a building category and year are not uniform. Numbers indicate the average CO_2 intensity in g/kWh of heating within each building category and year. Right columns list the percentage of buildings having PV, batteries, and solar thermal installed in 2045 within each building category.

Main heating technology.

As illustrated by the color coding, under the economic assumptions in the *reference* scenario, gas boilers are the cost-efficient option for the main heating technology across almost all building types. Even buildings with an existing electric or gas heat pumps switch to gas boilers. Technology replacement occurs exclusively when existing boilers reach the end of their lifetime. A major reason for this is that investment costs of existing technologies are considered as sunk. Therefore, a technology switch before the end of lifetime of a technology happens only if efficiency gains of the new technology lead to a reduction in variable costs that outweigh investment costs for a new technology. Contrarily, new buildings, which enter the building stock from 2025 on, have no pre-existing heating system with sunk costs or existing PV systems with persisting feed-in tariffs. Most new buildings opt to install gas boilers in combination with simple power to heat peak systems. However, some small MFH install electric heat pumps as they can profit from economies of scale but have relatively low energy demands compared to larger MFH, which do not install heat pumps. Conclusively, heat pumps can be optimal even without policy intervention, if no existing heating system with sunk costs is available. However, this affects only a limited number of buildings.

PV and battery storage systems.

In addition to the main heating system, many buildings invest into additional technologies such as PV, battery storage systems, solar thermal systems and thermal storage to reduce cost of electricity and hot water in light of increasing energy prices. Figure 2 illustrates the share of buildings that have a solar technology or a battery storage system installed in 2045. All buildings that have a PV option, install PV by 2040. Often, PV is installed when the existing boiler fails, in order to alllow for a joint optimization of capacity and buildings can wait for investment cost digression. In some cases, this means that buildings with an existing PV system go without PV for an intermediate period. High electricity demands in MFH or SFH with electric flow heaters and all buildings with night storage heaters[17] leads to early investment into PV immediately in 2025. Many buildings invest in battery storage to better align electricity demand and PV generation, i.e. to increase

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[17] These buildings are not displayed in 2 because it is assumed that they cannot change their main heating technologies. The same is true for buildings with *other* heating technologies which behave largely like buildings with oil and gas boilers in terms of their additional technologies.

self-consumption and avoid increasing electricity prices. Larger electricity demand favors early investment into a battery system in 2030 if a PV system exists by that year. Buildings with smaller demands chose to invest in 2045 when battery costs have decreased further. Small SFH do not invest into battery storage since they have low electricity demands and the energy cost savings do not justify investment into battery systems.

Hot water and thermal storage systems.

Many buildings opt for additional hot water heating technologies, which helps decreasing energy costs and capacity costs of the main boiler. The energy demand and their pre-existing hot water heating technologies determine this investment. For example, existing gas flow heaters are replaced by electric flow heaters in the long term. Often an investment is done prematurely, in order to avoid increased medium-term gas prices. Buildings with PV also invest into electric flow heaters to increase PV self-consumption and minimize the new boiler's capacity when re-investing their main heating technology. Central hot water generation is almost always accompanied by a buffering storage system to allow capacity reduction.

Additionally, buildings with existing condensing oil and gas boilers and high energy demands such as larger SFH and MFH invest into solar thermal to decrease energy demand in light of increased medium-term fuel prices (especially in the case of gas). In the case of large demands, efficiency gains outweigh the relatively high investment and maintenance costs of the solar thermal systems. Solar thermal systems are also typically accompanied by a thermal storage system to allow the alignment of generation and demand. MFH with gas single-story heating can only supply hot water but not heating with solar thermal, and thus they do not invest in this technology. Existing PV systems hinder investment into solar thermal systems as the systems compete for the same rooftop area.

Peak units.

Furthermore, most buildings invest into simple power to heat peak units to decrease the heat peak and thus the capacity costs of new boilers. SFH with small demand, who already install the smallest possible heat pump, and MFH with gas single-story systems form an exception. The latter cannot invest into simple power to heat because this technology requires a central space heating system and a larger scale thermal storage, which is typically not used in buildings with single-story heating.

CO_2 intensity.

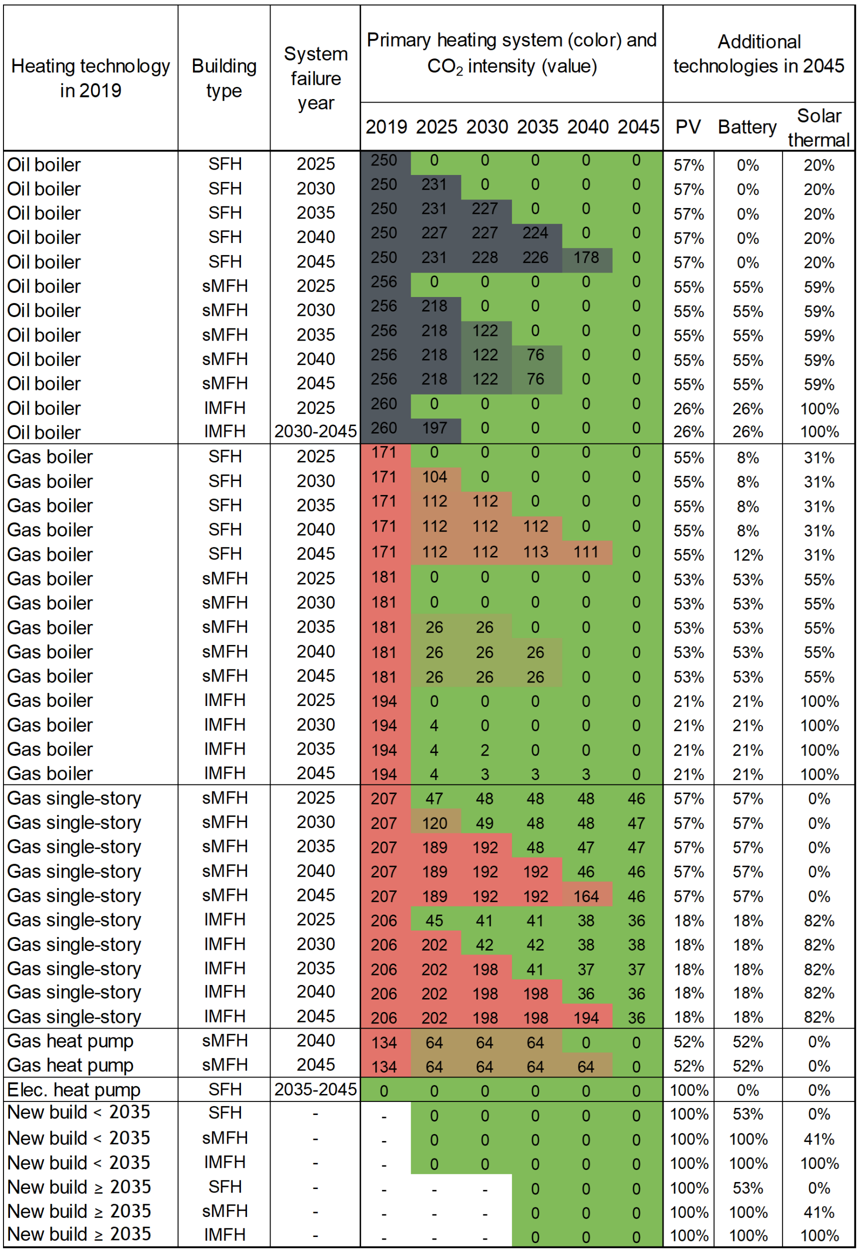
In addition to the technology choices, Figure 2 shows the resulting average CO_2 intensity of heating and hot water generation for the different building categories and in each year. All in all, investment in the *reference* scenario leads to a certain decarbonization that is mainly caused by oil boilers being replaced by gas boilers and self-consumption of PV-generated electricity from newly installed PV systems in electric space heat and hot water systems. However, for buildings with existing renewable systems, CO_2 intensity increases as they switch to gas boilers.

5.1.2. Policy scenario

In the *policy* scenario, the economics of heating investments are subject to the 65% renewable energy requirements, lump sum subsidies and feed-in tariffs, and CO_2 prices.

Main heating technology.

As shown in Figure 3, all buildings invest into electrical heat pumps at the latest, when their existing heating system fails. Under the increased decarbonization pressure associated with the policies, many buildings opt to invest prematurely, foregoing the benefits from exploiting their existing technologies with sunk costs. Especially MFH, which have significant capacity demands and can benefit from economies of scale on the heat pump investment, chose to invest early. Premature investment differs between buildings with existing oil and gas boilers. First, all premature investment in buildings with existing gas heating occurs in 2025 to avoid the high gas prices in the medium term. For buildings with oil boilers, CO_2 costs are the main driver for premature investment. As CO_2 price increases are more of a long-term factor, premature investment in buildings with oil boilers occurs later than in their gas heating counterparts. Second, all MFH with existing gas boilers invest into heat pumps immediately, while small MFH with existing oil boilers only invest into a heat pump prematurely if they have a PV option. Last, high medium-term gas prices trigger premature replacement of gas boilers in SFH with low flow temperatures, who can install more efficient heat pumps, while SFH with oil boilers do not replace their heating systems prematurely.



Heading technology in 2019	Building type	System failure year	Primary heating system (color) and CO$_2$ intensity (value)						Additional technologies in 2045		
			2019	2025	2030	2035	2040	2045	PV	Battery	Solar thermal
Oil boiler	SFH	2025	250	0	0	0	0	0	57%	0%	20%
Oil boiler	SFH	2030	250	231	0	0	0	0	57%	0%	20%
Oil boiler	SFH	2035	250	231	227	0	0	0	57%	0%	20%
Oil boiler	SFH	2040	250	227	227	224	0	0	57%	0%	20%
Oil boiler	SFH	2045	250	231	228	226	178	0	57%	0%	20%
Oil boiler	sMFH	2025	256	0	0	0	0	0	55%	55%	59%
Oil boiler	sMFH	2030	256	218	0	0	0	0	55%	55%	59%
Oil boiler	sMFH	2035	256	218	122	0	0	0	55%	55%	59%
Oil boiler	sMFH	2040	256	218	122	76	0	0	55%	55%	59%
Oil boiler	sMFH	2045	256	218	122	76	0	0	55%	55%	59%
Oil boiler	lMFH	2025	260	0	0	0	0	0	26%	26%	100%
Oil boiler	lMFH	2030-2045	260	197	0	0	0	0	26%	26%	100%
Gas boiler	SFH	2025	171	0	0	0	0	0	55%	8%	31%
Gas boiler	SFH	2030	171	104	0	0	0	0	55%	8%	31%
Gas boiler	SFH	2035	171	112	112	0	0	0	55%	8%	31%
Gas boiler	SFH	2040	171	112	112	112	0	0	55%	8%	31%
Gas boiler	SFH	2045	171	112	112	113	111	0	55%	12%	31%
Gas boiler	sMFH	2025	181	0	0	0	0	0	53%	53%	55%
Gas boiler	sMFH	2030	181	0	0	0	0	0	53%	53%	55%
Gas boiler	sMFH	2035	181	26	26	0	0	0	53%	53%	55%
Gas boiler	sMFH	2040	181	26	26	26	0	0	53%	53%	55%
Gas boiler	sMFH	2045	181	26	26	26	0	0	53%	53%	55%
Gas boiler	lMFH	2025	194	0	0	0	0	0	21%	21%	100%
Gas boiler	lMFH	2030	194	4	0	0	0	0	21%	21%	100%
Gas boiler	lMFH	2035	194	4	2	0	0	0	21%	21%	100%
Gas boiler	lMFH	2045	194	4	3	3	3	0	21%	21%	100%
Gas single-story	sMFH	2025	207	47	48	48	48	46	57%	57%	0%
Gas single-story	sMFH	2030	207	120	49	48	48	47	57%	57%	0%
Gas single-story	sMFH	2035	207	189	192	48	47	47	57%	57%	0%
Gas single-story	sMFH	2040	207	189	192	192	46	46	57%	57%	0%
Gas single-story	sMFH	2045	207	189	192	192	164	46	57%	57%	0%
Gas single-story	lMFH	2025	206	45	41	41	38	36	18%	18%	82%
Gas single-story	lMFH	2030	206	202	42	42	38	38	18%	18%	82%
Gas single-story	lMFH	2035	206	202	198	41	37	37	18%	18%	82%
Gas single-story	lMFH	2040	206	202	198	198	36	36	18%	18%	82%
Gas single-story	lMFH	2045	206	202	198	198	194	36	18%	18%	82%
Gas heat pump	sMFH	2040	134	64	64	64	0	0	52%	52%	0%
Gas heat pump	sMFH	2045	134	64	64	64	64	0	52%	52%	0%
Elec. heat pump	SFH	2035-2045	0	0	0	0	0	0	100%	0%	0%
New build < 2035	SFH	-	-	0	0	0	0	0	100%	53%	0%
New build < 2035	sMFH	-	-	0	0	0	0	0	100%	100%	41%
New build < 2035	lMFH	-	-	0	0	0	0	0	100%	100%	100%
New build ≥ 2035	SFH	-	-	-	-	0	0	0	100%	53%	0%
New build ≥ 2035	sMFH	-	-	-	-	0	0	0	100%	100%	41%
New build ≥ 2035	lMFH	-	-	-	-	0	0	0	100%	100%	100%

Figure 3: Investment, CO$_2$ footprint and timing in the *policy* scenario

Note: Colors indicate whether gas systems (red), oil systems (gray) or electric heat pumps (green) are installed by buildings in a category and in a year. Colors are mixed according to the weighted number of buildings using the corresponding technology, if choices within a building category and year are not uniform. Numbers indicate the average CO$_2$ intensity in g/kWh of heating within each building category and year. Right columns list the percentage of buildings having PV, batteries, and solar thermal installed in 2045 within each building category.

Contrarily to buildings with condensing boilers, which supply whole buildings, buildings with gas single-story heating rarely invest prematurely. We do not consider centralization of heat supply for these buildings and thus they have to rely on small-scale heat pumps for decarbonization. For single-story heating technologies, economies of scale are not expected, as multiple individual units have to be installed. Premature replacement only occurs in small MFH with a short remaining lifetime of the boiler and an existing PV system or the option to install one. These buildings have only small benefits from their existing boiler with its sunk costs and can cover large shares of their new electricity demand with PV.

PV and battery storage systems.

Similar to the *reference* scenario, buildings invest into additional technologies like PV, battery storage, and solar thermal to decrease energy costs. Again, all buildings with a PV option, including those with night storage heaters and exogenously modelled *other* main heating technologies, install PV. However, investment often occurs immediately in 2025 and thus earlier than in the *reference* scenario, as buildings receive feed-in tariffs when investing early. Feed-in tariffs, however, hinder investment into battery systems, as it is economical to feed (excess) electricity into the grid rather than to maximise self-consumption. Again, the earliest investment year for battery storage is 2030 when investment costs decreased.

Hot water and thermal storage.

In light of the renewable energy requirement, hot water generation is electrified. Buildings with low energy demand install electric flow heaters to decrease the capacity costs of the main boiler if PV is available. Furthermore, electric flow heaters replace existing gas flow heaters once they failed. Buildings without a PV option install (subsidized) solar thermal. Even MFH with gas single-story heating, who can only use it to supply hot water but not space heating, install solar thermal. Compared to the *reference* scenario, investments in solar thermal happen earlier and often before the main heating technology is replaced in order to avoid CO_2 prices. Solar thermal systems are always accompanied by thermal storage. Additionally, buildings with PV and electric flow heaters use existing or newly built thermal storage to align hot water demand and (PV) generation.

Peak units.

Like in the *reference* scenario, buildings complement their main heating system with simple power to heat peak units, which are used to decrease capacity costs. Additionally, some MFH keep their existing gas boilers and use them as peak boilers. For those buildings that require large capacities, capacity cost savings on the heat pump outweigh the significant fixed costs of the gas boiler and the resulting CO_2 costs. Additionally, feed-in tariffs of existing PV systems make selling (excess) electricity to the grid more beneficial than using it in electric peak systems or storing it until needed. This increases the attractiveness of gas peak boilers in buildings with existing PV.

5.1.3. CO_2 emissions

As is evident from the average CO_2 intensities given in Figure 3, substantial decarbonization is achieved early on.

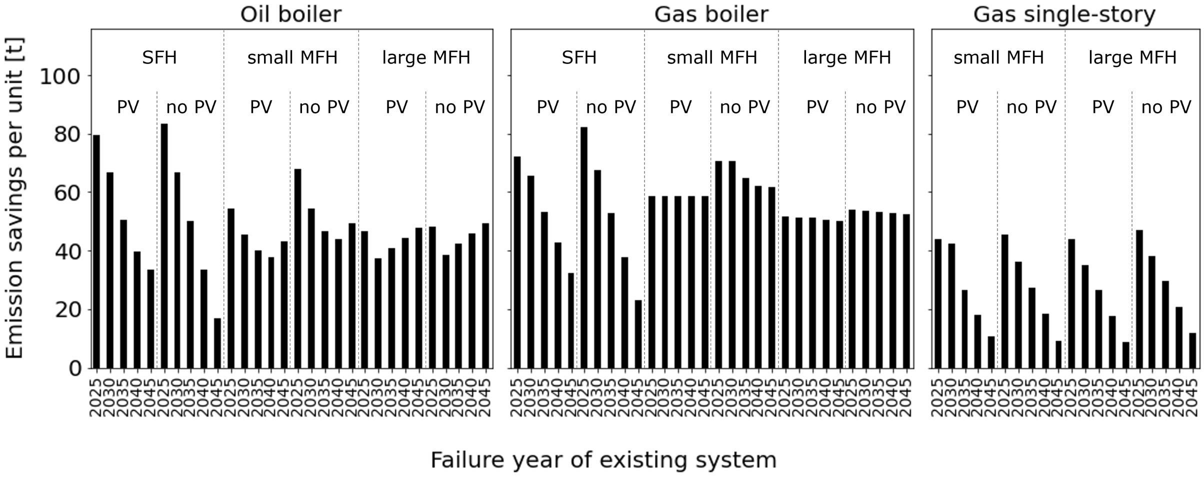


Figure 4: Average cumulative (2020-2045) emissions saved per residential unit for building categories compared to *reference*

Figure 4 shows the cumulative (2020-2045) abatement, i.e. the emissions saved under the policies in comparison to the *reference* scenario for the buildings that have the most significant abatement, i.e. buildings with existing oil and gas boilers. Abatement is expressed in saved t of CO_2 per residential unit in order to compare buildings with different sizes and across the main drivers for investment, i.e. building type, reinvest year, PV option, and existing technology. Compared to the *reference* scenario, the highest per-unit abatement is achieved in SFH with old existing systems.

Emission saving in SFH decreases with remaining system lifetime. This is due to the fact that there is little premature investment in SFH, and mostly old systems get replaced by heat pumps early. Despite oil having a higher emission factor, abatement is quite similar for SFH with oil and gas heating, as buildings replace their oil boilers with gas boilers in the *reference* scenario. The longer the remaining lifetime, the bigger the difference between oil and gas. Notably, having a PV option slightly decreases abatement in SFH. This is due to the fact that under feed-in tariffs in the *policy* scenario, SFH opt to feed PV electricity into the grid. Due to sector-based balancing of emissions, the respective abatement is not accounted for in the building sector. Contrarily, in the *reference* scenario with no feed-in tariffs for new PV, buildings optimize self-consumption, thereby reducing the consumption of fossil fuels in the building sector.

In small MFH with existing oil boilers, abatement is highest for old systems, which are replaced immediately, lowest for medium age system and higher again for recently installed systems, which are replaced prematurely. PV leads to slightly higher abatement, as self generated electricity can be used for peak supply. For small MFH with existing condensing gas boilers and a PV option, abatement is similar for all system failure years, as all of these buildings invest in electric heat pumps prematurely whereas they maintain gas boilers in the *reference* scenario. For small MFH without PV, some buildings with recently installed systems do not invest prematurely and thus have lower abatement than buildings who have to replace their systems immediately. Small MFH with gas single-story heating do not replace their gas heaters prematurely and thus abatement is higher, the older the existing system, i.e. the earlier it is expected to fail. Having PV has no effect on abatement in these buildings, as they cannot channel self-generated electricity for space heating in simple power to heat peakers.

For large MFH with existing oil boilers, abatement is highest for old systems, which are replaced immediately, and for recently installed systems that get replaced prematurely and lowest for medium age systems. Large MFH with existing condensing gas boilers all invest early, and thus abatement is independent of the system age. Abatement in large MFH with existing gas single-story heating is identical to small MFH with existing gas single-story heating.

5.2. Costs and cost distribution

The decarbonization policies lead to additional costs compared to the *reference* scenario, as they trigger investment into capital intensive technologies. We distinguish between *full costs*, i.e. investment, FOM and operation costs and the households *burden* that results from policy induces transfer payments: from the state to building owners (subsidies) and from households to the state (CO_2 prices). The earlier the replacement of the existing systems, the higher the full costs. Thus, buildings with old existing systems or building attributes that lead to premature investment have higher additional costs. MFH tend to have lower full costs (per residential unit) than SFH due to scale effects. For the majority of households, the burden differs from the full costs, depending on building attributes such as type, existing system and its age, demand, and PV potential.

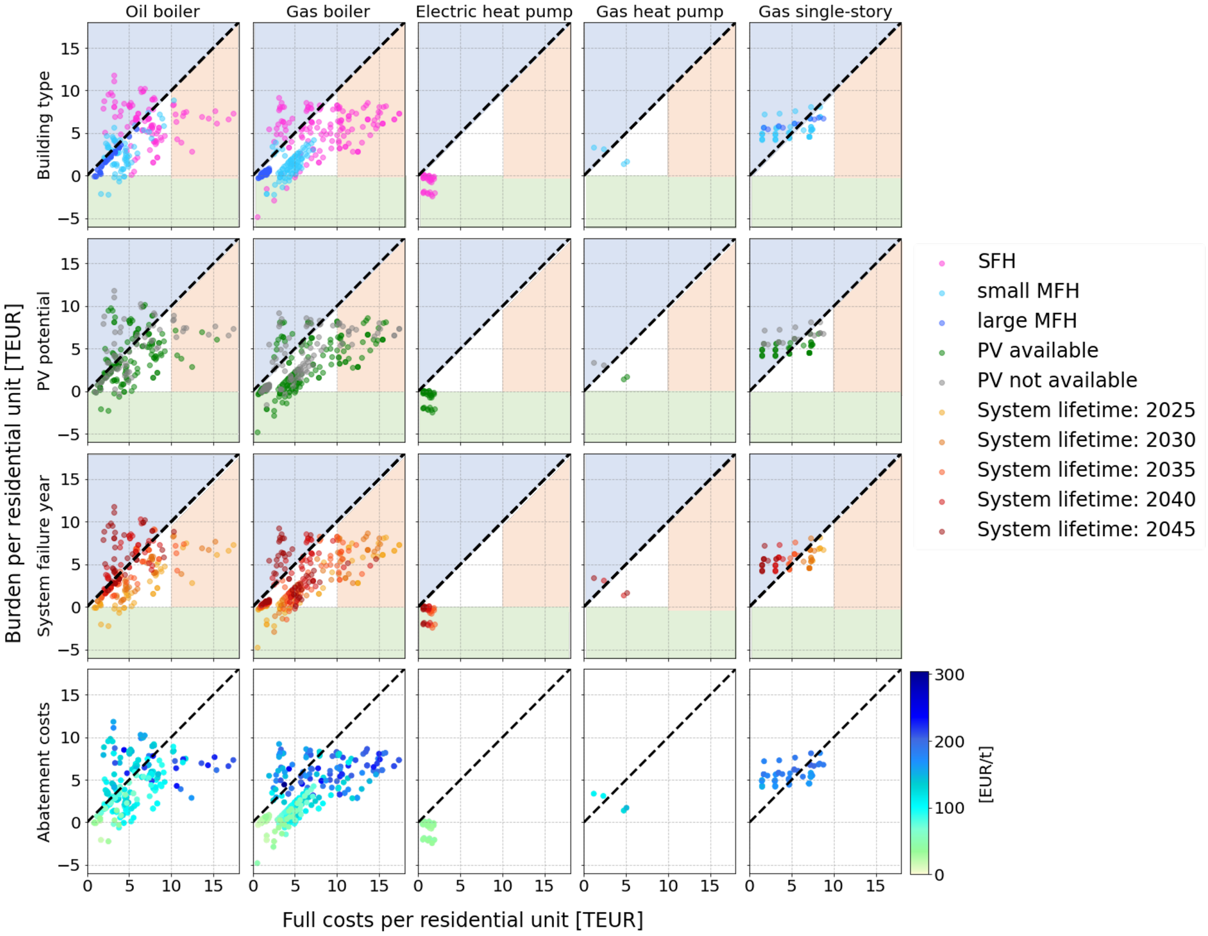


Figure 5: Burden vs. full costs per residential unit of the archetype buildings by existing heating system, building type, PV potential and year of system failure, and abatement costs 2020-2045.

Figure 5 illustrates the individual full costs and the specific burden per residential unit against these determining factors. Costs and burdens are expressed as additional expenditures compared to the *reference* scenario for the entire scenario time frame from 2020 to 2045.[18]

For most buildings the burden per residential unit is lower than the full costs, meaning that they have at least some net benefit from the policies (orange and white areas - orange are buildings with high full costs >10,000 EUR, white are buildings with relatively low full costs <10,000 EUR). However, for a significant number of building types, per unit burdens are higher than their full costs, i.e. CO_2 price payments outweigh subsidies and are added to investment, maintenance, and energy costs (blue area). A few buildings make a net profit from the policies, as their burden is lower than in the *reference* scenario due to the subsidies they receive (green area).

Orange area: Burden < additional full costs, high additional full costs.

