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Flexible electricity use for heating in markets with renewable energy

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HIGHLIGHTS

- Electric heating can contribute to decarbonization and provide flexibility for renewable integration.
- Analysis of electric storage heaters for German 2030 scenarios with open-source electricity sector model.
- Temporally flexible charging of storage heaters provides only small benefits.
- Electric storage heaters not suited to align seasonal mismatch between renewables and heat demand.
- Flexible power-to-heat generally fosters use of generation technologies with low variable costs.

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ABSTRACT

Using electricity for heating can contribute to decarbonization and provide flexibility to integrate variable renewable energy. We analyze the case of electric storage heaters in German 2030 scenarios with an open-source electricity sector model. We find that flexible electric heaters generally increase the use of generation technologies with low variable costs, which are not necessarily renewables. Yet making customary night-time storage heaters temporally more flexible offers only moderate benefits because renewable availability during daytime is limited in the heating season. Respective investment costs accordingly have to be very low in order to realize total system cost benefits. As storage heaters feature only short-term heat storage, they also cannot reconcile the seasonal mismatch of heat demand in winter and high renewable availability in summer. Future research should evaluate the benefits of longer-term heat storage.

1. Introduction

Mitigating climate change demands decarbonizing energy supply, and renewable electricity sources play an essential role [1]. In Germany, often considered a frontrunner in the transition to renewables, they supplied nearly 38% of gross electricity demand in 2018, up from around 6% in 2000 [2]. For 2030, current legislation foresees a growth to at least 50%, and the German government's 2019 climate package targets an even faster growth to 65% by 2030.[1] At the same time, decarbonization must go beyond current electricity use. By 2017, more than a quarter of gross energy consumption and 14% of greenhouse gas emissions stemmed from space heating [3]. In Germany and many other countries, substantial efforts are required to reach medium- and long-term climate policy goals. One option is the use of renewable electricity in the heating and transportation sectors, often referred to as sector coupling or electrification. In its latest report on limiting global warming to 1.5 degrees Celsius, the IPCC also puts an emphasis on such electrification of end energy use [1].

While electricity generation from wind and solar PV is largely carbon neutral, it comes with two peculiarities: its supply has virtually zero variable costs, and it cannot be dispatched at full discretion. Renewables' natural variability calls for flexibility within the electricity sector to efficiently use available low-cost renewables. One option is on the demand side of the electricity market: electricity demand, which has been largely inelastic in the past, could be shifted to hours with high renewable supply and avoid hours with scarce supply.

Against this background, this paper is motivated by the twin challenges of decarbonizing space heating supply and providing flexibility for the integration of renewable electricity. Specifically, we apply an open-source electricity sector model to a German 2030 setting to analyze the system effects of flexibilizing electric heating in Germany. Current electric night-time storage heaters demand electricity at night –

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[1] See https://www.bundesregierung.de/resource/blob/975226/1679914/e01d6bd855f09bf05cf7498e06d0a3ff/2019–10-09-klima-massnahmen-data.pdf (accessed December 22, 2019).

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when other demand and wholesale prices were, historically, low – and convert it to heat. This heat is stored and released again during the day to meet the households' space heat demand. An upgrade can render electric storage heaters more flexible such that they can demand electricity not only at night-time, but at each point in time and thus respond more flexibly to variable renewable energy supply. Across a range of scenarios, we analyze the effects on system costs, renewable energy integration, and emissions. In doing so, we also disentangle the drivers of cost savings.

Previous research has addressed various aspects of flexible electric heating in renewables-dominated electricity systems [4]. We contribute to the literature in several ways: first, we provide evidence on system effects of electric thermal storage heaters; past contributions on this technology are scarce and findings are mixed. Second, previous papers largely refrain from explicitly disentangling drivers of cost savings; a point that we analyze in depth. Specifically, we explicitly compare model outcomes for different assumptions on the flexibility of electric heating technologies, while most analyses in the literature generally assume flexible operations. Third, we offer a comprehensive formulation for modeling a range of power-to-heat technologies in an open-source framework. Finally, we provide evidence on the role of flexible electric heating in future decarbonization scenarios in Germany.