The buildings in the orange area, which exhibit the highest additional full costs, are buildings with existing oil and gas boilers, specifically SFH with the highest specific heat demands ($> 160 kWh/m^2$), and relatively old existing heating systems fall into this category. These heating systems must be replaced at an early stage by electric heat pumps, which leads to high full costs. The burden for these buildings is lower than the full costs (they are located below the dashed line in Figure 5) since the government covers parts of the costs via feed-in tariffs and subsidies. Due to the early heating system replacement, CO_2 price expenditures are low. Having a PV option decreases the burden due to the feed-in tariffs, while it increases the full costs. Buildings with gas heating have higher costs than those with oil heating, as they often invest earlier (prematurely) due to high medium term gas prices when heat pump costs are still relatively high. Buildings in the orange area have relatively high costs per unit. Conclusively, the policies seem useful to trigger substantial decarbonization, while relieving households of the burden.

In the literature, the efficiency of policy measures is often evaluated in terms of abatement costs, i.e. costs per saved tonne of CO_2. Intuitively, from a cost-saving perspective, it makes sense to decarbonize first, where abatement costs are the lowest. To determine whether this is the case, in

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[18] Buildings with night storage heaters and *other* heating technologies are excluded from this analysis, as they have to reinvest in their existing technology. Generally, their burdens are lower than their full costs, as they install subsidized technologies like PV and solar thermal.

theory, one would come up with a merit order of abatement options and determine whether policy has lead to picking the cheapest options up to the desired amount of decarbonization or the CO_2 price. Deriving such a curve would require running our model multiple times while sequentially reducing allowed CO_2 emissions for all archetype buildings, and is beyond the scope of this paper. However, looking at average abatement costs as a snapshot from the given scenario, the buildings in the orange category have relatively high abatement costs. This is due to the fact that as SFH, they cannot benefit from economies of scale and thus the heat pump investment costs per residential unit are higher than in MFH.

White area: Burden < additional full costs, low additional full costs.

Buildings that fall into the white area are diverse. They have additional full costs below 10,000 EUR, part of which is borne by the state (burden < full costs). For example, SFH with older existing systems and lower specific heating demands and low flow temperatures can be found here. These SFH have lower capacity needs and thus investment costs are lower, than for the SFH with high specific heat demands. Additionally, heat pumps are more efficient at low flow temperatures, which saves energy costs. All in all, SFH in the white area invest earlier than those in the orange area (either due to system failure or prematurely) and consequently abatement is higher, which leads to lower abatement costs for these buildings. Additionally, MFH with centralized heating can be found in the white area. MFH with centralized heating have lower per unit costs due to the economies of scale in the installation of large centralized heating systems, which reduce the costs per kW heating capacity. Thus, the per unit full costs and burden decrease with the number of residential units within a building. Having a PV option brings in additional subsidies, further decreasing their burden. The MFH in this category achieve relatively high abatement at low costs. All in all, in the case of MFH with centralized heating, the modelled policies seem to trigger substantial and low-cost decarbonisation, while lowering the burden.[19] Unlike MFH with centralized supply, MFH with single-story heating can only rely on split heat pumps for decarbonization, which do not achieve economies of scale. There is almost no premature investment in MFH with single-story

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[19] As mentioned before, inhabitants of MFH are often renters and may not benefit from subsidies, which is discussed in Section 6.1.

heating. Yet, buildings with old existing systems that have to be replaced until 2030 can benefit from subsidies and fall into the white area, too. However, due to the limited availability of decentralized decarbonization options, these buildings have high abatement costs and the discussion of building energy policy should include an assessment of additional options for them.

Blue area: Burden > additional full costs.
MFH with gas-fueled and rather new single-story heating systems do not invest prematurely into heat pumps. Thus, they have high CO_2 price expenditures and their burden exceeds their total costs. They are located in the blue area above the dashed line. These buildings have limited decarbonization options, and thus their abatement costs are high. Here, a discussion of the fairness of cost distribution is in order. SFH and small MFH with new oil and gas boilers, especially if they have no option for PV, can also be found in the blue area, where burdens exceed full costs. In one case, the burden from CO_2 price expenditures can double the costs. The buildings with the highest burden (>11,000 EUR) are SFH with high specific heat demand and oil boilers who cannot invest in PV and whose heating systems do not fail until 2045. These buildings have high abatement costs due to the fact that not having a PV option hinders investment into heat pumps. Additionally, as SFH, they do not benefit from economies of scale enough to justify premature investment even under subsidies in combination with CO_2 prices. Buildings with existing gas heat pumps and no PV option also fall into the blue category, even though to a lesser extent, as their heat pumps' efficiency helps to save energy and CO_2 price expenditures.

Green area: Profits.
Decarbonization policies lead to net profits for buildings with existing fossil boilers if they have low demands, old heating systems and a PV option. For these buildings, which lie in the green area, additional full costs under decarbonization policies are relatively low, as capacity needs are low. Subsidies and feed-in tariffs overcompensate their additional costs, resulting in windfall gains. The lowest burden (approx. -4,800 EUR) occurs for SFHs with the lowest assumed specific heat demand (101 kWh/m2), whose gas heating system needs to be replaced in 2025 and has a flow temperature of 35°C. The additional full costs in this well-insulated, modern house are very low: the electric heat pump is almost economical without state policies. In this case, subsidies

achieve substantial decarbonization. However, in some cases, costs are well over-compensated, which leads to a question of distributional fairness when compared to other buildings with high burdens. Additionally, buildings with existing electric heat pumps are particularly well-off and make net profits from subsidies. They can make the highest gains, if their existing PV system fails in 2025. In this case, they can invest in new PV systems in 2025, which still promise relatively high feed-in tariffs, leaving them with a negative burden of around -2,000 EUR. Nevertheless, it should be noted that especially buildings with existing electric heat pumps faced high investment costs rather recently. That means that they had comparably high investment costs, which are considered sunk in this analysis.

6. Discussion

Our analysis is focused on policy-driven decision-making with regard to decentralized technology options. To generalize the results, this section analyzes the impact of additional aspects not covered in the model: special subsidies in the BEG EM, recent CO_2 price increases, incentives for energy efficiency of the building envelope, municipal heat planning and additional heating technologies, incentives for centralization of single-story heating, building ownership structure, and CO_2 price revenue recycling. Additionally, analyze the robustness of the results in a sensitivity analysis and discuss the general caveats of perfect-foresight scenario modelling.

6.1. Additional policy aspects

Special investment subsidies

The investment decisions are significantly influenced by the 65% renewable requirement. This requirement is flanked by a variety of subsidies in the BEG EM. While our model considers the onetime investment subsidies of 30% for households, in reality there are additional subsidies for special cases. Firstly, the BEG EM grants an additional lump sum bonus for premature renewable investments fulfilling the GEG standards before 2037. This investment subsidy amounts to 20% until the end of 2028 and then linearly decreases until 2036. To benefit from the bonus, homeowners have to abolish their existing fossil heating system, which needs to be older than 20 years. The speed bonus is only granted for occupying owners, i.e. most likely owner occupied SFH. In our results, some SFH invest prematurely in the *policy* scenario in the early years. The additional subsidy would reduce the burden for these SFH. Furthermore, the subsidy may lead to SFH who do not invest prematurely in our results to do so, e.g. SFH without a PV option and a system older than 20 years. This would likely increase the full costs, as earlier investments are more expensive. However, the households would be able to avoid CO_2 prices. All in all, the speed bonus could decrease burdens for these households significantly and lead to even faster decarbonization in SFH than in the presented results. Next to the speed bonus, the BEG EM grants a bonus to homeowners with a taxable income of up to 40,000 EUR per year. Such socio-economic factors are not considered in this analysis. In reality, some of the investment resulting from our modelling might not take place due to limited financing capacities of households, although they are (under the assumptions made) profitable. This holds especially for premature investment, which might be postponed as far as possible (until system failure) if a household faces financing difficulties. The bonus for low-income households may mitigate this effect. However, as it is only granted to owner-occupiers, this may apply mostly to SFH. To summarize, some of the additional subsidies aim at relieving specific households from the cost burden associated with the decentralized heating transition. However, they mostly

CO_2 price increases

Building energy policy is subject to an ongoing political debate and as a result, the CO_2 price for 2025 was increased from 45 EUR/tCO_2 to 55 EUR/tCO_2 during the review of this paper. Increasing CO_2 prices in the short-term enhances the incentive for premature replacement of fossil-fuelled systems. Our results already show significant premature investment in buildings with existing gas boilers due to high medium-term gas prices. Higher CO_2 prices could lead to a similar effect in buildings with existing oil boilers. All in all, faster replacement would increase capital expenditures for the affected buildings, while decreasing operation costs. However, in buildings that do not invest prematurely, e.g. MFH with single-story heating, higher CO_2 prices would lead to even higher CO_2 price expenditures.

Incentives for building envelope efficiency

Increasing the building envelope efficiency and thereby decreasing heat demand is not included as an option in the endogenous decision-making modelled by our approach. Similarly, buildings cannot change their flow temperature. Building envelope efficiency and determining costs of increasing requires a detailed analysis of the different efficiency measures and the so-called anyway costs, i.e. costs that are related to building maintenance and not specifically to efficiency (e.g. as roof mending) (c.f. Galvin, 2023). Yet, our results give first insights into the role of building envelope refurbishment, as we model buildings with different specific energy demands and flow temperatures that otherwise have similar characteristics. For example, in the case of SFH, there are deltas of 5,000-12,000 EUR in household burdens between buildings with high demand (and high flow temperatures) and low demands (and low flow temperatures). The lower demand buildings invest prematurely into heat pumps because they have lower capacity costs and lower flow temperatures. Doing so, they make use of subsidies and avoid CO_2 prices and high medium-term gas prices. By implication, this delta would be equal to the maximum expenditure that SFH would be willing to pay for the corresponding demand reduction which is 50% in this case, and the change in flow temperature. In Germany, refurbishment is incentivized by government policies with lump sum subsidies of up to 20% or a maximum of 60,000 EUR. Additionally, under the BEG EM, homeowners can be eligible for subsidized loans with low interest rates. This makes refurbishment more attractive and may thus lead to more premature investment in SFH. In the case of MFH with central heating, the delta between high and low demand archetype buildings is around 3,000 EUR per unit at maximum. In MFH with central heating, the timing of investment does not depend on specific demand. For these buildings, it is optimal to decarbonize prematurely in any case, and cost savings are completely due to difference in energy costs. Thus, the impact on decarbonization would be negligible, however increased energy efficiency leads to lower electricity demands, which reduces electricity generation and infrastructure requirements. In MFH with single-story heating, the burden delta between high and low demand buildings can reach up to 8,000 EUR per unit for buildings with recently installed existing systems who can save significantly on energy and CO_2 costs if they decrease demand. All in all, our results indicate that refurbishment activity should be focused on SFH and MFH with single-story heating in order to increase decarbonization, but further research has to determine the effect on costs and burdens.

Municipal heat planning

Furthermore, our model of decentralized decarbonization excludes technology options that require centralized decision-making, i.e. district heating solutions or climate neutral hydrogen. Especially in densely populated areas and for multifamily homes, heat pump powered district heating solutions could provide lower cost heating(c.f. Moritz et al., 2024), while exploiting additional heat sources such as industrial waste heat or CHP, thus leading to cross-sectoral synergies (c.f. Manz et al., 2024). Additionally, we do not consider hydrogen heating in the set of technology choices. In a recent review of building sector studies, Rosenow (2022) concludes that heating with hydrogen is largely viewed as an edge-case at low hydrogen prices or as hybrid heating that makes use of (repurposed) existing infrastructure. Moritz et al. (2024) make a case for hydrogen heating in rural areas if electricity costs are high. In any case, both, district heating and hydrogen heating require additional infrastructure and decision-making is not in the hands of individual households. Instead, as described in Section 4, all German municipalities have to publish a detailed account of infrastructure plans regarding hydrogen and district heating until 2026 or 2028, depending on the population size. The municipal heat plans play a major role in determining the extent of decentralized decarbonization, as modelled in this paper. At the same time, our results can be used to inform heat planning, as they provide a benchmark or even a stress-test for a heating transition fully based on decentralized technologies. Policymakers could prioritize areas with buildings for alternative heat sources such as hydrogen and district heating, if they exhibit high costs or burdens for decentralized solutions in our scenario.

Before the municipal heat plans are due, it is still possible to install systems that do not meet the 65% renewable requirement, such as gas boilers. However, building owners making such a decision have to make sure that they have access to renewable gases starting in 2029. Whether or not this would lead to more investment in gas boilers than shown in our results, ultimately depends on the future costs and availability of renewable gases such as hydrogen, synthetic natural gas and biogas which are highly uncertain today. A first indication that German homeowners might in fact opt for gas boilers is given by recent data on electric heat pump sales figures, which show a 52% decline of wholesale sales between the last quarter of 2023 and the first one in 2024, i.e. after the new rules entered into force. At the same time, the data shows an overall decline in new heating investment of 29%. The Federation of the German heating industry, a heating system manufacturers' association that published the data, suspects this may be due to customers hesitating to make investments in the wake of the heated political debate that led to the new rules (Bundesverband der deutschen Heizungsindustrie (BDH), 2024, c.f.). Policy-makers should pay close attention to this development and reduce uncertainties that might distort household decision-making.

Incentives for centralization of single-story heating

Next to centralizing the supply of multiple buildings by means of district heating, another technology option excluded from the initial analysis is the centralization of supply in MFH with single-story heating. Our results show that these buildings achieve little decarbonization and have high costs under CO_2 prices. They have limited decarbonization options, which do not exhibit the same economies of scale as technologies for central supply in MFH. Comparing the costs between MFH with central heating and single-story heating yields burden deltas of 3,000 and 7,000 EUR per residential unit. If the costs for the required measures, such as new piping or substitute housing for the time of construction, were below this, centralization could be profitable. Policy-makers have already recognized centralization of supply in single-story heating MFH as an import measure for decarbonization and have implemented prolonged transition times for these buildings with regard to the 65% renewable requirement. If centralization is implemented, this could enhance decarbonization, as for central heating MFH, premature investment is optimal in the *policy* scenario. However, recent census data shows that in MFH, 84% of inhabitants rent (Statistisches Bundesamt, 2024). Thus, they might not be able to influence heating system investment decision-making. The arising owner-tenant incentive dilemma and the impact on our results is discussed in the next subsection.

Owner-Tenant Dilemma

The owner-tenant dilemma refers to the misguided incentives that arise due to the separation between the owner of the building and thus the owner of the heating system, i.e. the agent of the investment decision, and the tenant of a property, i.e. the user of the heating system. Owners and tenants have diverging objectives: Owners seek to minimize the investment costs and potential subsidies, while tenants consider energy costs, including the CO_2 price. Consequently, the owner tenant dilemma has the potential to hinder investment into capital intensive but more efficient heating technologies or refurbishment (c.f. Kühn et al., 2024).

The owner-tenant dilemma has been recognized by policymakers and consequently with the *Law on the allocation of carbon dioxide costs*, a mechanism was put in place that shifts part of the CO_2 cost burden to the owner, if buildings exhibit high per m^2 emissions. Specifically, building owners are obliged to bear a proportion of the CO_2 costs as soon as the building exceeds an emission value of 12 $kg_{CO_2}/m^2/a$. Owner shares start at 10% and increase in stages based on emission density. Buildings owners bear up to 95% of CO_2 costs for values 52 $kg_{CO_2}/m^2/a$ or more.[20]

In our scenario results, capital costs constitute a large share of the extra costs in buildings that invest into electric heat pumps prematurely. Thus, the premature investment, especially in MFH where many inhabitants are tenants, shown in our results might not emerge in practice. This would lead to a slower decarbonization and lower investment costs on the owners' side, while tenants would pay higher CO_2 expenditures. Once heating systems reach the end of their lifetime, the 65% renewable energy requirement dictates a change of heating system. However, owners might opt for solutions with lower capital costs, such as a combination of solar thermal systems, battery storage, simple power to heat and electric flow heaters with gas systems. This too would leave tenants with higher CO_2 expenditures and decrease decarbonization compared to our results.

CO_2 price revenue recycling

Despite the additional factors presented in the previous sections, our results show that due to the heterogeneity of the building stock, the building types are faced with different cost burdens when

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[20] Additionally, to incentivize building envelope efficiency, owners can pass on the costs for building envelope refurbishment to tenants by increasing annual rent by up to 8% of the costs for the modernization (c.f. Art. 559 German Civil Code).

investing into decentralized technologies. For the case of CO_2 prices, which lead to significant transfers from households to the state, there is an ongoing debate regarding distributional fairness since their implementation in 2020. The coalition agreement of the current German government promises recycling of the revenues from CO_2 prices by means of a "climate payment" (SPD et al., 2021). However, the exact recycling mechanism has yet to be defined. In fact, the literature on distributional effects of CO_2 pricing shows that CO_2 prices often have a regressive effect and redistribute from poorer to richer households (e.g. Frondel and Schubert, 2021; Schaffrin, 2013; Kirchner et al., 2019). Frondel and Schubert (2021) and Kirchner et al. (2019) discuss several options for revenue recycling, including for example uniform or targeted lump sum payments, tax-cuts on existing taxes, or funding of social benefits. While uniform lump sum payments are incentive neutral, other forms of revenue recycling may interfere with the decarbonization Kirchner et al. (2019) even find that there exists a trade-off between the decarbonization efficiency of a mechanism and its progressivity (c.f. Kirchner et al., 2019).

The impact of revenue recycling on the model results is dependent on the mechanism and remains unclear until this is defined. At the same time, existing analyses of revenue recycling mechanisms do not consider existing subsidies. Yet, the subsidies are financed by taxes, and could thus already be regarded as distribution - which is potentially rather unequal across building types according to our results. Additionally, as discussed in Section 2, distribution effect analyses often lack detailed representation of the techno-economic decision-making with regard to decentral heating decarbonization. Further research that couples the model presented in this paper with the socio-economic characteristics of the households and potentially a macro-model including taxation could provide valuable insight and help designing efficient and fair revenue recycling mechanisms.

6.2. Robustness of the results and methodological appraisal

6.3. Sensitivity analysis

Energy prices are subject to strong uncertainty. Prices can change quickly and due to various factors, such as increasing infrastructure costs or supply disruptions as observed during the recent energy crisis. To verify the robustness of the results against increase in electricity prices, a sensitivity analysis with an alternative electricity price path was performed. We chose a strictly increasing price path for the sensitivity analysis, which is depicted in Table 3. All other parameters are held the same as in the main analysis.

	2020	2025	2030	2035	2040	2045
Main	32.2	30.5	26.6	28.4	28.9	30.0
Sensitivity	32.2	30.5	32.6	36.4	38.8	42.0

Table 3: Electricity prices in the main scenario and the sensitivity analysis (ct/kWh)

Generally, the results of the *policy* scenario are robust against higher electricity prices because policy elements like the 65% renewable energy requirement dictate decarbonization until 2045. Figure G.8 in Appendix G gives and overview of the results obtained by the *policy* scenario under price sensitivity assumptions. Like in the main scenario, most buildings have electric heat pumps as well as - if they have the option to do so - PV installed by 2045. However, the incentive to invest into heat pumps prematurely decreases compared to the main scenario. Buildings with existing gas-fueled technologies are faced with a new trade-off between medium-term high gas prices and long-term high electricity prices. Consequently, buildings with high demands and longer remaining lifetimes of their existing boilers opt not to replace prematurely. Some MFH even stick to gas technologies in the long term and fulfil the 65% requirement with the help of solar thermal systems, additional electric heating, battery systems and PV. Similarly, some MFH opt to install gas heat pumps instead of electric heat pumps. Buildings with oil boilers do not replace their existing systems prematurely under increased electricity prices. All in all, increased electricity prices lead to higher energy costs and a slower decarbonization, which in turns leads to increased CO_2 price expenditures. Investment and FOM costs are similar to the main scenario because most buildings do invest into electric heat pumps eventually. Household burdens increase due to the increased energy and CO_2 costs.

6.3.1. Limitations

Even though our analysis gives valuable insights for policymaking, there are some general limitation associated with the chosen method that have to be considered when interpreting the results. Our model optimizes building energy provision from a pure cost perspective, neglecting any non-monetary preferences individual consumers might have and their influence on decision-making.

Additionally, in this model framework, consumers have perfect foresight and perfect information, while in reality, future (and present) fuel and technology costs are uncertain. In other words, emission and cost estimates provide a lower benchmark, since they result from an optimal and perfectly informed sizing of technologies. Finally, dynamic interdependencies with other sectors are neglected. In reality, residential energy consumption does affect electricity generation as well as the requirements and costs electricity and gas grid infrastructure. Our results have proven robust to increased electricity prices in a sensitivity analysis. This is due to the fact that the 65% renewable requirement is a major driver of investment decisions and energy prices mostly affect premature investment. Still, our model does not capture the endogeneity of building energy demand and energy prices and infrastructure costs.

Nonetheless, our research can provide valuable insights beyond the presented analysis. The *reference* scenario can be used in order to benchmark other policies than the ones considered here, as it derives the unavoidable or natural cost and emission reduction. Similarly, it can provide a benchmark when investigating the efficiency of any other potential abatement option, such as the use of hydrogen throughout the building sector. Moreover, the model framework could be applied for different building stocks, e.g. non-residential buildings or different countries as well as for analysis of other incentive-based policies.

7. Conclusion

This study quantifies the costs and cost distribution of investment in decentralized heating decarbonization driven by building energy policy. Specifically, we model the investment decisions in decentralized heating technologies of 770 archetype buildings that are representative of the German residential building stock under the consideration of renewable requirements, subsidies, and CO_2 prices. We find that under the policies, high medium-term gas prices and moderately increasing electricity prices, many households opt to replace their fossil systems prematurely by electric heat pumps and thus substantial decarbonization can be achieved quickly.

Compared to a reference scenario without policy intervention, the policies lead to additional costs for almost all building types when investing into decentralized technologies. However, the costs are distributed unequally between the building types, with some buildings facing high burdens, while other profit from subsidies. In summary, the following main findings can be formulated: First, in MFH with centralized heating, economies of scale on electric heat pumps lead to low abatement costs and in combination with subsidies to lower cost burdens. These buildings should be prioritized for decarbonization, however the owner-tenant dilemma might hinder optimal decision-making. Second, in MFH with single-story heating, abatement costs and cost burdens are high due to the limited decarbonization options. Supply in these buildings should potentially be centralized or considered for alternative options like district heating or hydrogen. Here, too, the owner-tenant dilemma might hinder optimal decision-making. Third, SFH with recently oil and gas heating systems, which were often subsidized if they replaced older and less efficient fossil boilers, face the highest costs due to significant future CO_2 expenditures. A potential way to mitigate the burdens would be to incentivize faster decarbonization, for example with an extension of the speed bonus to fossil systems younger than 20 years old. The finding on high cost burdens for SFH with new fossil boilers also holds a warning for building owners looking to invest into new fossil heating systems before the 65% renewable requirement becomes binding, at latest in 2028. Policy-makers should look to decrease information asymmetries regarding this aspect. Finally, there are households that benefit more from the current funding system than is necessary to achieve the desired heating system transformation and make a net profit.

Generally, the results show that burdens and benefits are distributed unequally across building types and additional measures may be in order to achieve redistribution. To enable a design of efficient redistribution policies, for example in the course of defining a CO_2 price revenue recycling mechanism, further research should focus on coupling detailed building stock models like the one proposed by this study with the socio-economic characteristics of the residents and the building ownership structure and potentially macroeconomic concerns.

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Authors' contribution

All authors contributed equally to designing the research and implementing the model. Berit Hanna Czock and Cordelia Frings analyzed the results and wrote the final manuscript, which was edited by all authors.

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Appendix A. Building optimization model

The model for "Consumer Management of Decentralized Options" (COMODO) was introduced by Frings and Helgeson (2022). In this paper, the consumer model is employed to design the technology specification and operation of the archetype residential buildings between 2019 and 2045. The model offers a choice of 16 different electricity, space heat or hot water heat generating and storage technologies.

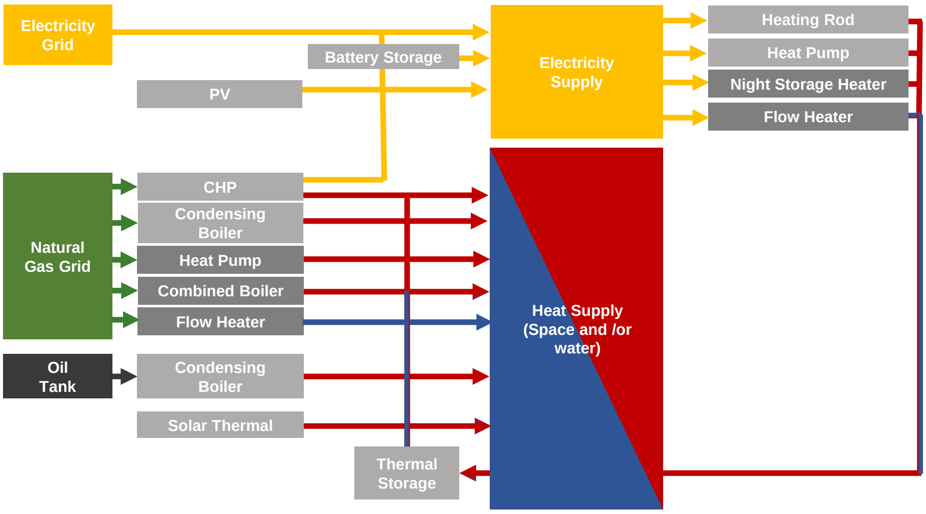

Figure A.1: Overview of the energy supply flows in COMODO: Energy flows are lines and energy demands or supplies are boxes. Yellow marks electricity, red marks space heat, blue marks hot water heat, green marks natural gas and black marks oil. Technologies are depicted by gray boxes. Technologies newly introduced for this paper are marked in a darker gray shadow. The graphic is based on the illustration of the model given in Frings and Helgeson (2022).

Technologies can be combined for different uses, i.e. output from one technology is used as the input for another technology, as shown in Figure A.1. Technologies, such as condensing boilers, generate heat from gas or oil. Power-to-heat technologies, such as heating rods, use electricity for heat generation. Some technologies generate heat for warming water (flow heaters), some space heat (e.g. heat pumps), and others have both options (combined boiler). Lastly, photovoltaic (PV) systems and solar thermal systems make solar radiation available as an electricity or heat source respectively. Energy can be fed to its purpose directly or stored in a battery system or thermal storage for later use. In the case of electricity generation, a direct feed-in into the grid is possible. We model both, SFH and MFH. For MFH, we distinguish between central heating systems and single-story heating. MFH with central heating are treated as a single consumer optimizing the whole building's energy provision. For MFH with single-story heating, each floor is treated as an individual consumer, all of which are however identical for a MFH type. To facilitate the analysis of MFH, the technology catalog given by Frings and Helgeson (2022), which includes mainly central heating systems, was extended. Technical and economic properties of all newly introduced technologies are described in detail in Appendix C.1.

Next to the technology overview, Figure A.1 shows how the technologies can supply the consumers' energy demands. Electricity can be supplied by decentralized residential technologies or obtained from a central supplier via the grid infrastructure. For heat provision, only decentralized generation is modelled.

Hourly time series for space heating, hot water and (non-heating) electricity demands for existing and newly constructed MFH and SFH are derived based on guidelines on standard profiles provided by Verein Deutscher Ingenieure (2019) (VDI). In order to depict the seasonality of space heat demand, the annual space heat was distributed over the year following the concept of heating degree days before applying the normalized structure of the typical days derived from the VDI guideline. All weather-dependent components of demand reflect reanalysis weather data from 2016 provided by the German Weather Service's COSMO-REA6 model.[21]

Next to the demand time series, COMODO takes into account the hourly potentials for solar energy. Both PV and solar thermal potential are calculated by deriving the global radiation onto the tilted roof surface, considering its cardinal direction (azimuth). Appendix D.3 gives a detailed account of the assumptions. Heat pump efficiencies, which specify the ratio of input energy (gas or electricity) to output energy (heat and/or hot water) also depend on the outside temperature. Details on the derivation of electric heat pump coefficients of performances (COPs) are given in Frings and Helgeson (2022). The derivation of a function for gas heat pump gas utilisation efficiencies (GUE) is presented in Appendix C.1.3.

Investment decisions are furthermore constrained by individual building characteristics such as the roof area available for PV and solar thermal installations, which are specified in the course of the

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[21] Essen, Germany was determined as a representative location by weather data clustering.

definition of archetype buildings (see Section 3.2).

Furthermore, the technology choice is constrained by the needs of heating circuit with respect to flow temperature. Exchange of the full circuit including radiators is not considered in the model. All technologies have to be replaced after their technology specific assumed lifetime. Consumers can replace existing technologies before their lifetime ends, i.e. prematurely, for example if operation costs for existing technologies outweigh the investment costs for new technologies.

In order to reduce computational expenses, 4 representative periods with a length of 168 hours (one week) each were derived based on the yearly time series. The representative weeks were derived using an error-minimizing search algorithm and standard k-means procedure. To achieve a further reduction in computational demand of the MILP model, we reduced the number of integer variables by adjusting the investment and FOM cost functions of the technologies compared to Frings and Helgeson (2022). Specifics regarding the investment and FOM cost functions are given in Appendix C.3.

Appendix B. Technical and economic technology assumptions

Appendix C. Technical and economic assumptions

Appendix C.1. Expansion of the technology catalog

The technology catalog introduced by Frings and Helgeson (2022) is designed for depicting the future technology decisions of single consumers. In order to allow the modelling of the technology stock and multifamily buildings, an expansion of the technology catalog is necessary. The following section presents the added technologies. The focus lies with their technical and economic definition.

Appendix C.1.1. Combined Space and Water Heating Boiler

The heating and hot water supply of individual flats can be achieved with a combined space and water heating boiler. The combined boilers are reduced in size and can be installed inside the living space of the individual flats. Nevertheless, such boilers are assumed to have an efficiency of 93% (c.f. Brown et al. (2018) and Henning and Palzer (2012)), which is significantly lower than the efficiency of a central system. This technology is the only gas supplied option for buildings with individual single-story heating systems. The assumed investment costs (based on manufacturer data including 13.33% installation costs) and fixed operation and maintenance costs (c.f. Brown et al. (2018) and Henning and Palzer (2012)) are given in Figure C.2.

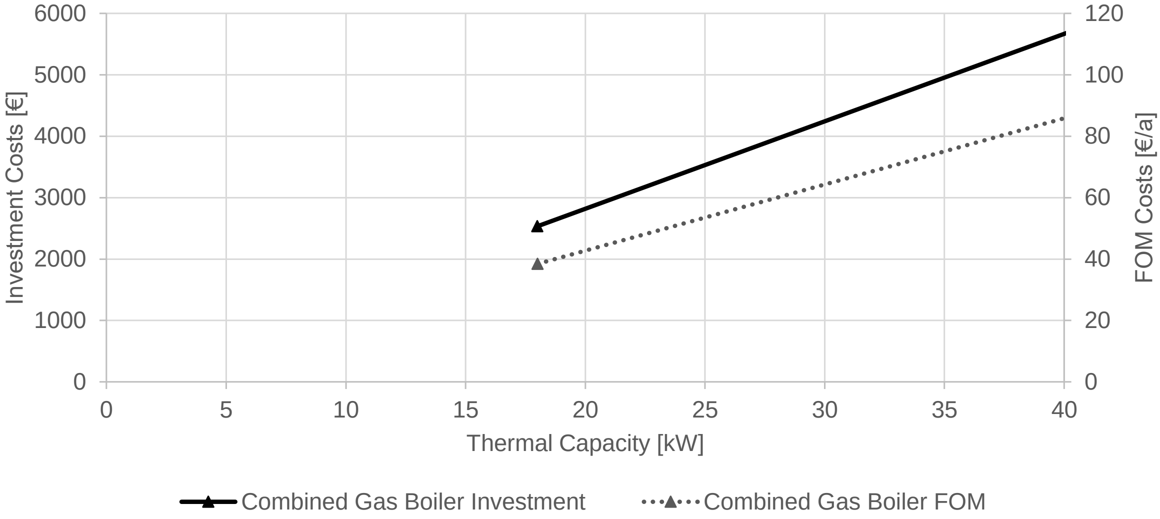

Figure C.2: Investment and FOM costs of condensing combined boilers in 2020

In order to depict the cost development of this established technology, a cost reduction of 0.2% per year is assumed in the model. Once installed, a combined gas boiler can operate for up to 20 years following Brown et al. (2018) and Henning and Palzer (2012).

Appendix C.1.2. Flow heater

Hot water can be provided by flow heating systems, which supply demand on spot. These systems can be installed in buildings in addition to central systems as well as in MFH, individually for each flat. On spot hot water heat provision can either be obtained by either fuel, electricity or gas. We assume that electrical flow heaters convert the provided electricity almost fully into heat for hot water. The efficiency of gas fueled flow heaters is assumed to be 85%. The assumed investment costs (based on manufacturer data including installation costs [22]) are illustrated in Figure C.3. Flow heaters cannot be used to cover space heating requirements, which can only be covered by a main heating system. We assume that the maintenance of the flow heaters is combined with the

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[22] Installation costs are assumed to be €200 for electrical flow heaters and €300 for gas flow heaters. These costs are given by Stiftung Warentest (2014)

main heating system. Therefore, we assume that the FOM costs of flow heaters are zero, i.e., no additional costs are caused.

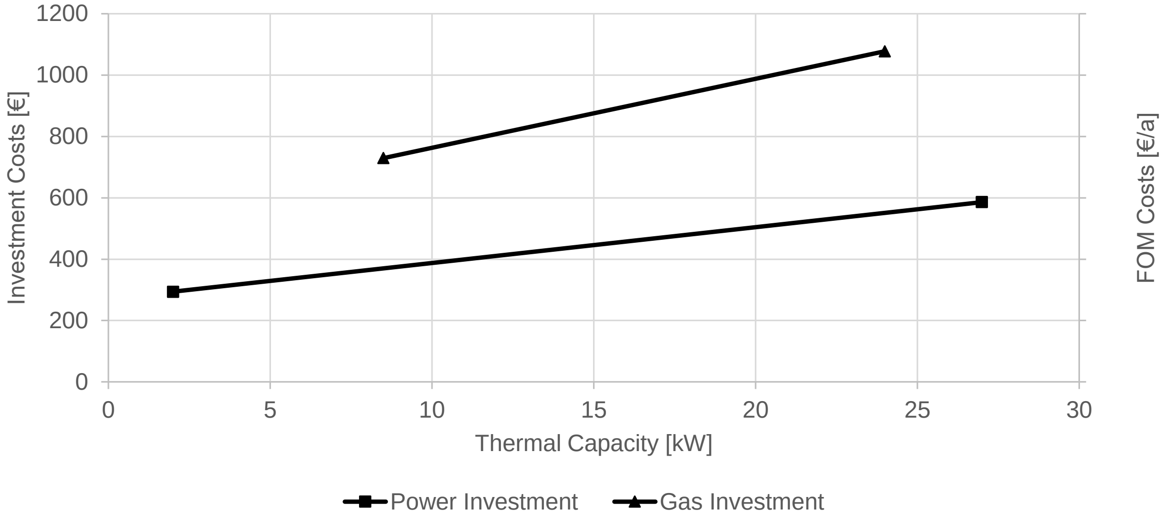

Figure C.3: Investment costs of gas and power flow heating systems in 2020

In order to depict cost development of these established technologies, a cost reduction of 0.2% per year is assumed in the model. Once installed, the electrical flow heater can function for up to 15 years, the lifetime of the gas fueled flow heater is assumed to be 20 years.

Appendix C.1.3. Gas heat pumps

The functionality of gas heat pumps is identical to that of electrical heat pumps. High enthalpy energy (gas in this case) is used to make ambient energy at low temperature available for heating. This method allows very high efficiencies, as more energy than supplied by the gas is made available. The gas utilization efficiency (GUE) of a gas heat pump describes the efficiency of the system with which gas is converted into usable heat in order to supply the heat demand of the consumer, i.e. $\eta_{y,t,x=GasHeatPump} = GUE_{y,t}$.[23] The COPs/GUEs are described as functions of outside temperature, furthermore depending on the energy carrier and the second energy source (air or ground)

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[23] Due to the electricity consumption of the gas heat pump system the COP and the GUE of the heat pump are not equivalent. While the GUE puts heat supply and gas consumption into relation, the COP incorporates the electricity consumption of the system. Nevertheless, the rather insignificant electricity consumption is neglected in the analysis. Therefore, the efficiency of the system is set equal to the GUE and describes only the transformation from gas into heat.

and the flow temperature of the system.

$$
\begin{aligned}
GUE_{y,t} &= 2 \cdot 10^{-6}(T_{supply} - T_{source,y,t})^3 \\
&\quad - 3 \cdot 10^{-4}(T_{supply} - T_{source,y,t})^2 \\
&\quad + 0,0054(T_{supply} - T_{source,y,t}) + 1,5605; \quad \forall\ 10\ K \leq (T_{supply} - T_{source,y,t}) \leq 85\ K && \text{(C.1)} \\
GUE_{y,t} &= 1,5865; \quad \forall\ (T_{supply} - T_{source,y,t}) < 10\ K && \text{(C.2)}
\end{aligned}
$$

Equations C.1 and C.2 give the functional estimations we derived for gas heat pumps. The function has a third degree polynomial format with a constant part for low temperature rises. These functions were estimated based on temperature-COP/GUE tables found in industry reports, as well as Garrabrant et al. (2017), HEAT4U Project (2013) and Bundesamt für Wirtschaft und Ausfuhrkontrolle (2019).

A supply temperature of 35°C for new builds and 50°C for existing buildings is assumed. Source temperatures are calculated as stated in Frings and Helgeson (2022) for the electrical heat pumps.

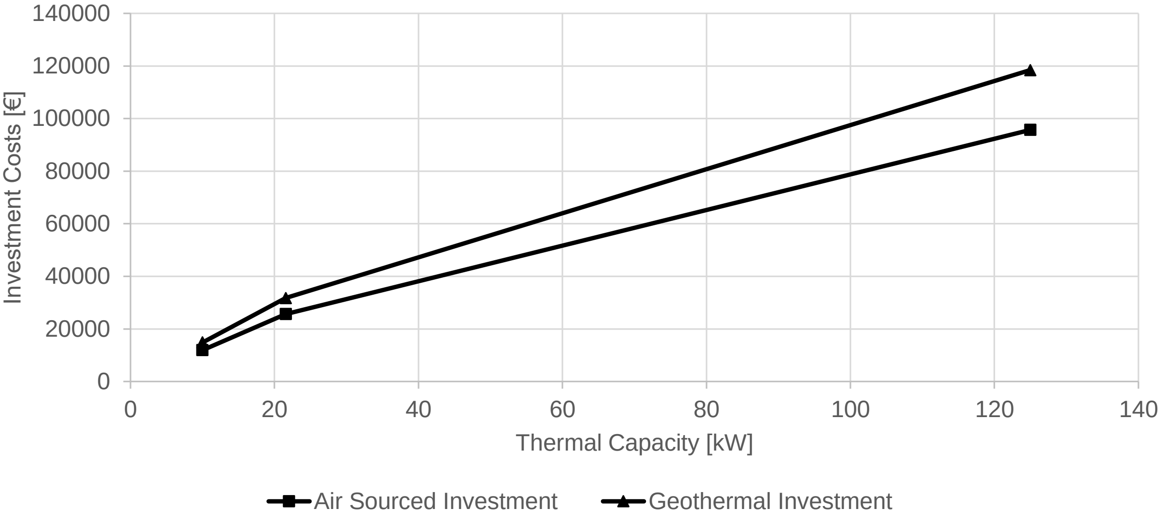

Figure C.4: Investment costs of gas heat pumps in 2020

Figure C.4 shows the assumed investment costs for gas heat pumps. These assumptions are based on an analysis of industry data.

In order to depict cost development of gas heat pumps in the model, a rather strong investment cost reduction as given in Table C.1 is assumed.

Year	2025	2030	2035	2040	2045	based on
Learning rate [%]	97	94	89	83	78	Conrad (2020) and Sterchele et al. (2020)

Table C.1: Learning Rates for Gas Heat Pump investment costs development in % compared to 2020

The FOM costs are assumed at 4.75% of the investment costs per year. This assumption is based on Jochen Conrad (2020) and Sterchele et al. (2020). Once installed, gas heat pumps are assumed to operate for 20 years following Conrad (2020), Henning and Palzer (2015) and Sterchele et al. (2020).

Appendix C.1.4. Night Storage Heaters

Night storage heaters are power-to-heat space heating systems which typically generate heat during the night. The systems allow storing this thermal energy in a sensible heat storage system, typically clay bricks or other ceramic material, and release the energy over the day, when needed.[24]

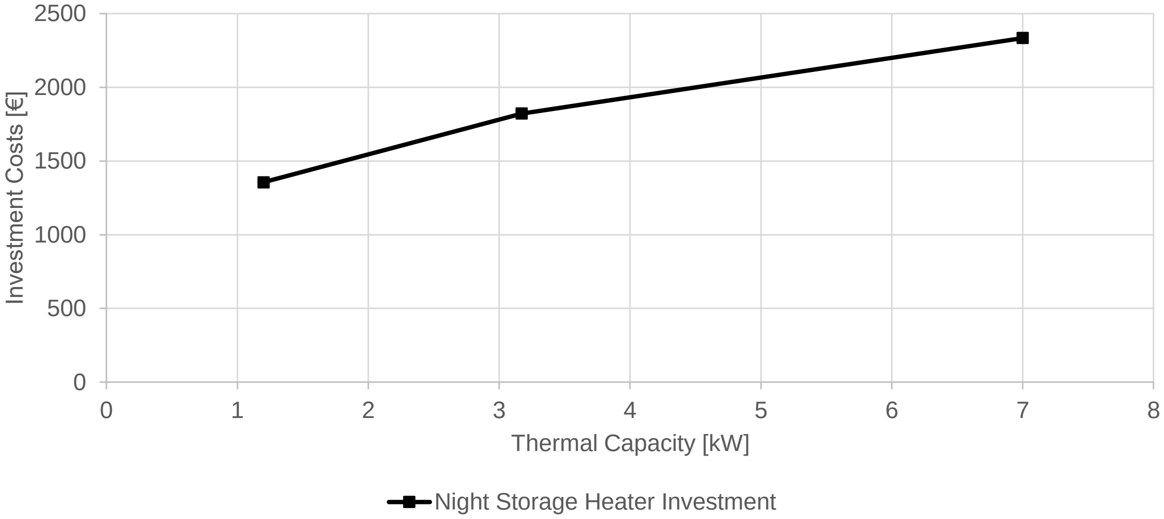

Figure C.5: Investment Costs of Night Storage Heaters in 2020

As night storage heaters only generate space heat, they have to be combined with a water heating device and in some cases with a water heat storage system. Night storage heaters have a fixed

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[24] In this paper the storage systems follow a specific power intake schedule given by SWM Infrastruktur GmbH & Co. KG (2022)

operation profile and cannot be flexibilized with storage. Electricity can almost fully be converted into space heat, and thus the night storage heaters' efficiency is assumed to be 100%.

C.5 gives the assumed installation costs for night storage heaters, these costs are based on collected manufacturer data. It is assumed that operators of night storage heaters are not facing any fixed operation and maintenance costs.

In order to depict cost development of this established technology, a cost reduction of 0.2% per year is assumed in the model. We assume a lifetime of 30 years for night storage heaters.

Appendix C.2. Existing technology definition

Within the scope of this paper, COMODO was used to derive the size of existing technology installations in existing buildings (compare 3.4). In order to obtain historic investment costs, we reconstructed historic learning rates. Table C.2 lists the assumed values.

Technology	Historic learning curve [%]	based on
Combined gas Boiler	101	own assumption
Electric air sourced Heat Pump	104	Bürger et al. (2016), Palzer (2016), Energinet.dk and Energi Styrelsen (2012), Petrović and Karlsson (2016)
Electrical flow heater	101	own assumption
Gas boiler	101	own assumption
Gas flow heater	101	own assumption
Geothermal gas heat pump	106	Conrad (2020) and Sterchele et al. (2020)
Night storage heater	101	own assumption
Oil boiler	101	own assumption
PV	108	Gerbert et al. (2018), Palzer (2016), Bürger et al. (2016)
Solar thermal heating	107	Energinet.dk and Energi Styrelsen (2012), Gerhardt et al. (2015)
Thermal storage	101	own assumption

Table C.2: Learning curves for investment Costs compared to 2020 in %

Appendix C.3. Integer reduction in the representation of investment costs

In order to reduce the computational demand, we reduced the amount of integer variables in the MILP model. Doing so, we set up investment cost and FOM cost functions which hold for the typically installed capacity sizes of the different building types with only one piece, i.e. only an x-axis intercept and one slope valid for all installations. These functions were derived based on the data collected by Frings and Helgeson (2022), the data collected for the technology definition given in Appendix C.1 and the results of numerous model runs. Table C.3 gives the x intercept and the slope of the reduced investment cost functions considered.

	Building Type			Investment Costs	
Technology	EFH	sMFH	lMFH	x intercept [€]	slope [€/kW]
Battery storage	x			2630	677
		x		1805	725
			x	4668	509
Electric air sourced heat pump	x			5279	1273
		x		5461	1220
			x	8951	579
Electric flow heater	x	x	x	270	12
Electric geothermal heat pump	x	x	x	18586	443
Fuel cell	x	x	x	8765	11618
Gas boiler	x	x		661	557
Gas flow heater	x	x	x	539	22
Geothermal gas heat pump (35°C)	x	x	x	186	1463
Geothermal gas heat pump (50°C)	x	x		186	1463
			x	13671	838
Otto motor CHP			x	19752	494
PV	x			6646	591
		x	x	4566	1036
Simple electric heater	x	x		240	5
Solar thermal system *		x	x	187	793
Split heat pump		x	x	5461	1220
Thermal storage	x	x	x	464	33

* The slope of the cost function for for Solar Thermal Systems is given in €/m^2

Table C.3: Simplified investment cost functions for 2020

Table C.4 shows the accompanying reduced FOM cost functions. For some technologies, for which capacities highly varied, or insufficient installations occurred, no reduced functional form could be derived. For these technologies, the piece wise linear functions were kept.

	Building Type			FOM Costs	
Technology	EFH	sMFH	lMFH	x intercept [€/a]	slope [€/kWa]
Battery Storage	x	x	x	84.48	1.31
Electric Air Sourced Heat Pump	x	x	x	89.04	71.18
Electric Geothermal Heat Pump	x	x	x	43.67	49.71
Fuel Cell	x	x	x	322.93	67.09
Gas Boiler	x	x		220.83	2.07
Geothermal Gas Heat Pump (35°C)	x	x	x	9.42	73.92
Geothermal Gas Heat Pump (50°C)	x	x		9.42	73.92
			x	690.84	42.35
Otto Motor CHP			x	489.59	29.48
PV	x			87	8
		x	x	108	8
Solar Thermal System *		x	x	4.02	16.94
Split Heat Pump		x	x	89.04	71.18

* The slope of the cost function for for Solar Thermal Systems is given in €/m^2a

Table C.4: Simplified FOM Cost Functions

Appendix D. Building definition

Appendix D.1. Building clustering

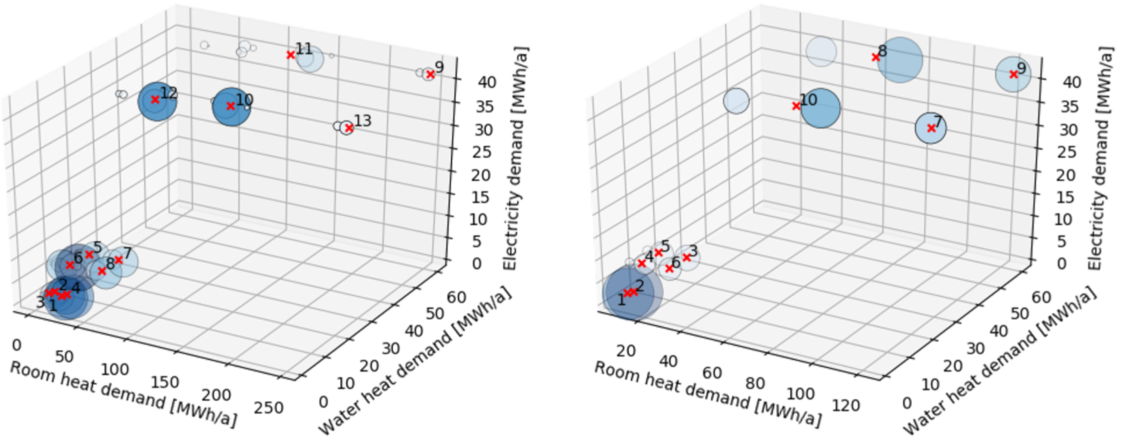

Figure D.6: Representative demand combinations (red), and demand combinations from Scharf et al. (2021) (blue). Left: 13 combinations representing the existing building stock. Right: 10 combinations representing buildings built after 2011. The latter are used as a basis for the definition of new constructed buildings. The size and shade of the blue marker represents the weight used in clustering and equals the sum of heat and electricity demand.

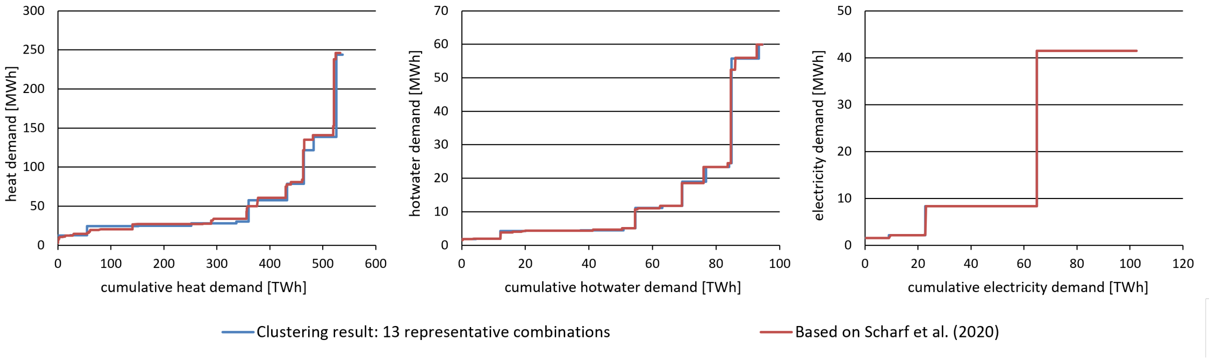

Figure D.7: Cumulative demand values of the building stock in Germany 2019 in comparison between the database of Scharf et al. (2021) and our model.

Appendix D.2. Existing PV systems and feed-in tariffs

Based on Bundesnetzagentur (2023), the new construction of PV systems over the last 20 years is divided into five-year periods, each defined by the respective middle year: 2005, 2010, 2015 and 2020. A distinction is made between systems of SFH (<10kW) and MFH (10-40kW). Table D.5 shows shares of each period on the construction of existing PV systems. In the model, the occurrences of the archetype buildings are divided according to the shares. A 20-year lifetime of the existing PV systems is assumed in relation to the average year of the period.

In both scenarios existing PV systems receive feed-in tariffs based on the historical support regimes. The historical construction-year-specific feed-in tariffs are weighted by the number of new PV systems built in the respective years to determine the average feed-in tariff of systems built in each period. The resulting feed-in tariffs assumed in the model are shown in Table D.5.

	Share		Feed-in tariff (ct/kWh)	
Construction year	SFH	MFH	SFH	MFH
2005	10.3%	12.2%	52.08	52.44
2010	29.2%	53.5%	33.52	34.39
2015	16.8%	7.1%	13.37	13.34
2020	43.7%	27.2%	8.5	7.59

Table D.5: Assumed share of existing PV systems and corresponding feed-in tariffs by construction year

Appendix D.3. Building specific solar potential

Hourly profiles of the generation of solar technologies are constructed based on weather data from 2016 provided by the German Weather Service's COSMO-REA6 model. Solar production is generally based on the sun irradiation on a tilted area, which we calculated using the isotropic diffuse irradiation model given in Eicker (2012). When deriving hourly PV and solar thermal potentials, for all buildings a tilt angle of 45° is assumed, which can be considered rather typical for a gable roof. Next to tilt, solar yield is influenced by the azimuth of the building and roof. For all buildings, a universal azimuth of 59° (East) was assumed. The number is derived based on Corradini (2013) who states that deviation from optimal solar yield due to cardinal building orientation lies between 84,4 and 86,1 % on average (Germany) which approximately corresponds to the assumed azimuth of 59° (East). Thus, the figure can be considered a German average and therefore a best guess that leads to a neither an underestimation nor overestimation of solar yields.

Furthermore, a reflection coefficient of 0.2 and an optical efficiency of 85% of PV plants is assumed. This combination of tilt and azimuth and efficiencies allows a close approximation of the average German full load hours for PV Systems, the assumed system has full load hours of 855h/a. To derive the production potential of solar thermal heating systems, we follow the methodology of European Solar Thermal Industry Federation (2007) using the same assumptions as Frings and Helgeson (2022).[25]

Corradini (2013) estimates available rooftop space for solar (thermal) installations on residential buildings in a bottom-up analysis. In his analysis, the author considers the same building types as this paper (before aggregation), listing a gross total rooftop area for each building type. Additionally, a factor for computing the net area available for solar installations is given. This factor is specified for different settlement types and building age groups. Doing so, the different styles of architecture that influence available rooftop space are considered. We computed an average net available rooftop area for each of our building types by matching our archetype buildings with a distribution of buildings into settlement types given by the author. The matching of building types to age group and settlement type is only provided for small municipalities in Corradini (2013). This distribution was applied to the whole of Germany for the present analysis. We estimate the total net available rooftop area of the building stock for SFH at 438 km^2, for small MFH at 137 km^2 and for large MFH at 85 km^2. We assume that there is enough available roof area on each building to build a solar thermal system of the size 1.5 m^2/resident (1 m^2 for large MFH). Regarding building type-specific potential, not all buildings are considered to be suitable for PV installations. We assume that rooftops must be able to harbor the building type specific calculated average installed capacity for installed PV systems. As a result of combining these two assumptions, 59% of SFH, 5% of small MFH and 23% of large MFH have the potential to install PV systems.

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[25] optical efficiency: 80%; first order heat loss coefficient: $3W/(m^2K)$; second order heat loss coefficient: $0.008W/(m^2K^2)$; mean collector temperature: 50°C for hot water supplying systems and 60°C for space heat supplying systems

No.	Type	IFH	FT [°C]	PVP [kW]	SW	Technology endowment in 2019												Demand in 2019 [kWh]			Number of Buildings*		
						Space Heating							Hot Water										
						GB	CB	OB	EP	GP	NS	O	ST	EH	GH	SFY	PV	Space	Water	Elec.	2019	2030	2045
1	SFH		35	7.0		x							x			2025		12347	4214	1537	197880	191250	182266
2	SFH		50	7.0				x								2025		12347	4214	1537	118022	114069	108710
3	SFH		35	0.0		x							x			2025		12347	4214	1537	168215	162579	154942
4	SFH		50	0.0				x								2025		12347	4214	1537	100329	96968	92413
5	SFH		50	7.0		x								x		2025		12860	1815	2147	144305	139471	132919
6	SFH		50	7.0				x								2025		12860	1815	2147	92110	89024	84842
7	SFH		50	7.0		x							x			2025		12860	1815	2147	111783	108038	102963
8	SFH		50	0.0		x								x		2025		12860	1815	2147	122672	118562	112992
9	SFH		50	0.0				x								2025		12860	1815	2147	78302	75678	72123
10	SFH		50	0.0		x							x			2025		12860	1815	2147	95025	91842	87527
11	SFH		50	7.0	x	x								x		2025	2005	24196	4300	1526	6563	6343	6045
12	SFH		50	7.0	x			x								2025	2005	24196	4300	1526	8266	7989	7614
13	SFH		50	7.0	x	x								x		2025	2010	24196	4300	1526	15653	15129	14418
14	SFH		50	7.0	x			x								2025	2010	24196	4300	1526	19715	19055	18160
15	SFH		50	7.0	x	x								x		2025	2015	24196	4300	1526	7905	7640	7281
16	SFH		50	7.0	x			x								2025	2015	24196	4300	1526	9956	9622	9170
17	SFH		50	7.0	x	x								x		2025	2020	24196	4300	1526	4055	3919	3735
18	SFH		50	7.0	x			x								2025	2020	24196	4300	1526	5108	4936	4705
19	SFH		50	7.0	x	x							x			2025		24196	4300	1526	65497	63303	60329
20	SFH		50	7.0	x	x										2025		24196	4300	1526	90942	87895	83766
21	SFH		50	7.0	x	x								x		2025		24196	4300	1526	40646	39284	37438
22	SFH		50	7.0	x	x									x	2025		24196	4300	1526	117629	113688	108347
23	SFH		50	7.0	x			x								2025		24196	4300	1526	41333	39949	38072
24	SFH		50	7.0	x			x						x		2025		24196	4300	1526	67667	65400	62327
25	SFH		50	7.0	x							x				2025		24196	4300	1526	119110	115120	109712
26	SFH		50	7.0	x							x		x		2025		24196	4300	1526	50797	49095	46789
27	SFH		50	0.0	x	x							x			2025		24196	4300	1526	55678	53813	51285
28	SFH		50	0.0	x	x										2025		24196	4300	1526	77308	74718	71208
29	SFH		50	0.0	x	x								x		2025		24196	4300	1526	34552	33395	31826
30	SFH		50	0.0	x	x									x	2025		24196	4300	1526	99994	96645	92105
31	SFH		50	0.0	x			x								2025		24196	4300	1526	35137	33960	32364
32	SFH		50	0.0	x			x						x		2025		24196	4300	1526	57522	55595	52984
33	SFH		50	0.0	x							x				2025		24196	4300	1526	101254	97862	93265
34	SFH		50	0.0	x							x		x		2025		24196	4300	1526	43182	41735	39775
35	SFH		50	7.0	x	x									x	2025	2005	25010	1934	2112	2001	1934	1843
36	SFH		50	7.0	x			x								2025	2005	25010	1934	2112	4067	3931	3746
37	SFH		50	7.0	x	x									x	2025	2010	25010	1934	2112	4772	4612	4395
38	SFH		50	7.0	x			x								2025	2010	25010	1934	2112	9701	9376	8935
39	SFH		50	7.0	x	x									x	2025	2015	25010	1934	2112	2410	2329	2220
40	SFH		50	7.0	x			x								2025	2015	25010	1934	2112	4899	4735	4512
41	SFH		50	7.0	x	x									x	2025	2020	25010	1934	2112	1236	1195	1139
42	SFH		50	7.0	x			x								2025	2020	25010	1934	2112	2513	2429	2315
43	SFH		50	7.0	x	x							x			2025		25010	1934	2112	82353	79594	75855
44	SFH		50	7.0	x	x								x		2025		25010	1934	2112	83961	81148	77336
45	SFH		50	7.0	x	x									x	2025		25010	1934	2112	98011	94728	90278
46	SFH		50	7.0	x			x								2025		25010	1934	2112	59618	57621	54914
47	SFH		50	7.0	x			x						x		2025		25010	1934	2112	61662	59596	56796
48	SFH		50	7.0	x						x			x		2025		25010	1934	2112	37342	36091	34396
49	SFH		50	7.0	x						x				x	2025		25010	1934	2112	20655	19963	19025
50	SFH		50	7.0	x							x				2025		25010	1934	2112	116288	112393	107113
51	SFH		50	7.0	x							x		x		2025		25010	1934	2112	53484	51693	49264
52	SFH		50	0.0	x	x							x			2025		25010	1934	2112	70007	67662	64483
53	SFH		50	0.0	x	x								x		2025		25010	1934	2112	71374	68983	65742
54	SFH		50	0.0	x	x									x	2025		25010	1934	2112	83318	80527	76744
55	SFH		50	0.0	x			x								2025		25010	1934	2112	50681	48983	46682
56	SFH		50	0.0	x			x						x		2025		25010	1934	2112	52418	50662	48282
57	SFH		50	0.0	x						x			x		2025		25010	1934	2112	31744	30681	29240
58	SFH		50	0.0	x						x				x	2025		25010	1934	2112	17559	16971	16173
59	SFH		50	0.0	x							x				2025		25010	1934	2112	98855	95543	91055
60	SFH		50	0.0	x							x		x		2025		25010	1934	2112	45466	43943	41879
61	SFH		35	7.0		x							x			2030		12347	4214	1537	94915	91735	87426
62	SFH		50	7.0				x								2030		12347	4214	1537	56610	54714	52144
63	SFH		35	0.0		x							x			2030		12347	4214	1537	80686	77983	74319
64	SFH		50	0.0				x								2030		12347	4214	1537	48124	46512	44327
65	SFH		50	7.0		x								x		2030		12860	1815	2147	69217	66898	63756
66	SFH		50	7.0				x								2030		12860	1815	2147	44181	42701	40695
67	SFH		50	7.0		x							x			2030		12860	1815	2147	53618	51821	49387
68	SFH		50	0.0		x								x		2030		12860	1815	2147	58841	56869	54198
69	SFH		50	0.0				x								2030		12860	1815	2147	37558	36300	34595
70	SFH		50	0.0		x							x			2030		12860	1815	2147	45580	44053	41983

*for buildings with individual floor heating: number of flats
IFH: individual floor heating; FT: flow temperature; PVP: PV potential; SW: secondary wood-fired system; GB: gas boiler;
CB: combined gas boiler; OB: oil boiler; EP: electric heat pump; GP: gas heat pump; NS: night storage heater; O: other; ST: solar thermal;
EH: electric flow heater; GH: gas flow heater; PV: PV system (construction year); SFY: system failure year of heating system.

Table D.6: Building Definition 1/12

No.	Type	IFH	FT [°C]	PVP [kW]	SW	Technology endowment in 2019												Demand in 2019 [kWh]			Number of Buildings*		
						Space Heating							Hot Water			SFY	PV	Space	Water	Elec.	2019	2030	2045
						GB	CB	OB	EP	GP	NS	O	ST	EH	GH								
71	SFH		50	7.0	x	x								x		2030	2005	24196	4300	1526	3148	3042	2899
72	SFH		50	7.0	x			x								2030	2005	24196	4300	1526	3965	3832	3652
73	SFH		50	7.0	x	x								x		2030	2010	24196	4300	1526	7508	7257	6916
74	SFH		50	7.0	x			x								2030	2010	24196	4300	1526	9457	9140	8710
75	SFH		50	7.0	x	x								x		2030	2015	24196	4300	1526	3791	3664	3492
76	SFH		50	7.0	x			x								2030	2015	24196	4300	1526	4775	4615	4399
77	SFH		50	7.0	x	x								x		2030	2020	24196	4300	1526	1945	1880	1792
78	SFH		50	7.0	x			x								2030	2020	24196	4300	1526	2450	2368	2257
79	SFH		50	7.0	x	x							x			2030		24196	4300	1526	31416	30364	28937
80	SFH		50	7.0	x	x										2030		24196	4300	1526	43621	42160	40179
81	SFH		50	7.0	x	x								x		2030		24196	4300	1526	19496	18843	17958
82	SFH		50	7.0	x	x									x	2030		24196	4300	1526	56422	54531	51970
83	SFH		50	7.0	x			x								2030		24196	4300	1526	19826	19162	18262
84	SFH		50	7.0	x			x						x		2030		24196	4300	1526	32457	31370	29896
85	SFH		50	7.0	x							x				2030		24196	4300	1526	57132	55218	52624
86	SFH		50	7.0	x							x		x		2030		24196	4300	1526	24365	23549	22443
87	SFH		50	0.0	x	x							x			2030		24196	4300	1526	26707	25812	24599
88	SFH		50	0.0	x	x										2030		24196	4300	1526	37082	35839	34156
89	SFH		50	0.0	x	x								x		2030		24196	4300	1526	16573	16018	15266
90	SFH		50	0.0	x	x									x	2030		24196	4300	1526	47963	46356	44179
91	SFH		50	0.0	x			x								2030		24196	4300	1526	16854	16289	15524
92	SFH		50	0.0	x			x						x		2030		24196	4300	1526	27591	26667	25414
93	SFH		50	0.0	x							x				2030		24196	4300	1526	48567	46940	44735
94	SFH		50	0.0	x							x		x		2030		24196	4300	1526	20713	20019	19078
95	SFH		50	7.0	x	x									x	2030	2005	25010	1934	2112	960	927	884
96	SFH		50	7.0	x			x								2030	2005	25010	1934	2112	1951	1885	1797
97	SFH		50	7.0	x	x									x	2030	2010	25010	1934	2112	2289	2212	2108
98	SFH		50	7.0	x			x								2030	2010	25010	1934	2112	4653	4497	4286
99	SFH		50	7.0	x	x									x	2030	2015	25010	1934	2112	1156	1117	1065
100	SFH		50	7.0	x			x								2030	2015	25010	1934	2112	2350	2271	2164
101	SFH		50	7.0	x	x									x	2030	2020	25010	1934	2112	593	573	546
102	SFH		50	7.0	x			x								2030	2020	25010	1934	2112	1205	1165	1110
103	SFH		50	7.0	x	x							x			2030		25010	1934	2112	39501	38178	36385
104	SFH		50	7.0	x	x								x		2030		25010	1934	2112	40273	38923	37095
105	SFH		50	7.0	x	x									x	2030		25010	1934	2112	47012	45437	43302
106	SFH		50	7.0	x			x								2030		25010	1934	2112	28596	27638	26340
107	SFH		50	7.0	x			x						x		2030		25010	1934	2112	29577	28586	27243
108	SFH		50	7.0	x						x			x		2030		25010	1934	2112	17912	17312	16498
109	SFH		50	7.0	x						x				x	2030		25010	1934	2112	9907	9576	9126
110	SFH		50	7.0	x							x				2030		25010	1934	2112	55779	53910	51378
111	SFH		50	7.0	x							x		x		2030		25010	1934	2112	25654	24795	23630
112	SFH		50	0.0	x	x							x			2030		25010	1934	2112	33580	32455	30930
113	SFH		50	0.0	x	x								x		2030		25010	1934	2112	34235	33088	31534
114	SFH		50	0.0	x	x									x	2030		25010	1934	2112	39964	38625	36811
115	SFH		50	0.0	x			x								2030		25010	1934	2112	24309	23495	22391
116	SFH		50	0.0	x			x						x		2030		25010	1934	2112	25143	24300	23159
117	SFH		50	0.0	x						x			x		2030		25010	1934	2112	15226	14716	14025
118	SFH		50	0.0	x						x				x	2030		25010	1934	2112	8422	8140	7758
119	SFH		50	0.0	x							x				2030		25010	1934	2112	47417	45828	43675
120	SFH		50	0.0	x							x		x		2030		25010	1934	2112	21808	21078	20088
121	SFH		35	7.0		x							x			2035		12347	4214	1537	81571	78838	75135
122	SFH		50	7.0				x								2035		12347	4214	1537	48652	47022	44813
123	SFH		35	0.0		x							x			2035		12347	4214	1537	69342	67019	63871
124	SFH		50	0.0				x								2035		12347	4214	1537	41358	39973	38095
125	SFH		35	7.0					x							2035	2005	12860	1815	2147	12839	12408	11826
126	SFH		35	7.0					x							2035	2010	12860	1815	2147	30622	29596	28206
127	SFH		35	7.0					x							2035	2015	12860	1815	2147	15464	14946	14244
128	SFH		35	7.0					x							2035	2020	12860	1815	2147	7933	7667	7307
129	SFH		50	7.0		x								x		2035		12860	1815	2147	59486	57493	54793
130	SFH		50	7.0				x								2035		12860	1815	2147	37970	36698	34974
131	SFH		50	7.0		x							x			2035		12860	1815	2147	46080	44536	42444
132	SFH		50	0.0		x								x		2035		12860	1815	2147	50568	48874	46578
133	SFH		50	0.0				x								2035		12860	1815	2147	32278	31197	29731
134	SFH		50	0.0		x							x			2035		12860	1815	2147	39172	37860	36081
135	SFH		50	7.0	x	x								x		2035	2005	24196	4300	1526	2705	2615	2492
136	SFH		50	7.0	x			x								2035	2005	24196	4300	1526	3407	3293	3139
137	SFH		35	7.0	x				x							2035	2005	24196	4300	1526	7415	7167	6830
138	SFH		50	7.0	x	x								x		2035	2010	24196	4300	1526	6453	6236	5943
139	SFH		50	7.0	x			x								2035	2010	24196	4300	1526	8127	7855	7486
140	SFH		35	7.0	x				x							2035	2010	24196	4300	1526	17687	17094	16291

*for buildings with individual floor heating: number of flats
IFH: individual floor heating; FT: flow temperature; PVP: PV potential; SW: secondary wood-fired system; GB: gas boiler;
CB: combined gas boiler; OB: oil boiler; EP: electric heat pump; GP: gas heat pump; NS: night storage heater; O: other; ST: solar thermal;
EH: electric flow heater; GH: gas flow heater; PV: PV system (construction year); SFY: system failure year of heating system.

Table D.7: Building Definition 2/12

No.	Type	IFH	FT [°C]	PVP [kW]	SW	Technology endowment in 2019												Demand in 2019 [kWh]			Number of Buildings*		
						Space Heating							Hot Water			SFY	PV	Space	Water	Elec.	2019	2030	2045
						GB	CB	OB	EP	GP	NS	O	ST	EH	GH								
141	SFH		50	7.0	x	x								x		2035	2015	24196	4300	1526	3258	3149	3001
142	SFH		50	7.0	x			x								2035	2015	24196	4300	1526	4104	3967	3780
143	SFH		35	7.0	x				x							2035	2015	24196	4300	1526	8931	8632	8227
144	SFH		50	7.0	x	x								x		2035	2020	24196	4300	1526	1672	1616	1540
145	SFH		50	7.0	x			x								2035	2020	24196	4300	1526	2105	2035	1939
146	SFH		35	7.0	x				x							2035	2020	24196	4300	1526	4582	4428	4220
147	SFH		50	7.0	x	x							x			2035		24196	4300	1526	27000	26095	24869
148	SFH		50	7.0	x	x										2035		24196	4300	1526	37488	36233	34530
149	SFH		50	7.0	x	x								x		2035		24196	4300	1526	16755	16194	15433
150	SFH		50	7.0	x	x									x	2035		24196	4300	1526	48490	46865	44664
151	SFH		50	7.0	x			x								2035		24196	4300	1526	17039	16468	15694
152	SFH		50	7.0	x			x						x		2035		24196	4300	1526	27894	26959	25693
153	SFH		50	7.0	x							x				2035		24196	4300	1526	49100	47455	45226
154	SFH		50	7.0	x							x		x		2035		24196	4300	1526	20940	20238	19288
155	SFH		50	0.0	x	x							x			2035		24196	4300	1526	22952	22183	21141
156	SFH		50	0.0	x	x										2035		24196	4300	1526	31868	30801	29354
157	SFH		50	0.0	x	x								x		2035		24196	4300	1526	14243	13766	13119
158	SFH		50	0.0	x	x									x	2035		24196	4300	1526	41220	39839	37968
159	SFH		50	0.0	x			x								2035		24196	4300	1526	14484	13999	13341
160	SFH		50	0.0	x			x						x		2035		24196	4300	1526	23712	22918	21841
161	SFH		50	0.0	x							x				2035		24196	4300	1526	41739	40341	38446
162	SFH		50	0.0	x							x		x		2035		24196	4300	1526	17801	17204	16396
163	SFH		50	7.0	x	x									x	2035	2005	25010	1934	2112	825	797	760
164	SFH		50	7.0	x			x								2035	2005	25010	1934	2112	1677	1620	1544
165	SFH		35	7.0	x				x							2035	2005	25010	1934	2112	7676	7418	7070
166	SFH		50	7.0	x	x									x	2035	2010	25010	1934	2112	1967	1901	1812
167	SFH		50	7.0	x			x								2035	2010	25010	1934	2112	3999	3865	3683
168	SFH		35	7.0	x				x							2035	2010	25010	1934	2112	18307	17694	16863
169	SFH		50	7.0	x	x									x	2035	2015	25010	1934	2112	993	960	915
170	SFH		50	7.0	x			x								2035	2015	25010	1934	2112	2019	1952	1860
171	SFH		35	7.0	x				x							2035	2015	25010	1934	2112	9245	8935	8516
172	SFH		50	7.0	x	x									x	2035	2020	25010	1934	2112	510	493	469
173	SFH		50	7.0	x			x								2035	2020	25010	1934	2112	1036	1001	954
174	SFH		35	7.0	x				x							2035	2020	25010	1934	2112	4743	4584	4369
175	SFH		50	7.0	x	x							x			2035		25010	1934	2112	33948	32811	31269
176	SFH		50	7.0	x	x								x		2035		25010	1934	2112	34611	33451	31880
177	SFH		50	7.0	x	x									x	2035		25010	1934	2112	40403	39049	37215
178	SFH		50	7.0	x			x								2035		25010	1934	2112	24576	23753	22637
179	SFH		50	7.0	x			x						x		2035		25010	1934	2112	25419	24567	23413
180	SFH		50	7.0	x						x			x		2035		25010	1934	2112	15394	14878	14179
181	SFH		50	7.0	x						x				x	2035		25010	1934	2112	8515	8229	7843
182	SFH		50	7.0	x							x				2035		25010	1934	2112	47937	46331	44155
183	SFH		50	7.0	x							x		x		2035		25010	1934	2112	22048	21309	20308
184	SFH		50	0.0	x	x							x			2035		25010	1934	2112	28859	27892	26582
185	SFH		50	0.0	x	x								x		2035		25010	1934	2112	29422	28437	27101
186	SFH		50	0.0	x	x									x	2035		25010	1934	2112	34346	33195	31636
187	SFH		50	0.0	x			x								2035		25010	1934	2112	20892	20192	19243
188	SFH		50	0.0	x			x						x		2035		25010	1934	2112	21608	20884	19903
189	SFH		50	0.0	x						x			x		2035		25010	1934	2112	13086	12647	12053
190	SFH		50	0.0	x						x				x	2035		25010	1934	2112	7238	6996	6667
191	SFH		50	0.0	x							x				2035		25010	1934	2112	40751	39385	37535
192	SFH		50	0.0	x							x		x		2035		25010	1934	2112	18742	18114	17264
193	SFH		35	7.0		x							x			2040		12347	4214	1537	85790	82916	79021
194	SFH		50	7.0				x								2040		12347	4214	1537	51168	49454	47131
195	SFH		35	0.0		x							x			2040		12347	4214	1537	72929	70485	67174
196	SFH		50	0.0				x								2040		12347	4214	1537	43497	42040	40065
197	SFH		35	7.0					x							2040	2005	12860	1815	2147	32096	31021	29564
198	SFH		35	7.0					x							2040	2010	12860	1815	2147	76555	73990	70514
199	SFH		35	7.0					x							2040	2015	12860	1815	2147	38659	37364	35609
200	SFH		35	7.0					x							2040	2020	12860	1815	2147	19833	19168	18268
201	SFH		50	7.0		x								x		2040		12860	1815	2147	62563	60467	57626
202	SFH		50	7.0				x								2040		12860	1815	2147	39934	38596	36783
203	SFH		50	7.0		x							x			2040		12860	1815	2147	48463	46839	44639
204	SFH		50	0.0		x								x		2040		12860	1815	2147	53184	51402	48987
205	SFH		50	0.0				x								2040		12860	1815	2147	33947	32810	31269
206	SFH		50	0.0		x							x			2040		12860	1815	2147	41198	39818	37947
207	SFH		50	7.0	x	x								x		2040	2005	24196	4300	1526	2845	2750	2621
208	SFH		50	7.0	x			x								2040	2005	24196	4300	1526	3584	3464	3301
209	SFH		35	7.0	x				x							2040	2005	24196	4300	1526	18538	17917	17075
210	SFH		50	7.0	x	x								x		2040	2010	24196	4300	1526	6786	6559	6251

*for buildings with individual floor heating: number of flats
IFH: individual floor heating; FT: flow temperature; PVP: PV potential; SW: secondary wood-fired system; GB: gas boiler;
CB: combined gas boiler; OB: oil boiler; EP: electric heat pump; GP: gas heat pump; NS: night storage heater; O: other; ST: solar thermal;
EH: electric flow heater; GH: gas flow heater; PV: PV system (construction year); SFY: system failure year of heating system.

Table D.8: Building Definition 3/12

No.	Type	IFH	FT [°C]	PVP [kW]	SW	Technology endowment in 2019												Demand in 2019 [kWh]			Number of Buildings*		
						Space Heating							Hot Water			SFY	PV	Space	Water	Elec.	2019	2030	2045
						GB	CB	OB	EP	GP	NS	O	ST	EH	GH								
211	SFH		50	7.0	x			x								2040	2010	24196	4300	1526	8547	8261	7873
212	SFH		35	7.0	x				x							2040	2010	24196	4300	1526	44216	42735	40727
213	SFH		50	7.0	x	x								x		2040	2015	24196	4300	1526	3427	3312	3157
214	SFH		50	7.0	x			x								2040	2015	24196	4300	1526	4316	4172	3976
215	SFH		35	7.0	x				x							2040	2015	24196	4300	1526	22329	21581	20567
216	SFH		50	7.0	x	x								x		2040	2020	24196	4300	1526	1758	1699	1619
217	SFH		50	7.0	x			x								2040	2020	24196	4300	1526	2214	2140	2040
218	SFH		35	7.0	x				x							2040	2020	24196	4300	1526	11455	11071	10551
219	SFH		50	7.0	x	x							x			2040		24196	4300	1526	28396	27445	26155
220	SFH		50	7.0	x	x										2040		24196	4300	1526	39427	38106	36316
221	SFH		50	7.0	x	x								x		2040		24196	4300	1526	17622	17031	16231
222	SFH		50	7.0	x	x									x	2040		24196	4300	1526	50997	49289	46973
223	SFH		50	7.0	x			x								2040		24196	4300	1526	17920	17320	16506
224	SFH		50	7.0	x			x						x		2040		24196	4300	1526	29337	28354	27022
225	SFH		50	7.0	x							x				2040		24196	4300	1526	51640	49910	47565
226	SFH		50	7.0	x							x		x		2040		24196	4300	1526	22023	21285	20285
227	SFH		50	0.0	x	x							x			2040		24196	4300	1526	24139	23330	22234
228	SFH		50	0.0	x	x										2040		24196	4300	1526	33517	32394	30872
229	SFH		50	0.0	x	x								x		2040		24196	4300	1526	14980	14478	13798
230	SFH		50	0.0	x	x									x	2040		24196	4300	1526	43352	41900	39931
231	SFH		50	0.0	x			x								2040		24196	4300	1526	15233	14723	14031
232	SFH		50	0.0	x			x						x		2040		24196	4300	1526	24939	24103	22971
233	SFH		50	0.0	x							x				2040		24196	4300	1526	43898	42428	40434
234	SFH		50	0.0	x							x		x		2040		24196	4300	1526	18721	18094	17244
235	SFH		50	7.0	x	x									x	2040	2005	25010	1934	2112	867	838	799
236	SFH		50	7.0	x			x								2040	2005	25010	1934	2112	1763	1704	1624
237	SFH		35	7.0	x				x							2040	2005	25010	1934	2112	19189	18546	17675
238	SFH		50	7.0	x	x									x	2040	2010	25010	1934	2112	2069	2000	1906
239	SFH		50	7.0	x			x								2040	2010	25010	1934	2112	4206	4065	3874
240	SFH		35	7.0	x				x							2040	2010	25010	1934	2112	45769	44235	42157
241	SFH		50	7.0	x	x									x	2040	2015	25010	1934	2112	1045	1010	962
242	SFH		50	7.0	x			x								2040	2015	25010	1934	2112	2124	2053	1956
243	SFH		35	7.0	x				x							2040	2015	25010	1934	2112	23113	22338	21289
244	SFH		50	7.0	x	x									x	2040	2020	25010	1934	2112	536	518	494
245	SFH		50	7.0	x			x								2040	2020	25010	1934	2112	1090	1053	1004
246	SFH		35	7.0	x				x							2040	2020	25010	1934	2112	11857	11460	10922
247	SFH		50	7.0	x	x							x			2040		25010	1934	2112	35704	34508	32887
248	SFH		50	7.0	x	x								x		2040		25010	1934	2112	36401	35181	33529
249	SFH		50	7.0	x	x									x	2040		25010	1934	2112	42492	41069	39139
250	SFH		50	7.0	x			x								2040		25010	1934	2112	25847	24981	23808
251	SFH		50	7.0	x			x						x		2040		25010	1934	2112	26733	25838	24624
252	SFH		50	7.0	x						x			x		2040		25010	1934	2112	16190	15647	14912
253	SFH		50	7.0	x						x				x	2040		25010	1934	2112	8955	8655	8248
254	SFH		50	7.0	x							x				2040		25010	1934	2112	50416	48727	46438
255	SFH		50	7.0	x							x		x		2040		25010	1934	2112	23188	22411	21358
256	SFH		50	0.0	x	x							x			2040		25010	1934	2112	30351	29335	27956
257	SFH		50	0.0	x	x								x		2040		25010	1934	2112	30944	29907	28502
258	SFH		50	0.0	x	x									x	2040		25010	1934	2112	36122	34912	33272
259	SFH		50	0.0	x			x								2040		25010	1934	2112	21972	21236	20239
260	SFH		50	0.0	x			x						x		2040		25010	1934	2112	22725	21964	20932
261	SFH		50	0.0	x						x			x		2040		25010	1934	2112	13763	13302	12677
262	SFH		50	0.0	x						x				x	2040		25010	1934	2112	7613	7357	7012
263	SFH		50	0.0	x							x				2040		25010	1934	2112	42858	41422	39476
264	SFH		50	0.0	x							x		x		2040		25010	1934	2112	19712	19051	18156
265	SFH		35	7.0		x							x			2045		12347	4214	1537	175863	169972	161987
266	SFH		50	7.0				x								2045		12347	4214	1537	104891	101377	96615
267	SFH		35	0.0		x							x			2045		12347	4214	1537	149499	144491	137703
268	SFH		50	0.0				x								2045		12347	4214	1537	89166	86179	82131
269	SFH		35	7.0					x							2045	2005	12860	1815	2147	32096	31021	29564
270	SFH		35	7.0					x							2045	2010	12860	1815	2147	76555	73990	70514
271	SFH		35	7.0					x							2045	2015	12860	1815	2147	38659	37364	35609
272	SFH		35	7.0					x							2045	2020	12860	1815	2147	19833	19168	18268
273	SFH		50	7.0		x								x		2045		12860	1815	2147	128250	123953	118130
274	SFH		50	7.0				x								2045		12860	1815	2147	81862	79119	75403
275	SFH		50	7.0		x							x			2045		12860	1815	2147	99346	96018	91507
276	SFH		50	0.0		x								x		2045		12860	1815	2147	109023	105371	100421
277	SFH		50	0.0				x								2045		12860	1815	2147	69590	67258	64099
278	SFH		50	0.0		x							x			2045		12860	1815	2147	84453	81623	77789
279	SFH		50	7.0	x	x								x		2045	2005	24196	4300	1526	5833	5637	5372
280	SFH		50	7.0	x			x								2045	2005	24196	4300	1526	7346	7100	6767

*for buildings with individual floor heating: number of flats
IFH: individual floor heating; FT: flow temperature; PVP: PV potential; SW: secondary wood-fired system; GB: gas boiler;
CB: combined gas boiler; OB: oil boiler; EP: electric heat pump; GP: gas heat pump; NS: night storage heater; O: other; ST: solar thermal;
EH: electric flow heater; GH: gas flow heater; PV: PV system (construction year); SFY: system failure year of heating system.

Table D.9: Building Definition 4/12

No.	Type	IFH	FT [°C]	PVP [kW]	SW	Technology endowment in 2019												Demand in 2019 [kWh]			Number of Buildings*		
						Space Heating							Hot Water			SFY	PV	Space	Water	Elec.	2019	2030	2045
						GB	CB	OB	EP	GP	NS	O	ST	EH	GH								
281	SFH		35	7.0	x				x							2045	2005	24196	4300	1526	18538	17917	17075
282	SFH		50	7.0	x	x								x		2045	2010	24196	4300	1526	13911	13445	12814
283	SFH		50	7.0	x			x								2045	2010	24196	4300	1526	17522	16935	16139
284	SFH		35	7.0	x				x							2045	2010	24196	4300	1526	44216	42735	40727
285	SFH		50	7.0	x	x								x		2045	2015	24196	4300	1526	7025	6790	6471
286	SFH		50	7.0	x			x								2045	2015	24196	4300	1526	8848	8552	8150
287	SFH		35	7.0	x				x							2045	2015	24196	4300	1526	22329	21581	20567
288	SFH		50	7.0	x	x								x		2045	2020	24196	4300	1526	3604	3483	3320
289	SFH		50	7.0	x			x								2045	2020	24196	4300	1526	4539	4387	4181
290	SFH		35	7.0	x				x							2045	2020	24196	4300	1526	11455	11071	10551
291	SFH		50	7.0	x	x							x			2045		24196	4300	1526	58210	56260	53617
292	SFH		50	7.0	x	x										2045		24196	4300	1526	80823	78116	74446
293	SFH		50	7.0	x	x								x		2045		24196	4300	1526	36123	34913	33273
294	SFH		50	7.0	x	x									x	2045		24196	4300	1526	104541	101039	96292
295	SFH		50	7.0	x			x								2045		24196	4300	1526	36735	35504	33836
296	SFH		50	7.0	x			x						x		2045		24196	4300	1526	60138	58123	55393
297	SFH		50	7.0	x							x				2045		24196	4300	1526	105858	102312	97505
298	SFH		50	7.0	x							x		x		2045		24196	4300	1526	45145	43633	41583
299	SFH		50	0.0	x	x							x			2045		24196	4300	1526	49483	47826	45579
300	SFH		50	0.0	x	x										2045		24196	4300	1526	68707	66405	63286
301	SFH		50	0.0	x	x								x		2045		24196	4300	1526	30708	29679	28285
302	SFH		50	0.0	x	x									x	2045		24196	4300	1526	88869	85892	81857
303	SFH		50	0.0	x			x								2045		24196	4300	1526	31228	30181	28764
304	SFH		50	0.0	x			x						x		2045		24196	4300	1526	51122	49410	47089
305	SFH		50	0.0	x							x				2045		24196	4300	1526	89988	86974	82888
306	SFH		50	0.0	x							x		x		2045		24196	4300	1526	38377	37092	35349
307	SFH		50	7.0	x	x									x	2045	2005	25010	1934	2112	1778	1719	1638
308	SFH		50	7.0	x			x								2045	2005	25010	1934	2112	3615	3494	3329
309	SFH		35	7.0	x				x							2045	2005	25010	1934	2112	19189	18546	17675
310	SFH		50	7.0	x	x									x	2045	2010	25010	1934	2112	4241	4099	3906
311	SFH		50	7.0	x			x								2045	2010	25010	1934	2112	8621	8333	7941
312	SFH		35	7.0	x				x							2045	2010	25010	1934	2112	45769	44235	42157
313	SFH		50	7.0	x	x									x	2045	2015	25010	1934	2112	2142	2070	1973
314	SFH		50	7.0	x			x								2045	2015	25010	1934	2112	4354	4208	4010
315	SFH		35	7.0	x				x							2045	2015	25010	1934	2112	23113	22338	21289
316	SFH		50	7.0	x	x									x	2045	2020	25010	1934	2112	1099	1062	1012
317	SFH		50	7.0	x			x								2045	2020	25010	1934	2112	2233	2159	2057
318	SFH		35	7.0	x				x							2045	2020	25010	1934	2112	11857	11460	10922
319	SFH		50	7.0	x	x							x			2045		25010	1934	2112	73190	70739	67415
320	SFH		50	7.0	x	x								x		2045		25010	1934	2112	74619	72120	68732
321	SFH		50	7.0	x	x									x	2045		25010	1934	2112	87106	84188	80233
322	SFH		50	7.0	x			x								2045		25010	1934	2112	52985	51210	48804
323	SFH		50	7.0	x			x						x		2045		25010	1934	2112	54801	52965	50477
324	SFH		50	7.0	x						x			x		2045		25010	1934	2112	33188	32076	30569
325	SFH		50	7.0	x						x				x	2045		25010	1934	2112	18357	17742	16909
326	SFH		50	7.0	x							x				2045		25010	1934	2112	103350	99888	95195
327	SFH		50	7.0	x							x		x		2045		25010	1934	2112	47534	45941	43783
328	SFH		50	0.0	x	x							x			2045		25010	1934	2112	62218	60134	57309
329	SFH		50	0.0	x	x								x		2045		25010	1934	2112	63433	61308	58428
330	SFH		50	0.0	x	x									x	2045		25010	1934	2112	74048	71567	68205
331	SFH		50	0.0	x			x								2045		25010	1934	2112	45042	43533	41488
332	SFH		50	0.0	x			x						x		2045		25010	1934	2112	46586	45025	42910
333	SFH		50	0.0	x						x			x		2045		25010	1934	2112	28212	27267	25986
334	SFH		50	0.0	x						x				x	2045		25010	1934	2112	15605	15082	14374
335	SFH		50	0.0	x							x				2045		25010	1934	2112	87856	84913	80924
336	SFH		50	0.0	x							x		x		2045		25010	1934	2112	40408	39054	37219
337	sMFH	x	50	5.8			x							x		2025	2005	10121	1606	3000	17263	16685	15901
338	sMFH	x	50	5.8			x							x		2025	2010	10121	1606	3000	70843	68469	65253
339	sMFH	x	50	5.8			x							x		2025	2015	10121	1606	3000	10668	10311	9826
340	sMFH	x	50	5.8			x							x		2025	2020	10121	1606	3000	3966	3833	3653
341	sMFH	x	50	5.8			x							x		2025		10121	1606	3000	183583	177433	169097
342	sMFH	x	50	5.8			x								x	2025		10121	1606	3000	123486	119349	113742
343	sMFH	x	50	5.8							x			x		2025		10121	1606	3000	41957	40552	38647
344	sMFH	x	50	5.8							x				x	2025		10121	1606	3000	24505	23684	22572
345	sMFH	x	50	0.0			x							x		2025		10121	1606	3000	168906	163247	155579
346	sMFH	x	50	0.0			x								x	2025		10121	1606	3000	113614	109807	104649
347	sMFH	x	50	0.0							x			x		2025		10121	1606	3000	38603	37310	35557
348	sMFH	x	50	0.0							x				x	2025		10121	1606	3000	22546	21791	20767
349	sMFH	x	50	5.8			x							x		2025		10889	4013	3000	200397	193684	184585
350	sMFH	x	50	0.0			x							x		2025		10889	4013	3000	184376	178199	169828

*for buildings with individual floor heating: number of flats
IFH: individual floor heating; FT: flow temperature; PVP: PV potential; SW: secondary wood-fired system; GB: gas boiler;
CB: combined gas boiler; OB: oil boiler; EP: electric heat pump; GP: gas heat pump; NS: night storage heater; O: other; ST: solar thermal;
EH: electric flow heater; GH: gas flow heater; PV: PV system (construction year); SFY: system failure year of heating system.

Table D.10: Building Definition 5/12

No.	Type	IFH	FT [°C]	PVP [kW]	SW	Technology endowment in 2019										SFY	PV	Demand in 2019 [kWh]			Number of Buildings*		
						Space Heating							Hot Water										
						GB	CB	OB	EP	GP	NS	O	ST	EH	GH			Space	Water	Elec.	2019	2030	2045
351	sMFH		50	16.0		x										2025	2005	27989	4441	8297	2418	2337	2228
352	sMFH		50	16.0				x						x		2025	2005	27989	4441	8297	5270	5093	4854
353	sMFH		50	16.0		x										2025	2010	27989	4441	8297	9925	9592	9142
354	sMFH		50	16.0				x						x		2025	2010	27989	4441	8297	21626	20901	19919
355	sMFH		50	16.0		x										2025	2015	27989	4441	8297	1495	1444	1377
356	sMFH		50	16.0				x						x		2025	2015	27989	4441	8297	3257	3147	3000
357	sMFH		50	16.0		x										2025	2020	27989	4441	8297	556	537	512
358	sMFH		50	16.0				x						x		2025	2020	27989	4441	8297	1211	1170	1115
359	sMFH		50	16.0		x							x			2025		27989	4441	8297	45121	43609	41561
360	sMFH		50	16.0		x										2025		27989	4441	8297	12786	12358	11777
361	sMFH		50	16.0		x								x		2025		27989	4441	8297	90476	87445	83337
362	sMFH		50	16.0				x								2025		27989	4441	8297	45767	44234	42156
363	sMFH		50	16.0				x						x		2025		27989	4441	8297	49342	47689	45449
364	sMFH		50	0.0		x							x			2025		27989	4441	8297	41514	40123	38238
365	sMFH		50	0.0		x										2025		27989	4441	8297	11764	11370	10836
366	sMFH		50	0.0		x								x		2025		27989	4441	8297	83242	80454	76674
367	sMFH		50	0.0				x								2025		27989	4441	8297	42108	40697	38786
368	sMFH		50	0.0				x						x		2025		27989	4441	8297	45398	43877	41816
369	sMFH		50	16.0				x								2025		30114	11098	8297	28408	27456	26166
370	sMFH		50	16.0		x										2025		30114	11098	8297	31621	30561	29126
371	sMFH		50	0.0				x								2025		30114	11098	8297	26137	25261	24075
372	sMFH		50	0.0		x										2025		30114	11098	8297	29093	28118	26797
373	sMFH		50	16.0		x										2025		57332	11756	8297	40210	38863	37038
374	sMFH		50	16.0				x								2025		57332	11756	8297	46454	44898	42789
375	sMFH		50	0.0		x										2025		57332	11756	8297	36996	35756	34077
376	sMFH		50	0.0				x								2025		57332	11756	8297	42740	41308	39368
377	sMFH		50	16.0		x							x			2025		57637	5111	8297	22418	21667	20649
378	sMFH		50	16.0		x										2025		57637	5111	8297	44725	43227	41196
379	sMFH		50	16.0				x								2025		57637	5111	8297	51557	49829	47489
380	sMFH		50	0.0		x							x			2025		57637	5111	8297	20625	19935	18998
381	sMFH		50	0.0		x										2025		57637	5111	8297	41149	39771	37903
382	sMFH		50	0.0				x								2025		57637	5111	8297	47435	45846	43692
383	sMFH	x	50	5.8			x							x		2030	2005	10121	1606	3000	8280	8003	7627
384	sMFH	x	50	5.8			x							x		2030	2010	10121	1606	3000	33980	32842	31299
385	sMFH	x	50	5.8			x							x		2030	2015	10121	1606	3000	5117	4946	4713
386	sMFH	x	50	5.8			x							x		2030	2020	10121	1606	3000	1902	1838	1752
387	sMFH	x	50	5.8			x							x		2030		10121	1606	3000	88057	85107	81109
388	sMFH	x	50	5.8			x								x	2030		10121	1606	3000	59231	57247	54557
389	sMFH	x	50	5.8							x			x		2030		10121	1606	3000	20125	19451	18537
390	sMFH	x	50	5.8							x				x	2030		10121	1606	3000	11754	11360	10827
391	sMFH	x	50	0.0			x							x		2030		10121	1606	3000	81017	78303	74625
392	sMFH	x	50	0.0			x								x	2030		10121	1606	3000	54496	52670	50196
393	sMFH	x	50	0.0							x			x		2030		10121	1606	3000	18516	17896	17055
394	sMFH	x	50	0.0							x				x	2030		10121	1606	3000	10814	10452	9961
395	sMFH	x	50	5.8			x							x		2030		10889	4013	3000	96122	92902	88538
396	sMFH	x	50	0.0			x							x		2030		10889	4013	3000	88438	85475	81459
397	sMFH		50	16.0		x										2030	2005	27989	4441	8297	1160	1121	1069
398	sMFH		50	16.0				x						x		2030	2005	27989	4441	8297	2528	2443	2328
399	sMFH		50	16.0		x										2030	2010	27989	4441	8297	4760	4601	4385
400	sMFH		50	16.0				x						x		2030	2010	27989	4441	8297	10373	10025	9554
401	sMFH		50	16.0		x										2030	2015	27989	4441	8297	717	693	660
402	sMFH		50	16.0				x						x		2030	2015	27989	4441	8297	1562	1510	1439
403	sMFH		50	16.0		x										2030	2020	27989	4441	8297	266	258	245
404	sMFH		50	16.0				x						x		2030	2020	27989	4441	8297	581	561	535
405	sMFH		50	16.0		x							x			2030		27989	4441	8297	21643	20918	19935
406	sMFH		50	16.0		x										2030		27989	4441	8297	6133	5928	5649
407	sMFH		50	16.0		x								x		2030		27989	4441	8297	43397	41944	39973
408	sMFH		50	16.0				x								2030		27989	4441	8297	21953	21217	20220
409	sMFH		50	16.0				x						x		2030		27989	4441	8297	23668	22875	21800
410	sMFH		50	0.0		x							x			2030		27989	4441	8297	19912	19245	18341
411	sMFH		50	0.0		x										2030		27989	4441	8297	5643	5454	5197
412	sMFH		50	0.0		x								x		2030		27989	4441	8297	39928	38590	36777
413	sMFH		50	0.0				x								2030		27989	4441	8297	20197	19521	18604
414	sMFH		50	0.0				x						x		2030		27989	4441	8297	21775	21046	20057
415	sMFH		50	16.0				x								2030		30114	11098	8297	13626	13170	12551
416	sMFH		50	16.0		x										2030		30114	11098	8297	15167	14659	13970
417	sMFH		50	0.0				x								2030		30114	11098	8297	12537	12117	11548
418	sMFH		50	0.0		x										2030		30114	11098	8297	13955	13487	12854
419	sMFH		50	16.0		x										2030		57332	11756	8297	19287	18641	17765
420	sMFH		50	16.0				x								2030		57332	11756	8297	22282	21536	20524

*for buildings with individual floor heating: number of flats
IFH: individual floor heating; FT: flow temperature; PVP: PV potential; SW: secondary wood-fired system; GB: gas boiler;
CB: combined gas boiler; OB: oil boiler; EP: electric heat pump; GP: gas heat pump; NS: night storage heater; O: other; ST: solar thermal;
EH: electric flow heater; GH: gas flow heater; PV: PV system (construction year); SFY: system failure year of heating system.

Table D.11: Building Definition 6/12

No.	Type	IFH	FT [°C]	PVP [kW]	SW	Technology endowment in 2019												Demand in 2019 [kWh]			Number of Buildings*		
						Space Heating							Hot Water										
						GB	CB	OB	EP	GP	NS	O	ST	EH	GH	SFY	PV	Space	Water	Elec.	2019	2030	2045
421	sMFH		50	0.0		x										2030		57332	11756	8297	17745	17151	16345
422	sMFH		50	0.0				x								2030		57332	11756	8297	20501	19814	18883
423	sMFH		50	16.0		x							x			2030		57637	5111	8297	10753	10393	9904
424	sMFH		50	16.0		x										2030		57637	5111	8297	21453	20734	19760
425	sMFH		50	16.0				x								2030		57637	5111	8297	24730	23901	22778
426	sMFH		50	0.0		x							x			2030		57637	5111	8297	9893	9562	9113
427	sMFH		50	0.0		x										2030		57637	5111	8297	19738	19076	18180
428	sMFH		50	0.0				x								2030		57637	5111	8297	22752	21990	20957
429	sMFH	x	50	5.8			x							x		2035	2005	10121	1606	3000	7116	6878	6555
430	sMFH	x	50	5.8			x							x		2035	2010	10121	1606	3000	29203	28225	26899
431	sMFH	x	50	5.8			x							x		2035	2015	10121	1606	3000	4398	4250	4051
432	sMFH	x	50	5.8			x							x		2035	2020	10121	1606	3000	1635	1580	1506
433	sMFH	x	50	5.8			x							x		2035		10121	1606	3000	75677	73142	69706
434	sMFH	x	50	5.8			x								x	2035		10121	1606	3000	50904	49199	46887
435	sMFH	x	50	5.8							x			x		2035		10121	1606	3000	17296	16716	15931
436	sMFH	x	50	5.8							x				x	2035		10121	1606	3000	10102	9763	9305
437	sMFH	x	50	0.0			x							x		2035		10121	1606	3000	69627	67295	64133
438	sMFH	x	50	0.0			x								x	2035		10121	1606	3000	46834	45265	43139
439	sMFH	x	50	0.0							x			x		2035		10121	1606	3000	15913	15380	14658
440	sMFH	x	50	0.0							x				x	2035		10121	1606	3000	9294	8983	8561
441	sMFH	x	50	5.8			x							x		2035		10889	4013	3000	82609	79841	76091
442	sMFH	x	50	0.0			x							x		2035		10889	4013	3000	76004	73458	70007
443	sMFH		50	16.0		x										2035	2005	27989	4441	8297	997	964	918
444	sMFH		50	16.0				x						x		2035	2005	27989	4441	8297	2172	2100	2001
445	sMFH		50	16.0		x										2035	2010	27989	4441	8297	4091	3954	3768
446	sMFH		50	16.0				x						x		2035	2010	27989	4441	8297	8915	8616	8211
447	sMFH		50	16.0		x										2035	2015	27989	4441	8297	616	595	567
448	sMFH		50	16.0				x						x		2035	2015	27989	4441	8297	1342	1297	1237
449	sMFH		50	16.0		x										2035	2020	27989	4441	8297	229	221	211
450	sMFH		50	16.0				x						x		2035	2020	27989	4441	8297	499	482	460
451	sMFH		50	16.0		x							x			2035		27989	4441	8297	18600	17977	17132
452	sMFH		50	16.0		x										2035		27989	4441	8297	5271	5094	4855
453	sMFH		50	16.0		x								x		2035		27989	4441	8297	37296	36047	34353
454	sMFH		50	16.0				x								2035		27989	4441	8297	18866	18234	17378
455	sMFH		50	16.0				x						x		2035		27989	4441	8297	20340	19659	18735
456	sMFH		50	0.0		x							x			2035		27989	4441	8297	17113	16540	15763
457	sMFH		50	0.0		x										2035		27989	4441	8297	4849	4687	4467
458	sMFH		50	0.0		x								x		2035		27989	4441	8297	34315	33165	31607
459	sMFH		50	0.0				x								2035		27989	4441	8297	17358	16777	15988
460	sMFH		50	0.0				x						x		2035		27989	4441	8297	18714	18087	17237
461	sMFH		50	16.0				x								2035		30114	11098	8297	11710	11318	10786
462	sMFH		50	16.0		x										2035		30114	11098	8297	13035	12598	12006
463	sMFH		50	0.0				x								2035		30114	11098	8297	10774	10413	9924
464	sMFH		50	0.0		x										2035		30114	11098	8297	11993	11591	11046
465	sMFH		50	16.0		x										2035		57332	11756	8297	16576	16020	15268
466	sMFH		50	16.0				x								2035		57332	11756	8297	19150	18508	17639
467	sMFH		50	0.0		x										2035		57332	11756	8297	15251	14740	14047
468	sMFH		50	0.0				x								2035		57332	11756	8297	17619	17028	16228
469	sMFH		50	16.0		x							x			2035		57637	5111	8297	9241	8932	8512
470	sMFH		50	16.0		x										2035		57637	5111	8297	18437	17819	16982
471	sMFH		50	16.0				x								2035		57637	5111	8297	21253	20541	19576
472	sMFH		50	0.0		x							x			2035		57637	5111	8297	8502	8218	7831
473	sMFH		50	0.0		x										2035		57637	5111	8297	16963	16395	15624
474	sMFH		50	0.0				x								2035		57637	5111	8297	19554	18899	18011
475	sMFH	x	50	5.8			x							x		2040	2005	10121	1606	3000	7484	7234	6894
476	sMFH	x	50	5.8			x							x		2040	2010	10121	1606	3000	30714	29685	28290
477	sMFH	x	50	5.8			x							x		2040	2015	10121	1606	3000	4625	4470	4260
478	sMFH	x	50	5.8			x							x		2040	2020	10121	1606	3000	1719	1662	1584
479	sMFH	x	50	5.8			x							x		2040		10121	1606	3000	79591	76925	73311
480	sMFH	x	50	5.8			x								x	2040		10121	1606	3000	53537	51743	49312
481	sMFH	x	50	5.8							x			x		2040		10121	1606	3000	18190	17581	16755
482	sMFH	x	50	5.8							x				x	2040		10121	1606	3000	10624	10268	9786
483	sMFH	x	50	0.0			x							x		2040		10121	1606	3000	73228	70775	67450
484	sMFH	x	50	0.0			x								x	2040		10121	1606	3000	49257	47606	45370
485	sMFH	x	50	0.0							x			x		2040		10121	1606	3000	16736	16175	15416
486	sMFH	x	50	0.0							x				x	2040		10121	1606	3000	9775	9447	9004
487	sMFH	x	50	5.8			x							x		2040		10889	4013	3000	86881	83971	80026
488	sMFH	x	50	0.0			x							x		2040		10889	4013	3000	79935	77257	73628
489	sMFH		50	16.0		x										2040	2005	27989	4441	8297	1049	1013	966
490	sMFH		50	16.0				x						x		2040	2005	27989	4441	8297	2285	2208	2104

*for buildings with individual floor heating: number of flats
IFH: individual floor heating; FT: flow temperature; PVP: PV potential; SW: secondary wood-fired system; GB: gas boiler;
CB: combined gas boiler; OB: oil boiler; EP: electric heat pump; GP: gas heat pump; NS: night storage heater; O: other; ST: solar thermal;
EH: electric flow heater; GH: gas flow heater; PV: PV system (construction year); SFY: system failure year of heating system.

Table D.12: Building Definition 7/12

No.	Type	IFH	FT [°C]	PVP [kW]	SW	Technology endowment in 2019												Demand in 2019 [kWh]			Number of Buildings*		
						Space Heating							Hot Water			SFY	PV						
						GB	CB	OB	EP	GP	NS	O	ST	EH	GH			Space	Water	Elec.	2019	2030	2045
491	sMFH		50	16.0		x										2040	2010	27989	4441	8297	4303	4159	3963
492	sMFH		50	16.0				x						x		2040	2010	27989	4441	8297	9376	9062	8636
493	sMFH		50	16.0		x										2040	2015	27989	4441	8297	648	626	597
494	sMFH		50	16.0				x						x		2040	2015	27989	4441	8297	1412	1365	1300
495	sMFH		50	16.0		x										2040	2020	27989	4441	8297	241	233	222
496	sMFH		50	16.0				x						x		2040	2020	27989	4441	8297	525	507	483
497	sMFH		50	16.0		x							x			2040		27989	4441	8297	19562	18907	18018
498	sMFH		50	16.0		x										2040		27989	4441	8297	5543	5358	5106
499	sMFH		50	16.0		x								x		2040		27989	4441	8297	39225	37911	36130
500	sMFH		50	16.0				x								2040		27989	4441	8297	19842	19177	18276
501	sMFH		50	16.0				x						x		2040		27989	4441	8297	21392	20675	19704
502	sMFH		50	16.0						x						2040		27989	4441	8297	57007	55097	52509
503	sMFH		50	0.0		x							x			2040		27989	4441	8297	17998	17395	16578
504	sMFH		50	0.0		x										2040		27989	4441	8297	5100	4929	4698
505	sMFH		50	0.0		x								x		2040		27989	4441	8297	36089	34880	33242
506	sMFH		50	0.0				x								2040		27989	4441	8297	18256	17644	16815
507	sMFH		50	0.0				x						x		2040		27989	4441	8297	19682	19023	18129
508	sMFH		50	0.0						x						2040		27989	4441	8297	52450	50692	48311
509	sMFH		50	16.0				x								2040		30114	11098	8297	12316	11904	11344
510	sMFH		50	16.0		x										2040		30114	11098	8297	13709	13250	12627
511	sMFH		50	0.0				x								2040		30114	11098	8297	11332	10952	10437
512	sMFH		50	0.0		x										2040		30114	11098	8297	12613	12190	11618
513	sMFH		50	16.0		x										2040		57332	11756	8297	17433	16849	16057
514	sMFH		50	16.0				x								2040		57332	11756	8297	20140	19465	18551
515	sMFH		50	0.0		x										2040		57332	11756	8297	16039	15502	14774
516	sMFH		50	0.0				x								2040		57332	11756	8297	18530	17909	17068
517	sMFH		50	16.0		x							x			2040		57637	5111	8297	9719	9393	8952
518	sMFH		50	16.0		x										2040		57637	5111	8297	19390	18741	17860
519	sMFH		50	16.0				x								2040		57637	5111	8297	22352	21603	20588
520	sMFH		50	0.0		x							x			2040		57637	5111	8297	8942	8643	8237
521	sMFH		50	0.0		x										2040		57637	5111	8297	17840	17242	16432
522	sMFH		50	0.0				x								2040		57637	5111	8297	20565	19876	18942
523	sMFH	x	50	5.8			x							x		2045	2005	10121	1606	3000	15342	14828	14132
524	sMFH	x	50	5.8			x							x		2045	2010	10121	1606	3000	62961	60851	57993
525	sMFH	x	50	5.8			x							x		2045	2015	10121	1606	3000	9481	9164	8733
526	sMFH	x	50	5.8			x							x		2045	2020	10121	1606	3000	3525	3406	3246
527	sMFH	x	50	5.8			x							x		2045		10121	1606	3000	163157	157691	150283
528	sMFH	x	50	5.8			x								x	2045		10121	1606	3000	109747	106070	101087
529	sMFH	x	50	5.8							x			x		2045		10121	1606	3000	37289	36040	34347
530	sMFH	x	50	5.8							x				x	2045		10121	1606	3000	21779	21049	20060
531	sMFH	x	50	0.0			x							x		2045		10121	1606	3000	150113	145084	138269
532	sMFH	x	50	0.0			x								x	2045		10121	1606	3000	100973	97590	93006
533	sMFH	x	50	0.0							x			x		2045		10121	1606	3000	34308	33159	31601
534	sMFH	x	50	0.0							x				x	2045		10121	1606	3000	20038	19366	18457
535	sMFH	x	50	5.8			x							x		2045		10889	4013	3000	178101	172134	164048
536	sMFH	x	50	0.0			x							x		2045		10889	4013	3000	163862	158373	150933
537	sMFH		50	16.0		x										2045	2005	27989	4441	8297	2149	2077	1980
538	sMFH		50	16.0				x						x		2045	2005	27989	4441	8297	4683	4527	4314
539	sMFH		50	16.0		x										2045	2010	27989	4441	8297	8820	8525	8125
540	sMFH		50	16.0				x						x		2045	2010	27989	4441	8297	19219	18576	17703
541	sMFH		50	16.0		x										2045	2015	27989	4441	8297	1328	1284	1223
542	sMFH		50	16.0				x						x		2045	2015	27989	4441	8297	2894	2797	2666
543	sMFH		50	16.0		x										2045	2020	27989	4441	8297	494	477	455
544	sMFH		50	16.0				x						x		2045	2020	27989	4441	8297	1076	1040	991
545	sMFH		50	16.0		x							x			2045		27989	4441	8297	40101	38757	36937
546	sMFH		50	16.0		x										2045		27989	4441	8297	11364	10983	10467
547	sMFH		50	16.0		x								x		2045		27989	4441	8297	80409	77715	74065
548	sMFH		50	16.0				x								2045		27989	4441	8297	40675	39312	37465
549	sMFH		50	16.0				x						x		2045		27989	4441	8297	43852	42383	40392
550	sMFH		50	16.0						x						2045		27989	4441	8297	142518	137743	131272
551	sMFH		50	0.0		x							x			2045		27989	4441	8297	36895	35659	33984
552	sMFH		50	0.0		x										2045		27989	4441	8297	10455	10105	9630
553	sMFH		50	0.0		x								x		2045		27989	4441	8297	73981	71502	68143
554	sMFH		50	0.0				x								2045		27989	4441	8297	37423	36169	34470
555	sMFH		50	0.0				x						x		2045		27989	4441	8297	40347	38995	37163
556	sMFH		50	0.0						x						2045		27989	4441	8297	131124	126731	120778
557	sMFH		50	16.0				x								2045		30114	11098	8297	25247	24401	23255
558	sMFH		50	16.0		x										2045		30114	11098	8297	28103	27161	25885
559	sMFH		50	0.0				x								2045		30114	11098	8297	23229	22451	21396
560	sMFH		50	0.0		x										2045		30114	11098	8297	25856	24990	23816

*for buildings with individual floor heating: number of flats
IFH: individual floor heating; FT: flow temperature; PVP: PV potential; SW: secondary wood-fired system; GB: gas boiler;
CB: combined gas boiler; OB: oil boiler; EP: electric heat pump; GP: gas heat pump; NS: night storage heater; O: other; ST: solar thermal;
EH: electric flow heater; GH: gas flow heater; PV: PV system (construction year); SFY: system failure year of heating system.

Table D.13: Building Definition 8/12

No.	Type	IFH	FT [°C]	PVP [kW]	SW	Technology endowment in 2019										SFY	PV	Demand in 2019 [kWh]			Number of Buildings*		
						Space Heating							Hot Water										
						GB	CB	OB	EP	GP	NS	O	ST	EH	GH			Space	Water	Elec.	2019	2030	2045
561	sMFH		50	16.0		x										2045		57332	11756	8297	35736	34539	32917
562	sMFH		50	16.0				x								2045		57332	11756	8297	41286	39902	38028
563	sMFH		50	0.0		x										2045		57332	11756	8297	32879	31778	30285
564	sMFH		50	0.0				x								2045		57332	11756	8297	37985	36712	34988
565	sMFH		50	16.0		x							x			2045		57637	5111	8297	19923	19256	18351
566	sMFH		50	16.0		x										2045		57637	5111	8297	39749	38417	36613
567	sMFH		50	16.0				x								2045		57637	5111	8297	45820	44285	42205
568	sMFH		50	0.0		x							x			2045		57637	5111	8297	18331	17717	16884
569	sMFH		50	0.0		x										2045		57637	5111	8297	36571	35346	33685
570	sMFH		50	0.0				x								2045		57637	5111	8297	42157	40745	38831
571	lMFH	x	50	1.8			x								x	2025		10036	1694	3000	60964	58922	56154
572	lMFH	x	50	0.0			x								x	2025		10036	1694	3000	281999	272552	259748
573	lMFH		35	25.0								x				2025	2005	78501	18960	41432	764	738	704
574	lMFH		35	25.0								x				2025	2010	78501	18960	41432	2939	2841	2707
575	lMFH		35	25.0								x				2025	2015	78501	18960	41432	380	368	350
576	lMFH		35	25.0								x				2025	2020	78501	18960	41432	225	217	207
577	lMFH		35	25.0				x								2025		78501	18960	41432	5895	5697	5430
578	lMFH		35	25.0								x				2025		78501	18960	41432	8048	7779	7413
579	lMFH		35	25.0		x										2025		78501	18960	41432	7174	6933	6608
580	lMFH		35	0.0				x								2025		78501	18960	41432	27268	26354	25116
581	lMFH		35	0.0								x				2025		78501	18960	41432	37228	35981	34291
582	lMFH		35	0.0		x										2025		78501	18960	41432	33182	32071	30564
583	lMFH		50	25.0								x				2025		121673	55748	41432	2142	2071	1973
584	lMFH		50	25.0		x										2025		121673	55748	41432	3375	3262	3109
585	lMFH		50	25.0				x								2025		121673	55748	41432	3079	2976	2836
586	lMFH		50	0.0								x				2025		121673	55748	41432	9910	9578	9128
587	lMFH		50	0.0		x										2025		121673	55748	41432	15612	15089	14380
588	lMFH		50	0.0				x								2025		121673	55748	41432	14242	13765	13118
589	lMFH		50	25.0		x										2025	2005	138597	23392	41432	666	643	613
590	lMFH		50	25.0				x						x		2025	2005	138597	23392	41432	1008	974	928
591	lMFH		50	25.0								x				2025	2005	138597	23392	41432	561	542	517
592	lMFH		50	25.0		x										2025	2010	138597	23392	41432	2561	2476	2359
593	lMFH		50	25.0				x						x		2025	2010	138597	23392	41432	3878	3748	3572
594	lMFH		50	25.0								x				2025	2010	138597	23392	41432	2160	2087	1989
595	lMFH		50	25.0		x										2025	2015	138597	23392	41432	331	320	305
596	lMFH		50	25.0				x						x		2025	2015	138597	23392	41432	502	485	462
597	lMFH		50	25.0								x				2025	2015	138597	23392	41432	279	270	257
598	lMFH		50	25.0		x										2025	2020	138597	23392	41432	196	189	181
599	lMFH		50	25.0				x						x		2025	2020	138597	23392	41432	297	287	273
600	lMFH		50	25.0								x				2025	2020	138597	23392	41432	165	160	152
601	lMFH		50	25.0		x										2025		138597	23392	41432	2183	2110	2011
602	lMFH		50	25.0								x				2025		138597	23392	41432	8150	7877	7507
603	lMFH		50	0.0		x										2025		138597	23392	41432	10097	9759	9300
604	lMFH		50	0.0								x				2025		138597	23392	41432	37699	36436	34725
605	lMFH		50	25.0		x										2025		243785	24529	41432	1299	1255	1196
606	lMFH		50	25.0				x								2025		243785	24529	41432	375	363	346
607	lMFH		50	0.0		x										2025		243785	24529	41432	6008	5807	5534
608	lMFH		50	0.0				x								2025		243785	24529	41432	1736	1678	1599
609	lMFH		50	25.0		x										2025		243903	59887	41432	1059	1024	976
610	lMFH		50	0.0		x										2025		243903	59887	41432	4900	4735	4513
611	lMFH	x	50	1.8			x								x	2030		10036	1694	3000	29242	28263	26935
612	lMFH	x	50	0.0			x								x	2030		10036	1694	3000	135263	130732	124590
613	lMFH		35	25.0								x				2030	2005	78501	18960	41432	366	354	337
614	lMFH		35	25.0								x				2030	2010	78501	18960	41432	1410	1363	1299
615	lMFH		35	25.0								x				2030	2015	78501	18960	41432	182	176	168
616	lMFH		35	25.0								x				2030	2020	78501	18960	41432	108	104	99
617	lMFH		35	25.0				x								2030		78501	18960	41432	2828	2733	2604
618	lMFH		35	25.0								x				2030		78501	18960	41432	3860	3731	3556
619	lMFH		35	25.0		x										2030		78501	18960	41432	3441	3326	3169
620	lMFH		35	0.0				x								2030		78501	18960	41432	13079	12641	12047
621	lMFH		35	0.0								x				2030		78501	18960	41432	17857	17259	16448
622	lMFH		35	0.0		x										2030		78501	18960	41432	15916	15383	14660
623	lMFH		50	25.0								x				2030		121673	55748	41432	1028	993	947
624	lMFH		50	25.0		x										2030		121673	55748	41432	1619	1565	1491
625	lMFH		50	25.0				x								2030		121673	55748	41432	1477	1427	1360
626	lMFH		50	0.0								x				2030		121673	55748	41432	4753	4594	4378
627	lMFH		50	0.0		x										2030		121673	55748	41432	7488	7237	6897
628	lMFH		50	0.0				x								2030		121673	55748	41432	6831	6603	6292
629	lMFH		50	25.0		x										2030	2005	138597	23392	41432	319	309	294
630	lMFH		50	25.0				x						x		2030	2005	138597	23392	41432	483	467	445

*for buildings with individual floor heating: number of flats
IFH: individual floor heating; FT: flow temperature; PVP: PV potential; SW: secondary wood-fired system; GB: gas boiler;
CB: combined gas boiler; OB: oil boiler; EP: electric heat pump; GP: gas heat pump; NS: night storage heater; O: other; ST: solar thermal;
EH: electric flow heater; GH: gas flow heater; PV: PV system (construction year); SFY: system failure year of heating system.

Table D.14: Building Definition 9/12

No.	Type	IFH	FT [°C]	PVP [kW]	SW	Technology endowment in 2019												Demand in 2019 [kWh]			Number of Buildings*		
						Space Heating							Hot Water			SFY	PV	Space	Water	Elec.	2019	2030	2045
						GB	CB	OB	EP	GP	NS	O	ST	EH	GH								
631	lMFH		50	25.0								x				2030	2005	138597	23392	41432	269	260	248
632	lMFH		50	25.0		x										2030	2010	138597	23392	41432	1229	1187	1132
633	lMFH		50	25.0				x						x		2030	2010	138597	23392	41432	1860	1798	1713
634	lMFH		50	25.0								x				2030	2010	138597	23392	41432	1036	1001	954
635	lMFH		50	25.0		x										2030	2015	138597	23392	41432	159	154	146
636	lMFH		50	25.0				x						x		2030	2015	138597	23392	41432	241	233	222
637	lMFH		50	25.0								x				2030	2015	138597	23392	41432	134	130	123
638	lMFH		50	25.0		x										2030	2020	138597	23392	41432	94	91	87
639	lMFH		50	25.0				x						x		2030	2020	138597	23392	41432	142	138	131
640	lMFH		50	25.0								x				2030	2020	138597	23392	41432	79	77	73
641	lMFH		50	25.0		x										2030		138597	23392	41432	1047	1012	964
642	lMFH		50	25.0								x				2030		138597	23392	41432	3909	3778	3601
643	lMFH		50	0.0		x										2030		138597	23392	41432	4843	4681	4461
644	lMFH		50	0.0								x				2030		138597	23392	41432	18083	17477	16656
645	lMFH		50	25.0		x										2030		243785	24529	41432	623	602	574
646	lMFH		50	25.0				x								2030		243785	24529	41432	180	174	166
647	lMFH		50	0.0		x										2030		243785	24529	41432	2882	2785	2654
648	lMFH		50	0.0				x								2030		243785	24529	41432	833	805	767
649	lMFH		50	25.0		x										2030		243903	59887	41432	508	491	468
650	lMFH		50	0.0		x										2030		243903	59887	41432	2350	2271	2165
651	lMFH	x	50	1.8			x								x	2035		10036	1694	3000	25131	24289	23148
652	lMFH	x	50	0.0			x								x	2035		10036	1694	3000	116247	112353	107075
653	lMFH		35	25.0								x				2035	2005	78501	18960	41432	315	304	290
654	lMFH		35	25.0								x				2035	2010	78501	18960	41432	1212	1171	1116
655	lMFH		35	25.0								x				2035	2015	78501	18960	41432	157	152	144
656	lMFH		35	25.0								x				2035	2020	78501	18960	41432	93	90	85
657	lMFH		35	25.0				x								2035		78501	18960	41432	2430	2349	2238
658	lMFH		35	25.0								x				2035		78501	18960	41432	3318	3207	3056
659	lMFH		35	25.0		x										2035		78501	18960	41432	2957	2858	2724
660	lMFH		35	0.0				x								2035		78501	18960	41432	11241	10864	10354
661	lMFH		35	0.0								x				2035		78501	18960	41432	15346	14832	14135
662	lMFH		35	0.0		x										2035		78501	18960	41432	13679	13220	12599
663	lMFH		50	25.0								x				2035		121673	55748	41432	883	854	813
664	lMFH		50	25.0		x										2035		121673	55748	41432	1391	1345	1282
665	lMFH		50	25.0				x								2035		121673	55748	41432	1269	1227	1169
666	lMFH		50	0.0								x				2035		121673	55748	41432	4085	3948	3763
667	lMFH		50	0.0		x										2035		121673	55748	41432	6436	6220	5928
668	lMFH		50	0.0				x								2035		121673	55748	41432	5871	5674	5408
669	lMFH		50	25.0		x										2035	2005	138597	23392	41432	274	265	253
670	lMFH		50	25.0				x						x		2035	2005	138597	23392	41432	415	402	383
671	lMFH		50	25.0								x				2035	2005	138597	23392	41432	231	224	213
672	lMFH		50	25.0		x										2035	2010	138597	23392	41432	1056	1021	973
673	lMFH		50	25.0				x						x		2035	2010	138597	23392	41432	1599	1545	1473
674	lMFH		50	25.0								x				2035	2010	138597	23392	41432	890	860	820
675	lMFH		50	25.0		x										2035	2015	138597	23392	41432	137	132	126
676	lMFH		50	25.0				x						x		2035	2015	138597	23392	41432	207	200	191
677	lMFH		50	25.0								x				2035	2015	138597	23392	41432	115	111	106
678	lMFH		50	25.0		x										2035	2020	138597	23392	41432	81	78	74
679	lMFH		50	25.0				x						x		2035	2020	138597	23392	41432	122	118	113
680	lMFH		50	25.0								x				2035	2020	138597	23392	41432	68	66	63
681	lMFH		50	25.0		x										2035		138597	23392	41432	900	870	829
682	lMFH		50	25.0								x				2035		138597	23392	41432	3360	3247	3095
683	lMFH		50	0.0		x										2035		138597	23392	41432	4162	4023	3834
684	lMFH		50	0.0								x				2035		138597	23392	41432	15541	15020	14314
685	lMFH		50	25.0		x										2035		243785	24529	41432	535	517	493
686	lMFH		50	25.0				x								2035		243785	24529	41432	155	150	143
687	lMFH		50	0.0		x										2035		243785	24529	41432	2477	2394	2281
688	lMFH		50	0.0				x								2035		243785	24529	41432	716	692	659
689	lMFH		50	25.0		x										2035		243903	59887	41432	437	422	402
690	lMFH		50	0.0		x										2035		243903	59887	41432	2020	1952	1860
691	lMFH	x	50	1.8			x								x	2040		10036	1694	3000	26431	25545	24345
692	lMFH	x	50	0.0			x								x	2040		10036	1694	3000	122259	118163	112612
693	lMFH		35	25.0								x				2040	2005	78501	18960	41432	331	320	305
694	lMFH		35	25.0								x				2040	2010	78501	18960	41432	1274	1232	1174
695	lMFH		35	25.0								x				2040	2015	78501	18960	41432	165	159	152
696	lMFH		35	25.0								x				2040	2020	78501	18960	41432	98	94	90
697	lMFH		35	25.0				x								2040		78501	18960	41432	2556	2470	2354
698	lMFH		35	25.0								x				2040		78501	18960	41432	3489	3372	3214
699	lMFH		35	25.0		x										2040		78501	18960	41432	3110	3006	2865
700	lMFH		35	0.0				x								2040		78501	18960	41432	11822	11426	10889

*for buildings with individual floor heating: number of flats
IFH: individual floor heating; FT: flow temperature; PVP: PV potential; SW: secondary wood-fired system; GB: gas boiler; CB: combined gas boiler; OB: oil boiler; EP: electric heat pump; GP: gas heat pump; NS: night storage heater; O: other; ST: solar thermal; EH: electric flow heater; GH: gas flow heater; PV: PV system (construction year); SFY: system failure year of heating system.

Table D.15: Building Definition 10/12

No.	Type	IFH	FT [°C]	PVP [kW]	SW	Technology endowment in 2019										SFY	PV	Demand in 2019 [kWh]			Number of Buildings*		
						Space Heating							Hot Water										
						GB	CB	OB	EP	GP	NS	O	ST	EH	GH			Space	Water	Elec.	2019	2030	2045
701	lMFH		35	0.0								x				2040		78501	18960	41432	16140	15599	14866
702	lMFH		35	0.0		x										2040		78501	18960	41432	14386	13904	13251
703	lMFH		50	25.0								x				2040		121673	55748	41432	929	898	856
704	lMFH		50	25.0		x										2040		121673	55748	41432	1463	1414	1348
705	lMFH		50	25.0				x								2040		121673	55748	41432	1335	1290	1230
706	lMFH		50	0.0								x				2040		121673	55748	41432	4296	4152	3957
707	lMFH		50	0.0		x										2040		121673	55748	41432	6768	6542	6234
708	lMFH		50	0.0				x								2040		121673	55748	41432	6175	5968	5687
709	lMFH		50	25.0		x										2040	2005	138597	23392	41432	289	279	266
710	lMFH		50	25.0				x						x		2040	2005	138597	23392	41432	437	422	402
711	lMFH		50	25.0								x				2040	2005	138597	23392	41432	243	235	224
712	lMFH		50	25.0		x										2040	2010	138597	23392	41432	1111	1073	1023
713	lMFH		50	25.0				x						x		2040	2010	138597	23392	41432	1681	1625	1549
714	lMFH		50	25.0								x				2040	2010	138597	23392	41432	936	905	862
715	lMFH		50	25.0		x										2040	2015	138597	23392	41432	144	139	132
716	lMFH		50	25.0				x						x		2040	2015	138597	23392	41432	218	210	200
717	lMFH		50	25.0								x				2040	2015	138597	23392	41432	121	117	112
718	lMFH		50	25.0		x										2040	2020	138597	23392	41432	85	82	78
719	lMFH		50	25.0				x						x		2040	2020	138597	23392	41432	129	124	119
720	lMFH		50	25.0								x				2040	2020	138597	23392	41432	72	69	66
721	lMFH		50	25.0		x										2040		138597	23392	41432	946	915	872
722	lMFH		50	25.0								x				2040		138597	23392	41432	3533	3415	3255
723	lMFH		50	0.0		x										2040		138597	23392	41432	4378	4231	4032
724	lMFH		50	0.0								x				2040		138597	23392	41432	16344	15797	15055
725	lMFH		50	25.0		x										2040		243785	24529	41432	563	544	519
726	lMFH		50	25.0				x								2040		243785	24529	41432	163	157	150
727	lMFH		50	0.0		x										2040		243785	24529	41432	2605	2517	2399
728	lMFH		50	0.0				x								2040		243785	24529	41432	753	727	693
729	lMFH		50	25.0		x										2040		243903	59887	41432	459	444	423
730	lMFH		50	0.0		x										2040		243903	59887	41432	2124	2053	1957
731	lMFH	x	50	1.8			x								x	2045		10036	1694	3000	54182	52366	49906
732	lMFH	x	50	0.0			x								x	2045		10036	1694	3000	250623	242227	230848
733	lMFH		35	25.0								x				2045	2005	78501	18960	41432	679	656	625
734	lMFH		35	25.0								x				2045	2010	78501	18960	41432	2612	2525	2406
735	lMFH		35	25.0								x				2045	2015	78501	18960	41432	338	327	311
736	lMFH		35	25.0								x				2045	2020	78501	18960	41432	200	193	184
737	lMFH		35	25.0				x								2045		78501	18960	41432	5239	5064	4826
738	lMFH		35	25.0								x				2045		78501	18960	41432	7153	6913	6588
739	lMFH		35	25.0		x										2045		78501	18960	41432	6375	6162	5872
740	lMFH		35	0.0				x								2045		78501	18960	41432	24234	23422	22322
741	lMFH		35	0.0								x				2045		78501	18960	41432	33086	31978	30475
742	lMFH		35	0.0		x										2045		78501	18960	41432	29490	28502	27164
743	lMFH		50	25.0								x				2045		121673	55748	41432	1904	1840	1754
744	lMFH		50	25.0		x										2045		121673	55748	41432	3000	2899	2763
745	lMFH		50	25.0				x								2045		121673	55748	41432	2736	2645	2520
746	lMFH		50	0.0								x				2045		121673	55748	41432	8807	8512	8112
747	lMFH		50	0.0		x										2045		121673	55748	41432	13875	13410	12780
748	lMFH		50	0.0				x								2045		121673	55748	41432	12658	12234	11659
749	lMFH		50	25.0		x										2045	2005	138597	23392	41432	592	572	545
750	lMFH		50	25.0				x						x		2045	2005	138597	23392	41432	896	866	825
751	lMFH		50	25.0								x				2045	2005	138597	23392	41432	499	482	459
752	lMFH		50	25.0		x										2045	2010	138597	23392	41432	2276	2200	2097
753	lMFH		50	25.0				x						x		2045	2010	138597	23392	41432	3447	3331	3175
754	lMFH		50	25.0								x				2045	2010	138597	23392	41432	1919	1855	1768
755	lMFH		50	25.0		x										2045	2015	138597	23392	41432	295	285	271
756	lMFH		50	25.0				x						x		2045	2015	138597	23392	41432	446	431	411
757	lMFH		50	25.0								x				2045	2015	138597	23392	41432	248	240	229
758	lMFH		50	25.0		x										2045	2020	138597	23392	41432	174	168	160
759	lMFH		50	25.0				x						x		2045	2020	138597	23392	41432	264	255	243
760	lMFH		50	25.0								x				2045	2020	138597	23392	41432	147	142	135
761	lMFH		50	25.0		x										2045		138597	23392	41432	1940	1875	1787
762	lMFH		50	25.0								x				2045		138597	23392	41432	7243	7001	6672
763	lMFH		50	0.0		x										2045		138597	23392	41432	8974	8673	8266
764	lMFH		50	0.0								x				2045		138597	23392	41432	33505	32382	30861
765	lMFH		50	25.0		x										2045		243785	24529	41432	1154	1116	1063
766	lMFH		50	25.0				x								2045		243785	24529	41432	334	322	307
767	lMFH		50	0.0		x										2045		243785	24529	41432	5339	5161	4918
768	lMFH		50	0.0				x								2045		243785	24529	41432	1543	1491	1421
769	lMFH		50	25.0		x										2045		243903	59887	41432	941	910	867
770	lMFH		50	0.0		x										2045		243903	59887	41432	4354	4209	4011

*for buildings with individual floor heating: number of flats
IFH: individual floor heating; FT: flow temperature; PVP: PV potential; SW: secondary wood-fired system; GB: gas boiler;
CB: combined gas boiler; OB: oil boiler; EP: electric heat pump; GP: gas heat pump; NS: night storage heater; O: other; ST: solar thermal;
EH: electric flow heater; GH: gas flow heater; PV: PV system (construction year); SFY: system failure year of heating system.

Table D.16: Building Definition 11/12

No.	Type	IFH	FT [°C]	PVP [kW]	SW	Technology endowment in 2019												Demand in 2019 [kWh]			Number of Buildings*		
						Space Heating							Hot Water			SFY	PV	Space	Water	Elec.	2019	2030	2045
						GB	CB	OB	EP	GP	NS	O	ST	EH	GH								
771	SFH		35	7.0														10437	1934	2112	0	426723	426723
772	SFH		35	7.0														10437	4300	1526	0	426723	426723
773	sMFH		35	16.0														26753	11756	8297	0	27599	27599
774	sMFH		35	16.0														14555	4538	8297	0	33968	33968
775	sMFH		35	16.0														14497	11017	8297	0	33968	33968
776	sMFH		35	16.0														26753	5111	8297	0	27599	27599
777	lMFH		35	25.0														121647	24529	41432	0	10615	10615
778	lMFH		35	25.0														65471	54886	41432	0	31845	31845
779	lMFH		35	25.0														121647	59887	41432	0	10615	10615
780	lMFH		35	25.0														65957	21986	41432	0	31845	31845
781	SFH		35	7.0														10437	1934	2112	0	0	581895
782	SFH		35	7.0														10437	4300	1526	0	0	581895
783	sMFH		35	16.0														26753	11756	8297	0	0	37635
784	sMFH		35	16.0														14555	4538	8297	0	0	46320
785	sMFH		35	16.0														14497	11017	8297	0	0	46320
786	sMFH		35	16.0														26753	5111	8297	0	0	37635
787	lMFH		35	25.0														121647	24529	41432	0	0	14475
788	lMFH		35	25.0														65471	54886	41432	0	0	43425
789	lMFH		35	25.0														121647	59887	41432	0	0	14475
790	lMFH		35	25.0														65957	21986	41432	0	0	43425
791	SFH		35	7.0								x						10437	1934	2112	0	335500	335500
792	SFH		35	7.0								x						10437	4300	1526	0	335500	335500
793	SFH		35	7.0								x						10437	1934	2112	0	0	457500
794	SFH		35	7.0								x						10437	4300	1526	0	0	457500

*for buildings with individual floor heating: number of flats
IFH: individual floor heating; FT: flow temperature; PVP: PV potential; SW: secondary wood-fired system; GB: gas boiler;
CB: combined gas boiler; OB: oil boiler; EP: electric heat pump; GP: gas heat pump; NS: night storage heater; O: other; ST: solar thermal;
EH: electric flow heater; GH: gas flow heater; PV: PV system (construction year); SFY: system failure year of heating system.

Table D.17: Building Definition 12/12 (new builds)

Appendix E. Scenario Assumptions

Appendix E.1. Wholesale electricity price and market value

To project the development of wholesale electricity prices up to 2045, we use the energy system model DIMENSION. DIMENSION is an optimization model for energy supply in Europe based on assumptions regarding the development of energy demand in the end-use sectors. The model was first published in Richter (2011). Subsequently, it was used and extended in various scientific papers (e.g. Bertsch et al. (2016), Peter (2019), Helgeson and Peter (2020), Bucksteeg et al. (2022)). We employ the version used and assumptions made in the dena Leitstudie, a recent study on climate neutrality for Germany (EWI, 2021). In addition, we adjust the fuel price assumptions based on (Mendelevitch et al., 2022), to be consistent to the assumptions of the COMODO model. Table E.18 shows the wholesale electricity prices resulting from the modelling, as well as the assumed value factors of electricity generation from PV, which are the basis for the market remuneration of PV systems in the model.

	2025	2030	2035	2040	2045
Wholesale electricity price [€/kWh]	0.083	0.044	0.056	0.057	0.064
Value factor PV	0.8	0.7	0.6	0.5	0.4

Table E.18: Assumed wholesale electricity price and value factors of PV systems. The value factors of PV systems is based on Hirth (2013).

Appendix E.2. Future development of the building stock

As described in Section 3.2, the occurrence of each archetype building is determined to approximate the building stock of the year 2019. To project the existing building stock into the future, we further assume an annual, uniform demolition rate of 0.3 % of the residential area based on Bürger et al. (2017).

As a basis for the definition of archetype buildings for new buildings, we use a k-means clustering approach to identify 10 representative combinations of the three demand variables for buildings built between 2011 and 2019.[26] For buildings built between 2011 and 2019, Scharf et al. (2021) assume a specific heat demand for space heating of 55 kWh/m^2. For buildings built between 2019 and 2030, we assume a heat demand for space heating following EnEV 55 of 38.5 kWh/m^2 for single-family homes (SFH) and 30.25 kWh/m^2 for multifamily homes (MFH). We assume heat demand for buildings built after 2030 according to EnEV 40: 28 kWh/m^2 for SFH, 22 kWh/m^2 for MFH.[27] Besides the 20 archetype buildings obtained by distinguishing between buildings built before 2030 and buildings built after 2030, four additional archetype buildings are added to represent future new construction with pre-installed exogenously modelled heating systems such as *biomass heating* and *district heating*. We assume that the share of flats with these heating technologies remains stable at 2021 levels of 27.2%. For the remainder of the technologies included in the category of *others*, we assume that they leave the building stock until 2045.

The annual number of archetype new construction is determined based on the assumption that the aggregated living space will increase by 9.4% by 2050 (Kemmler et al. (2020)). The assumed

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[26] Figure D.6 shows the graphical representation of the clustering results.

[27] The specific heat demand for space heating for EnEV 55 and EneV 40 were estimated based on an EnEV reference demand of 70 kWh/m^2 for SFH and 55 kWh/m^2 for MFH.

demolition rate and the defined archetype buildings imply an annual addition of 259,900 flats (156,700 buildings).

Appendix F. Detailed investment decisions

Appendix F.1. Reference scenario

Buildings with existing condensing gas boilers

Buildings that have a condensing gas boiler installed in 2020 face the least change of all buildings. They replace their gas boiler with a new one after the end of its lifetime. However, all buildings install complementary simple power to heat systems, which supplies peaks and with its very low investment costs reduces capacity costs.

PV is strictly lucrative for buildings with existing condensing gas boilers in the *reference* scenario, and all buildings that have the option to install PV, do so. For new PV systems, the timing of investment into PV is determined by the time of failure of the original gas boiler, as well as the size of heat and electricity demand. Buildings with a high heat demand and an increased electricity demand (larger SFH buildings with existing electrical flow heaters for hot water or MFH), decide to invest into a PV system as early as possible, i.e. in 2025. For buildings with lower electricity demand, investment in a newly installed PV system is mostly dictated by the failure year of the main heating system and the opportunity for a joint optimization of capacity. Notably, PV investment can precede investment into the new main boiler by five years, to avoid the increased electricity prices. If buildings have an existing PV system, it is replaced by a new one at the end of its lifetime. As a result, most buildings have PV installed by 2040.

PV is often combined with a battery system, the earliest investment into battery storage, however, occurs in 2030 when costs have decreased sufficiently. Investment into battery storage is mainly driven by the option to supply electricity demand with self generated PV electricity. Therefore, the higher the demand, the higher the incentive to increase self-consumption by means of a battery system. Consequently, buildings without the option to install PV and buildings with low demand, such as small SFH, do not invest into battery systems at all. Investment often occurs jointly with PV investment or jointly with the heating system reinvestment. High demand and increased demand due to electric flow heaters triggers earlier investments.

We distinguish between buildings with existing central supply, where the boiler provides both, space heat and hot water and those with additional hot water technologies. When reinvesting, buildings can choose between central supply or additional technologies for hot water. Many buildings opt for additional hot water technologies to decrease the capacity of their boiler. The energy demand and (if applicable) their pre-existing hot water technologies determine this investment. For example, existing gas flow heaters are replaced by electric flow heaters in the long term. Often an investment is done prematurely, i.e. before the existing gas flow heater has reached its end of lifetime, in order to avoid midterm rising gas prices. Furthermore, high energy demand and an installed PV system favor investment in electric flow heaters. Therefore, small MFH with an increased heat demand and large MFH often invest directly in 2025 or latest, when the existing heating system fails.

Additionally, buildings with increased energy demands such as larger SFH and MFH invest into solar thermal systems to further decrease medium term gas demand. In their case, efficiency gains outweigh the relatively high investment and maintenance costs of the solar thermal systems. Existing PV systems are likely to postpone the investment into a solar thermal system as the systems compete for the same rooftop area. Solar thermal systems are often accompanied by thermal storage for buffering. Likewise, buildings with central supply of hot water invest into a thermal storage system to allow buffering for the hot water. Additionally, larger demands favor the investment into a storage system.

The upsurge of simple power to heat systems, PV and solar thermal leads to a slight decrease in the average carbon footprint of the buildings with existing condensing gas boilers already in 2025 and no further decarbonization after that.

Buildings with existing combined gas boilers

Combined gas boilers are used as single-story heating systems in MFH and provide space heat and hot water. Like buildings with existing condensing gas boilers, buildings with existing combined gas boilers replace their old systems with new combined gas boilers at the end of the original heating systems' lifetime.

If they have the option, all buildings with combined gas boilers invest into a PV system immediately and have PV installed for the full period between 2025 and 2045. As there is no option for a peak heating systems, there is no need to time PV investment with the heating system to allow an optimal interaction. PV systems are accompanied by a battery storage from 2030 on to allow flexibility and increased self-consumption. Buildings with PV also invest into electric flow heaters to minimize the new boiler's capacity when re-investing their main heating technology. Solar thermal systems do not play a role in buildings with combined gas boilers due to high maintenance costs. However, these buildings install small thermal storage systems for hot water buffering if they have PV and electric flow heaters to increase self-consumption. All in all, the investment into PV in combination with electric flow heaters leads to a slight decrease in the average carbon footprint of these buildings already in 2025 but no further decarbonization after that.

Buildings with existing condensing oil boilers

As oil heating systems are assumed to be an outdated technology in light of climate change, we assume that buildings have no option to reinvest into oil technologies. Thus, buildings with condensing oil boilers perform a fuel switch and replace their existing oil boilers with condensing gas boilers once the oil heating system fails. The new boilers are complemented by simple power to heat peak units, which reduce peaks and capacity costs - except for SFH with low demands, which already invest into the smallest available gas boiler.

All buildings with a PV option invest into PV. High electricity demand triggers early investment in 2025. If demand is lower, PV is implemented in 2025 only if this is when the main boiler is replaced, as to optimize the entire technology set-up simultaneously. For all other buildings with a lower electricity demand, investments into new PV system are feasible starting from 2035, when investment costs have decreased and electricity prices have increased. Again, joint investment with the main boiler is preferred, but by 2040, PV is strictly profitable. Waiting for decreased investment costs may even lead to buildings with existing PV systems going without PV for an intermediate period if their PV system fails before their boiler.

Once again, PV is often paired with a battery system to increase self-consumption starting in 2030, when investment costs for batteries have decreased. Larger electricity demand favors the early investment into a battery system in 2030 if a PV system exists by that year. Buildings with smaller demands chose to invest in 2045 when battery costs have decreased further. To reduce the capacity of boilers and/or increase PV self-consumption, all buildings install thermal storage systems - except for those with an existing PV system, in which case receiving feed-in tariffs is more lucrative than self-consumption.

Solar thermal systems are almost exclusively installed immediately in 2025. Investments are lucrative for buildings with a large heat demand, explicitly large MFH and small MFH with increased space or hot water heating demand.

The fuel switch and the investment into electric and thermal solar systems leads to a substantial decrease in carbon intensity of heating in buildings with existing oil boilers. Due to coordination of the investment into heating and additional systems, the decrease is usually achieved when the fuel switch is performed, i.e. in the failure year of the existing oil boiler.

Buildings with existing electrical heat pumps

Buildings with existing electric heat pumps replace their heat pumps by a condensing gas boiler combined with an electric peak heater at the end of the heat pump's lifetime. All buildings in this category have an existing PV system per assumption, which is maintained and replaced when it fails. Furthermore, all buildings use a thermal storage system to optimize coefficients of performance and align production and demand. SFH and smaller MFH add a battery system in 2045 to increase self-consumption. Larger MFH, i.e. those that have higher demands, already consume the self-generated electricity, so that a battery system is not needed. Due to the fuel switch from electricity to gas, these buildings substantially increase their carbon footprint at the time of their existing heat pump's failure.

Buildings with existing gas heat pumps

Buildings with existing gas heat pumps also replace their heat pumps by condensing gas boilers at the end of the existing heat pump's lifetime. Furthermore, all buildings use a thermal storage system to optimize coefficients of performance and align production and demand. If they have a PV option, buildings install and maintain a PV system for the full period 2025 to 2045 and install battery systems in 2030. Buildings with existing PV install simple power to heat peaker in 2025 to

utilize self-generated electricity. Buildings without PV install a simple power to heat peaker when their existing heat pump fails, together with the new gas boiler.
Here, too, the carbon footprint increases when the gas heat pumps are swapped for the less efficient gas boilers.

Buildings with existing night storage heaters

Buildings that have an existing night storage heater are bound to this technology by assumption. Thus, they replace their night storage heaters with new ones at the end of their lifetime. All buildings with night storage heaters and a PV option have PV installed for the full period from 2025 to 2045, because of the high electricity demand from the night storage heater. MFH with night storage heaters and PV invest into battery systems from 2030 on, to better align daytime PV generation and electricity demand from the night storage heater. SFH without a PV option install solar thermal systems in 2040 or 2045 making use of their rooftop area, as to decrease demand for (electrical) heating in light of electricity prices. All buildings with night storage heaters install electric flow heaters, immediately in 2025 if they have PV or when their existing night storage heater fails and has to be replaced if they do not have PV. Solar thermal systems or PV and electric flow heater systems are always accompanied by thermal storage to align supply and demand of hot water.

Buildings with existing other technologies

Buildings with other heating technologies, such as district heating or biomass, are assumed to continue using their initial heat source for the full period between 2025 and 2045. Nevertheless, these buildings invest into additional technologies to supply their hot water heating and electricity demand. High electricity demand in MFH and SFH with electrical flow heaters leads to immediate investment in PV. If SFH have central heating and thus a lower electricity demand, than those with electric flow heaters, they install PV in 2040 when investment costs have decreased. PV is usually paired with battery systems to increase self-consumption, battery systems are installed in 2030, when investment in a PV system happens early or there is an existing system, or in 2040, if the PV system is installed later. Regarding hot water, it is notable that in light of increasing electricity prices, flow heaters are not replaced after they reach the end of their lifetime. Also, none of the buildings without an existing flow heater invests into one. Instead, many buildings invest into solar thermal systems to cover their hot water heating demands.

New buildings

New buildings have lower energy demands and no pre-existing heating system with sunk costs or existing PV systems with persisting feed-in tariffs. Most new buildings opt to install gas boilers in combination with simple power to heat peak systems. Only small MFH install electric heat pumps as they can profit from economies of scale but have relatively low capacity demands compared to larger MFH, which do not install heat pumps. Conclusively, heat pumps can be optimal even without policy intervention, if no existing heating system with sunk costs is available. All new buildings are assumed to have the option to install PV and do so and combine them with battery systems from 2030 (MFH) or 2040 (SFH) on. More flexibility is gained by installing thermal storage systems as soon as possible. Furthermore, MFH opt to install solar thermal systems, while SFH do not. Again, MFH profit from economies of scale, especially with solar thermal system maintenance costs.

Appendix F.2. Policy scenario

Buildings with existing condensing gas boilers

Buildings with existing gas-fueled heating systems have an increased incentive to prematurely replace their gas boiler in 2025 by an electric heat pump due to high medium-term gas prices. All large MFH invest prematurely, as their high demands lead to scale effects on heat pump capacity costs. Additionally, having a PV option also triggers premature investment into an electric heat pump in smaller MFH. In fact, all buildings with the option to invest into PV do so, often together with the premature investment with the heat pump. Notably, SFH and small MFH with a small demand do not invest early into a heat pump if they have an existing PV system installed before 2025. Here the PV systems receive a high feed-in tariff and thus feeding electricity into the grid is more lucrative than potential self-consumption via an electrical heating system. Consequently, early investment in electric heating systems is less lucrative. Additionally, SFH with low flow temperatures and high hot water demands (i.e., many inhabitants) invest prematurely into a heat pump. These buildings can make use of higher efficiencies at lower flow temperatures and achieve higher utilization due to their constant load.

Similar to the investments in the *reference* scenario, all buildings invest into a simple power to heat peak unit simultaneously with the main heating technology, to reduce the capacity of the heat pump and thus its investment costs. Additionally, buildings with low energy demand install electric flow heaters to increase the self-consumption of PV systems if PV is available. Furthermore, electric flow heaters replace existing gas flow heaters once they failed.

Investments in battery systems are tied to having PV, but are less popular in the *policy* scenario than in the *reference* scenario. Battery systems are not needed to increase self-consumption, as increased electricity demand from heat pumps already uses up PV production. Furthermore, PV installed until 2030 receives feed-in tariffs and thus excess electricity is rather fed into the grid than into a battery.

Thermal storage investments are similar to the reference scenario. Only for large MFH, the existing storage systems are decommissioned early. Here, the early investment into an electric heat pumps and the combination of either very high or very low demand can lead to a situation in which additional flexibility of the limited resources of existing thermal storage does not suffice. Therefore, the system is decommissioned early and not replaced until it can be optimized jointly with the other additional systems. The battery storage systems cover storage needs for the interim period.

As mentioned above and similar to the *reference* scenario, buildings without the option to invest into PV, install solar thermal systems.[28] Investments into solar thermal systems happen earlier compared to the *reference* scenario and in conjunction with the premature investment into the heat pumps as to size capacity together.

Though under the modelled policies buildings decide to electrify their energy supply prematurely, large MFH keep their gas heating systems and use them as peak boilers. For those buildings, that require large capacities, capacity cost savings on the heat pump outweigh the significant fixed costs of the gas boiler. Buildings with an existing PV system benefit from a comparably high feed-in

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[28] An exception are SFH with low demands, for which maintenance costs outweigh the energy savings of solar thermal systems. They thus do not invest into these systems.

tariff and thus choose to feed electricity into the grid rather than using it on large scale in an electric peak heating system, thus making gas peak boilers even more attractive.

Despite the continued use of gas boilers as peak units, buildings with existing condensing gas boilers achieve substantial decarbonization already in 2025 due to early replacement of the boilers by electric heat pumps except in SFH without a PV option.

Buildings with existing combined gas boilers

Combined gas boilers are used as single-story heating systems in MFH and provide space heat and hot water. We do not consider centralization of heat supply for these buildings, and thus they have to rely on split single-story heat pumps for decarbonization. For single-story heating technologies, economies of scale are not expected, as multiple individual units have to be installed. All buildings invest into the split heat pumps after their existing systems reach the end of their lifetime. Additionally, all buildings invest into PV immediately in 2025, if they have the option to do so, just as in the *reference* scenario. Premature replacement only occurs in small MFH with a short remaining lifetime of the boiler and an existing PV system or the option to install one. These buildings have only small benefits from their existing boiler with its sunk costs and can cover large shares of their new electricity demand with PV.[29] Small MFH with newer existing boilers, large MFH and generally all MFH without the option to invest into PV do not invest early. Without self-generated electricity, the additional electricity demand of the heat pump would have to be covered by grid electricity and results in an unfavorable investment situation if heat demands are high.

When heat pumps are installed, they cover the majority of heat demand. Yet, the buildings use the existing combined gas boiler as a peak unit. As a result, buildings with combined gas boilers have remaining CO_2 emissions even in 2045, while all other buildings are fully decarbonized. Whenever the existing gas boiler fails, it is instantly replaced by a new combined gas boiler. It should be noted that by assumption, MFH with single-story heating have no option to invest into simple power to heat peak units.

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[29] Small MFH with a PV system from 2010 are an exception and choose not to invest early. These buildings benefit from high feed-in tariffs, rendering self-consumption uneconomical.

Investment in battery systems is identical to the *reference* scenario. PV is always accompanied by a battery from 2030 on. Small MFH install electric flow heaters to maximize self-consumption of electricity. Also, the investment into thermal storage systems is very similar to the *reference* scenario, though the installation of solar systems triggers additional investments. If small MFH invest into PV and an accompanying electric flow heater early, then thermal storage systems can be profitable to increase self-consumption.

In the *reference* scenario, buildings in this category do not install solar thermal systems. Under the pressure of decarbonization policies, large MFH with existing combined gas boilers invest in solar thermal systems [30] in 2025 if PV installation is not allowed. Solar thermal systems are always accompanied by thermal storage systems for hot water buffering. These buildings do not invest early in electrical heating systems and thus go for other options to reduce gas consumption.

Buildings with existing condensing oil boilers

Like all other buildings in the policy scenario, buildings with existing condensing oil boilers replace their old systems by electric heat pumps. As it is the case for buildings with condensing gas boilers, all buildings combine their heat pumps with electric peak boilers to reduce investment costs. Compared to buildings with condensing gas boilers, there is less premature investment into electric heat pumps. Additionally, if it occurs, premature investment does not happen immediately in 2025 as for buildings with condensing gas boilers, but only from 2030 on. This is due to the fact that by assumption, gas prices increase in the medium term, while oil prices (including CO_2 prices) increase in the long term. Thus, buildings have no incentive to perform a fuel switch in the medium term. Similarly to the *reference* scenario, all buildings with a PV option invest directly in 2025 and benefit from the feed-in tariffs.

Premature investment into the electric heat pump is mostly determined by demand and the PV option. SFH and small MFH do not invest prematurely, their low energy demands are not as exposed to CO_2 prices, and they cannot benefit from economies of scale on heat pumps. Larger demands trigger premature investment. High-demand buildings, which are exposed to higher energy costs, can benefit from economies of scale in heat pump investment costs. Small MFH with

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[30] for hot water generation only

central heating (and thus a larger oil demand) with a PV option invest in 2030. Without a PV option, premature investment happens by 2035. All large MFH invest in 2030 independent of other building attributes in order to avoid increased CO_2 prices in the long term.

As it is the case for buildings with existing gas boilers, there is less investment into battery systems under policy intervention compared to the *reference* scenario. Feed in tariffs for PV generated electricity and increased simultaneity of demand and supply due to higher electricity demand, result in less need for flexibility. However, PV is often combined with electric flow heaters to maximize self-consumption in buildings with low demand.

Thermal storage systems accompany new investments in the buildings, similar to the *reference* scenario. However, just like for buildings with existing gas condensing boilers, the early investment into heat pumps of large MFH can lead to early decommissioning of the existing thermal storage system. This is due to the fact that the existing storage capacity does no longer suffice. Therefore, it is quickly replaced by a battery system and later on, when the other additional systems are replaced, a new thermal storage system is installed.

Solar thermal systems can help to decrease energy demand and, like in the *reference* scenario, it is often installed by buildings without a PV option and demand high enough to justify high maintenance costs of solar thermal systems. Compared to the *reference* scenario, investments happen earlier due to CO_2 prices.

Buildings with existing electrical heat pumps

Under the modelled policies, buildings that have existing electric heat pumps maintain them and replace them with new ones when the existing technologies fail. When this is the case, the buildings install simple power to heat peak units to decrease capacity costs. By assumption, the buildings in this category have existing PV systems, which they maintain and replace when they cease to exist, just as in the *reference* scenario. As self-consumption is already high and stays high due to the reinvestment into heat pumps, unlike in the *reference* scenario, buildings do not invest into battery systems. Nevertheless, buildings always invest into a thermal storage system.

Buildings with existing gas heat pumps

Buildings with existing gas heat pumps perform an immediate fuel switch and install electrical heat pumps if they have a PV option (with or without an existing system). If they do not have a PV option, they invest in an electric heat pump in 2040 and 2045 when their gas heat pumps reach the end of their lifetime. The fuel switch does not influence the investment strategy for additional technologies, which is similar to the *reference* scenario.

Buildings with existing night storage heaters

Buildings with existing night storage heaters stick with this technology by assumption in both scenarios. Just as in the *reference* scenario, the buildings build and maintain PV to supply their electricity demand from the night storage heater if they have a PV option. Again, just as in the *reference* scenario, all MFH build battery systems in 2030. Similarly, all buildings with night storage heaters install electric flow heaters, immediately in 2025 if they have PV or when their existing night storage heater fails and has to be replaced if they do not have PV. Additionally, SFH without PV invest into solar thermal systems, however they do so earlier than in the *reference* scenario. Buildings install thermal storage systems to increase self-consumption of PV and solar thermal systems. SFH invest into a thermal storage system when they reinvest into their other technologies, while MFH invest into a thermal storage systems jointly with PV.

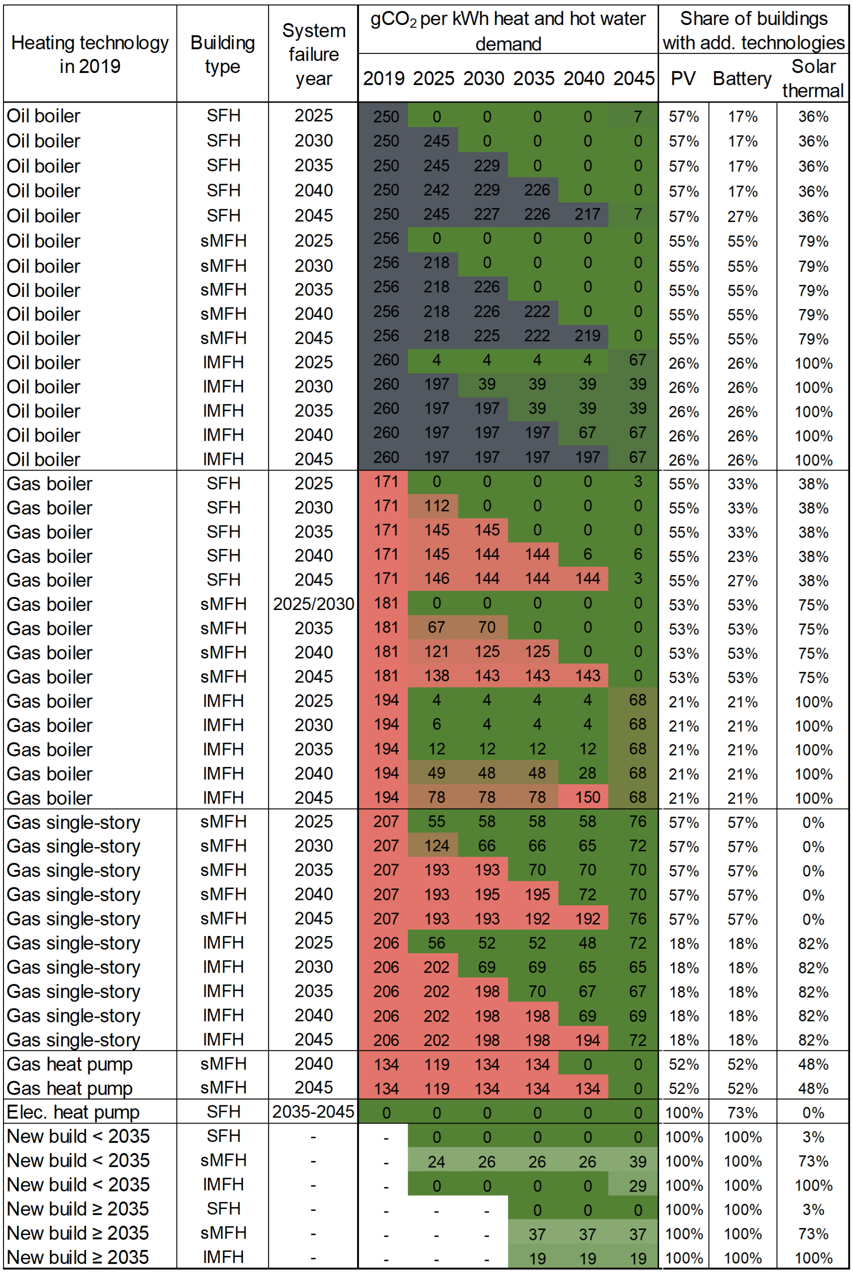
Buildings with existing other technologies

Buildings with other main heating technologies such as district heating or biomass continue to use those technologies by assumption. However, they may install additional technologies to self-generate electricity or hot water. Unlike in the *reference* scenario, all buildings with the option to do so install PV immediately in 2025 and maintain a PV system until 2045. Doing so, they profit from feed-in tariffs. Yet, PV is often combined with battery systems and electric flow heaters. However, investments differ slightly compared to the reference scenario. For example, SFH with electric flow heaters install battery systems in 2030 to better align electricity generation and consumption.

New buildings

Unlike in the *reference* scenario, new buildings invest in electric heat pumps directly when entering the building stock. The investment into additional technologies is similar to the *reference* scenario. The main heating system is often combined with a simple power to heat peak unit to decrease capacity costs. By assumption, all new buildings have a PV option, which they use without any exception throughout the full time period. Most buildings, except for the smallest SFH, invest into battery systems to increase self-consumption of electricity. The bigger the demand, the earlier battery investment occurs. Investments into thermal storage systems are identical to the *reference* scenario.

Appendix G. Results of the Sensitivity analysis



Heating technology in 2019	Building type	System failure year	gCO_2 per kWh heat and hot water demand						Share of buildings with add. technologies		
			2019	2025	2030	2035	2040	2045	PV	Battery	Solar thermal
Oil boiler	SFH	2025	250	0	0	0	0	7	57%	17%	36%
Oil boiler	SFH	2030	250	245	0	0	0	0	57%	17%	36%
Oil boiler	SFH	2035	250	245	229	0	0	0	57%	17%	36%
Oil boiler	SFH	2040	250	242	229	226	0	0	57%	17%	36%
Oil boiler	SFH	2045	250	245	227	226	217	7	57%	27%	36%
Oil boiler	sMFH	2025	256	0	0	0	0	0	55%	55%	79%
Oil boiler	sMFH	2030	256	218	0	0	0	0	55%	55%	79%
Oil boiler	sMFH	2035	256	218	226	0	0	0	55%	55%	79%
Oil boiler	sMFH	2040	256	218	226	222	0	0	55%	55%	79%
Oil boiler	sMFH	2045	256	218	225	222	219	0	55%	55%	79%
Oil boiler	lMFH	2025	260	4	4	4	4	67	26%	26%	100%
Oil boiler	lMFH	2030	260	197	39	39	39	39	26%	26%	100%
Oil boiler	lMFH	2035	260	197	197	39	39	39	26%	26%	100%
Oil boiler	lMFH	2040	260	197	197	197	67	67	26%	26%	100%
Oil boiler	lMFH	2045	260	197	197	197	197	67	26%	26%	100%
Gas boiler	SFH	2025	171	0	0	0	0	3	55%	33%	38%
Gas boiler	SFH	2030	171	112	0	0	0	0	55%	33%	38%
Gas boiler	SFH	2035	171	145	145	0	0	0	55%	33%	38%
Gas boiler	SFH	2040	171	145	144	144	6	6	55%	23%	38%
Gas boiler	SFH	2045	171	146	144	144	144	3	55%	27%	38%
Gas boiler	sMFH	2025/2030	181	0	0	0	0	0	53%	53%	75%
Gas boiler	sMFH	2035	181	67	70	0	0	0	53%	53%	75%
Gas boiler	sMFH	2040	181	121	125	125	0	0	53%	53%	75%
Gas boiler	sMFH	2045	181	138	143	143	143	0	53%	53%	75%
Gas boiler	lMFH	2025	194	4	4	4	4	68	21%	21%	100%
Gas boiler	lMFH	2030	194	6	4	4	4	68	21%	21%	100%
Gas boiler	lMFH	2035	194	12	12	12	12	68	21%	21%	100%
Gas boiler	lMFH	2040	194	49	48	48	28	68	21%	21%	100%
Gas boiler	lMFH	2045	194	78	78	78	150	68	21%	21%	100%
Gas single-story	sMFH	2025	207	55	58	58	58	76	57%	57%	0%
Gas single-story	sMFH	2030	207	124	66	66	65	72	57%	57%	0%
Gas single-story	sMFH	2035	207	193	193	70	70	70	57%	57%	0%
Gas single-story	sMFH	2040	207	193	195	195	72	70	57%	57%	0%
Gas single-story	sMFH	2045	207	193	193	192	192	76	57%	57%	0%
Gas single-story	lMFH	2025	206	56	52	52	48	72	18%	18%	82%
Gas single-story	lMFH	2030	206	202	69	69	65	65	18%	18%	82%
Gas single-story	lMFH	2035	206	202	198	70	67	67	18%	18%	82%
Gas single-story	lMFH	2040	206	202	198	198	69	69	18%	18%	82%
Gas single-story	lMFH	2045	206	202	198	198	194	72	18%	18%	82%
Gas heat pump	sMFH	2040	134	119	134	134	0	0	52%	52%	48%
Gas heat pump	sMFH	2045	134	119	134	134	134	0	52%	52%	48%
Elec. heat pump	SFH	2035-2045	0	0	0	0	0	0	100%	73%	0%
New build < 2035	SFH	-	-	0	0	0	0	0	100%	100%	3%
New build < 2035	sMFH	-	-	24	26	26	26	39	100%	100%	73%
New build < 2035	lMFH	-	-	0	0	0	0	29	100%	100%	100%
New build ≥ 2035	SFH	-	-	-	-	0	0	0	100%	100%	3%
New build ≥ 2035	sMFH	-	-	-	-	37	37	37	100%	100%	73%
New build ≥ 2035	lMFH	-	-	-	-	19	19	19	100%	100%	100%

Figure G.8: Investment, CO_2 footprint and timing in the *policy* with increased electricity prices

Note: Colors indicate whether gas systems (red), oil systems (gray) or electric heat pumps (green) are installed by buildings in a category and in a year. Colors are mixed according to the weighted number of buildings using the corresponding technology, if choices within a building category and year are not uniform. Numbers indicate the average CO_2 intensity in g/kWh of heating within each building category and year. Right columns list the percentage of buildings having PV, batteries, and solar thermal installed in 2045 within each building category.

References

AGEB (2021). Anwendungsbilanzen zur Energiebilanz Deutschland - Endenergieverbrauch nach Energieträgern und Anwendungszwecken.

Bauermann, K. (2016). German Energiewende and the heating market – Impact and limits of policy. *Energy Policy* 94: 235–246.

BDEW (2020). Studie: Wie heizt Deutschland 2023? Tech. rep.

Bertsch, J., Growitsch, C., Lorenczik, S. and Nagl, S. (2016). Flexibility in Europe's power sector — An additional requirement or an automatic complement? *Energy Economics* 53: 118–131, doi:10.1016/j.eneco.2014.10.022.

Brown, T., Schlachtberger, D., Kies, A., Schramm, S. and Greiner, M. (2018). Synergies of sector coupling and transmission reinforcement in a cost-optimised, highly renewable European energy system. *Energy* 160: 720–739, doi:10.1016/j.energy.2018.06.222.

Bucksteeg, M., Wiedmann, M., Pöstges, A., Haller, M., Böttger, D., Ruhnau, O. and Schmitz, R. (2022). The transformation of integrated electricity and heat systems—Assessing mid-term policies using a model comparison approach. *Renewable and Sustainable Energy Reviews* 160: 112270, doi:10.1016/j.rser.2022.112270.

Bundesamt für Wirtschaft und Ausfuhrkontrolle (2019). Erneuerbare Energien - Wärmepumpen mit Prüf- / Effizienznachweis.

Bundesnetzagentur (2023). *Marktstammdatenregister*.

Bundesverband der deutschen Heizungsindustrie (BDH) (2024). Pressemitteilung -Heizungen: Absatz bricht im ersten Quartal.

Bürger, V., Hesse, T., Köhler, B., Palzer, A. and Engelmann, P. (2019). German Energiewende—different visions for a (nearly) climate neutral building sector in 2050. *Energy Efficiency* 12: 73–87, doi:10.1007/s12053-018-9660-6.

Bürger, V., Hesse, T., Palzer, A., Köhler, B., Herkel, S., Engelmann, P. and Quack, D. (2017). *Klimaneutraler Gebäudebestand 2050*. Climate Change | 26/2017. Umweltbundesamt.

Bürger, V., Hesse, T., Quack, D., Palzer, A., Köhler, B., Herkel, S. and Engelmann, P. (2016). Klimaneutraler Gebäudebestand 2050. Tech. Rep. Forschungskennzahl 3713 49 101 UBA-FB 002280, Umweltbundesamt, Dessau-Roßlau.

Conrad, J. (2020). Modellierung und Bewertung von Maßnahmen zur kosteneffizienten CO2-Verminderung im Sektor private Haushalte. Dissertation, Technische Universität München, München.

Corgnati, S. P., Fabrizio, E., Filippi, M. and Monetti, V. (2013). Reference buildings for cost optimal analysis: Method of definition and application. *Applied Energy* 102: 983–993, doi:10.1016/j.apenergy.2012.06.001.

Corradini, R. (2013). Regional differenzierte Solarthermie-Potenziale für Gebäude mit einer Wohneinheit.

Diefenbach, N., Loga, T. and Stein, B. (2016). Reaching the climate protection targets for the heat supply of the German residential building stock: How and how fast? *Energy and Buildings* 132: 53–73, doi:10.1016/j.enbuild.2016.06.095.

Döring, P., Glasenapp, S. and Mantau, U. (2020). *Energieholzverwendung in privaten Haushalten 2018. Marktvolumen und verwendete Holzsortimente*. Hamburg.

Eicker, U. (2012). *Solare Technologien für Gebäude: Grundlagen und Praxisbeispiele ; mit 47 Tabellen*. Studium. Wiesbaden: Vieweg + Teubner, 2nd ed., oCLC: 760203309.

Energinet.dk and Energi Styrelsen (2012). Technology Data for Energy Plants.

European Central Bank (2021). Composite cost-of-borrowing indicator for long-term loans to both households and non-financial corporations. Tech. rep.

European Solar Thermal Industry Federation (2007). Objective methodology for simple calculation of the energy delivery of (small) Solar Thermal systems.

EWI (2021). dena-Leitstudie Aufbruch Klimaneutralität. Klimaneutralität 2045 - Transformation der Verbrauchssektoren und des Energiesystems. Tech. rep., Deutschen Energie-Agentur GmbH (dena), Berlin.

FNR (2019). *Basisdaten Wald und Holz 2019*. Fachagentur Nachwachsende Rohstoffe e.V.

Frings, C. and Helgeson, B. (2022). Developing a Model for Consumer Management of Decentralized Options.

Frondel, M. and Schubert, S. A. (2021). Carbon pricing in Germany's road transport and housing sector: Options for reimbursing carbon revenues. *Energy Policy* 157: 112471, doi:10.1016/j.enpol.2021.112471.

Galvin, R. (2023). Policy pressure to retrofit Germany's residential buildings to higher energy efficiency standards: A cost-effective way to reduce CO2 emissions? *Building and Environment* 237: 110316, doi:10.1016/j.buildenv.2023.110316.

Garrabrant, M., Stout, R., Blaylock, M. and Keinath, C. (2017). Residential and Commercial Capacity Absorption Heat Pumps for Space and Domestic Water Heating Applications.

Gerbert, P., Herhold, P., Burchardt, J., Schönberger, S., Rechenmacher, F., Kirchner, A., Kemmler, A. and Wünsch, M. (2018). Klimapfade für Deutschland.

Gerhardt, N., Sandau, F., Scholz, A., Hahn, H., Schumacher, P., Sager, C., Bergk, F., Kämper, C., Knörr, W., Kräck, J., Lambrecht, U., Antoni, O., Hilpert, J., Merkel, K. and Müller, T. (2015). Interaktion EE-Strom, Wärme und Verkehr - Analyse der Interaktion zwischen den

Sektoren Strom, Wärme/Kälte und Verkehr in Deutschland in Hinblick auf steigende Anteile fluktuierender Erneuerbarer Energien im Strombereich unter Berücksichtigung der europäischen Entwicklung - Endbericht. Enbericht, Fraunhofer-Institut für Bauphysik, Institut für Energie- und Umweltforschung, Stiftung Umweltenergierecht, Kassel, Heidelberg, Würzburg.

HEAT4U Project (2013). Gas Absorption Heat Pump solution for existing residential buildings. HEAT4U Collaborative project Grant Agreement no.285158 D1.1 & D1.2, Bosch Thermotechnik.

Hecking, H. and Löffler/Dieckhöner, C. (2017). Greenhouse Gas Abatement Cost Curves of the Residential Heating Market: A Microeconomic Approach. *Environmental and Resource Economics* 68: 915–947, doi:10.1007/s10640-016-0052-0.

Heitkoetter, W., Medjroubi, W., Vogt, T. and Agert, C. (2020). Regionalised heat demand and power-to-heat capacities in Germany – An open dataset for assessing renewable energy integration. *Applied Energy* 259: 114161, doi:10.1016/j.apenergy.2019.114161.

Helgeson, B. and Peter, J. (2020). The role of electricity in decarbonizing European road transport – Development and assessment of an integrated multi-sectoral model. *Applied Energy* 262: 114365, doi:10.1016/j.apenergy.2019.114365.

Henkel, J. (2012). Modelling the Diffusion of Innovative Heating Systems in Germany – Decision Criteria, Influence of Policy Instruments and Vintage Path Dependencies doi:10.14279/depositonce-3189.

Hennenberg, K. and Böttcher, H. (2023). Biomasse und Klimaschutz. Tech. rep., Öko-Institut e.V., Berlin/Darmstadt.

Henning, H.-M. and Palzer, A. (2012). 100% Erneuerbare Energien für Strom und Wärme in Deutschland. Tech. rep., Fraunhofer-Institut für Solare Energiesysteme ISE, Freiburg.

Henning, H.-M. and Palzer, A. (2015). Was kostet die Energiewende? - Wege zur Transformation des deutschen Energiesystems bis 2050. Tech. rep., Fraunhofer-Institut für Solare Energiesysteme ISE, Freiburg.

Hirth, L. (2013). The market value of variable renewables: The effect of solar wind power variability on their relative price. *Energy Economics* 38: 218–236, doi:10.1016/j.eneco.2013.02.004.

Jochen Conrad (2020). Modellierung und Bewertung von Maßnahmen zur kosteneffizienten CO2-Verminderung im Sektor private Haushalte. Dissertation, Technischen Universität München, München.

Kemmler, A., Kirchner, A., Maur, A. Auf der, Ess, F., Kreidelmeyer, S., Piégsa, A., Spillmann, T., Wünsch, M. and Ziegenhagen, I. (2020). Energiewirtschaftliche Projektionen und Folgeabschätzungen 2030/2050.

Kirchner, M., Sommer, M., Kratena, K., Kletzan-Slamanig, D. and Kettner-Marx, C. (2019). CO2 taxes, equity and the double dividend – Macroeconomic model simulations for Austria. *Energy Policy* 126: 295–314, doi:10.1016/j.enpol.2018.11.030.

Kotzur, L., Markewitz, P., Robinius, M., Cardoso, G., Stenzel, P., Heleno, M. and Stolten, D. (2020). Bottom-up energy supply optimization of a national building stock. *Energy and Buildings* 209: 109667, doi:10.1016/j.enbuild.2019.109667.

Kühn, L., Fuchs, N., Braun, L., Maier, L. and Müller, D. (2024). Landlord–Tenant Dilemma: How Does the Conflict Affect the Design of Building Energy Systems? *Energies* 17: 686, doi: 10.3390/en17030686.

Löffler/Dieckhöner, C. and Hecking, H. (2014). Developments of the German Heat Market of Private Households Until 2030: A Simulation Based Analysis. *Zeitschrift für Energiewirtschaft* 38: 117–130, doi:10.1007/s12398-014-0131-2.

Manz, P., Billerbeck, A., Kök, A., Fallahnejad, M., Fleiter, T., Kranzl, L., Braungardt, S. and

Eichhammer, W. (2024). Spatial analysis of renewable and excess heat potentials for climate-neutral district heating in Europe. *Renewable Energy* 224: 120111, doi:10.1016/j.renene.2024.120111.

Markewitz, P., Hansen, P., Kuckshinrichs, W. and Hake, J. (2016). Germany's path towards a nearly climate-neutral residential building stock: A techno-economic comparison of greenhouse gas mitigation strategies. *Euro-Asian Journal of sustainable energy development policy* 1.

McKenna, R., Merkel, E. and Fichtner, W. (2017). Energy autonomy in residential buildings: A techno-economic model-based analysis of the scale effects. *Applied Energy* 189: 800–815, doi:10.1016/j.apenergy.2016.03.062.

Mendelevitch, R., Repenning, J. and Matthes, F. C. (2022). *Rahmendaten für den Projektionsbericht 2023*. Weiterentwicklung der Methoden und Umsetzung der Europäischen Governance-Verordnung und des Bundes-Klimaschutzgesetzes im Projektionsbericht 2023 ("Politikszenarien XI"). Umweltbundesamt.

Moritz, M., Czock, B. H. and Ruhnau, O. (2024). A heated debate - The long-term cost-efficiency of climate-neutral heating options under consideration of heterogeneity and uncertainty.

Olonscheck, M., Holsten, A. and Kropp, J. P. (2011). Heating and cooling energy demand and related emissions of the German residential building stock under climate change. *Energy Policy* 39: 4795–4806, doi:10.1016/j.enpol.2011.06.041.

Palzer, A. (2016). Sektorübergreifende Modellierung und Optimierung eines zukünftigen deutschen Energiesystems unter Berücksichtigung von Energieeffizienzmaßnahmen im Gebäudesektor. Ph.D. thesis, Karlsruher Institut für Technologie, Karlsruhe.

Peter, J. (2019). How does climate change affect electricity system planning and optimal allocation of variable renewable energy? *Applied Energy* 252: 113397, doi:10.1016/j.apenergy.2019.113397.

Petrović, S. N. and Karlsson, K. B. (2016). Residential heat pumps in the future Danish energy system. *Energy* 114: 787–797, doi:10.1016/j.energy.2016.08.007.

Pitel, L. (2023). Germany passes watered-down ‘boiler ban’ law after months of infighting. *Financial Times* .

Rausch, S., Metcalf, G. E. and Reilly, J. M. (2011). Distributional impacts of carbon pricing: A general equilibrium approach with micro-data for households. *Energy Economics* 33: S20–S33, doi:10.1016/j.eneco.2011.07.023.

Richter, J. (2011). DIMENSION - A Dispatch and Investment Model for European Electricity Markets. *EWI Working Papers* .

Rosenow, J. (2022). Is heating homes with hydrogen all but a pipe dream? An evidence review. *Joule* 6: 2225–2228, doi:10.1016/j.joule.2022.08.015.

Schaffrin, A. (2013). Who pays for climate mitigation? An empirical investigation on the distributional effects of climate policy in the housing sector. *Energy and Buildings* 59: 265–272, doi:10.1016/j.enbuild.2012.12.033.

Scharf, H., Anke, C.-P., Möst, D., Rändler, L., Arnold, F., Çam, E., Lencz, D., Schulte, S. and Stopnevich, A. (2021). Data Documentation Erdgas-BRidGE – Input data for modeling the power, building, and gas sector (Version 1.1.0) [Data set]. doi:10.5281/ZENODO.4420042.

SPD, Bündnis 90/Die Grünen and FDP (2021). Mehr Fortschritt wagen: Bündnis für Freiheit, Gerechtigkeit und nachhaltigkeit. Koalitionsvertrag 2021–2025.

Statistisches Bundesamt (2024). Wohnen in Deutschland - Zusatzprogramm des Mikrozensus 2022.

Sterchele, P., Brandes, J., Heilig, J., Wrede, D., Kost, C., Schlegl, T., Bett, A. and Henning, H.-M. (2020). Wege zu einem klimaneutralen Energiesystem -Die deutsche Energiewende im Kontext gesellschaftlicher Verhaltensweisen. Tech. rep., Fraunhofer-Institut für Solare Energiesysteme ISE, Freiburg.

Stiftung Warentest (2014). Systemvergleich: Kostenfalle Durchlauferhitzer. URL: https://www.test.de/Durchlauferhitzer-im-Test-Preis-Schock-fuer-Warmduscher-4796802-4798406/. Accessed on: 08/01/2022.

SWM Infrastruktur GmbH & Co. KG (2022). Lastprofil Speicherheizung. URL: https://www.swm-infrastruktur.de/strom/netzzugang/bedingungen/speicherheizung. Accessed on 08/01/2022.

Verein Deutscher Ingenieure (2019). VDI-RICHTLINIE 4655 Blatt 1 - Referenzlastprofile von Wohngebäuden für Strom, Heizung und Trinkwarmwasser sowie Referenzerzeugungsprofile für Fotovoltaikanlagen.

Weitzman, M. L. (1974). Prices vs. Quantities. *The Review of Economic Studies* 41: 477–491, doi:10.2307/2296698.