Our analysis illustrates that additional power system flexibility related to electric heating generally increases the use of generation technologies with low variable costs, but not necessarily renewables. Results further show that overall cost savings of making customary night-time storage heaters more flexible are rather moderate. Accordingly, upgrades must come at very low costs to be economical. This is driven by mismatching patterns of heat demand and renewable supply in Germany, which serves as an example for temperate countries, and a lack of seasonal storage capabilities of electric heaters. During summer and spring, the value of additional flexibility is modest because absolute heat demand is low, and electric heaters cannot benefit from high renewable electricity supply during daytime. During the heating season in winter and fall, the absolute value of additional flexibility is also modest because there is relatively low supply of low-cost renewable electricity during daytime. Even in case of substantially higher shares of renewable energy sources than today, flexible electric heaters would still mainly charge at night-time. Yet additional demand-side flexibility proves more valuable when the merit order is steeper, for instance in case of a coal phase-out or higher CO_2 prices.

The remainder of this paper is structured as follows: Section 2 gives an overview of the related literature. Section 3 presents the model. Section 4 exhibits data and scenarios. We describe and interpret results in Section 5. Section 6 sets our findings into perspective and outlines avenues for future research. The final Section 7 concludes.

2. Related literature

The literature highlights a vital role for power-to-heat technologies to decarbonize energy systems beyond current electricity use. Based on a comprehensive model of a future German electricity and heating system which was first introduced by Henning and Palzer [5], Palzer and Henning [6] put forward that a complete renewable supply is not more costly than the existing energy system. Comparing cost-effectiveness across sectors, Merkel et al. [7] highlight that the heat sector plays a prominent role in efficient and ambitious German decarbonization pathways to 2050. Kiviluoma and Meibom [8] provide a similar result for Finland, and Connolly et al. [9] draw an analogous conclusion in their analysis of a complete decarbonization of the European energy system, comprising electricity, heat, and mobility. They identify a central role for heating electrification as low-cost option with a high impact for reducing emissions.

Yet such decarbonization requires that electricity for space heating is increasingly generated by renewable energy sources. In many countries, these are predominantly variable wind power and solar photovoltaics (PV) because potentials for hydro power or bioenergy are limited. Thus, the temporally flexible use of variable renewable energy gains relevance. Systematically reviewing model-based studies, Bloess et al. [4] provide a focused overview on flexibility potentials of power-to-heat technologies in energy systems.

Specifically for heat pumps, previous research yields rich evidence on the benefits of their flexible operation in power systems with high shares of renewable energy. In a stream of papers for a Belgian application, Patteeuw and co-authors identify reduced total system costs [10], CO_2 abatement costs, necessary peak load capacities [11], and curtailment [12] compared to an inflexible heat pump operation, and reduced emissions compared to a baseline with natural gas-based heating [13]. For Denmark, Hedegaard and Balyk [14] conclude that flexible operation of residential heat pumps saves on system costs through both arbitrage gains from shifting power-to-heat electricity demand to low-price hours with high renewable supply and a reduced need for investments into peak generation capacity. In their analysis, heat storage plays a vital role. Kiviluoma and Meibom [8] derive a comparable result for Finland. In contrast, Hedegaard and Münster [15] highlight the potential of flexible heat pumps to integrate wind energy and thus reduce CO_2 emissions and total system costs even without making use of flexibility from heat storage. For Germany, Bloess [16] similarly finds that heat pumps play a large role in future scenarios with large shares of renewables, while heat storage is of minor importance. The literature provides comparable evidence on the benefits of flexible heat pumps also for other countries such as China [17], Germany [18], the UK [19], and the US [20].

Yet the role of other power-to-heat technologies, specifically electric storage heaters, is less well understood. While Dodds [19] highlights, for the UK, that electric night-time storage heaters continue to play a role, evidence on power system effects is scarce and mixed. Barton et al. [21] emphasize that their flexible operation can reduce electricity peak load and smooth the electricity demand profile. For China, Chen et al. [17] conclude that they do not help to mitigate emissions to a great extent due to the relatively low efficiency compared to heat pumps; considerably, this result is based on the assumption of a high share of coal power in the electricity mix. For the PJM system in the US, Pensini et al. [22] stress that flexible decentral electric storage heaters can greatly reduce curtailment, but centralized heat pumps with heat storage would be more cost effective. For the Finnish housing stock, Rasku and Kiviluoma [23] find that electric storage heaters can become more beneficial than energy efficiency improvements from a system cost perspective when assuming very high shares of variable renewables; yet from a house owner's perspective, the opposite may be true.

3. Model

To analyze the electricity sector effects of electric storage heaters, we augment the open-source electricity sector model DIETER by a power-to-heat module. DIETER is a dispatch and investment model with a long-run equilibrium perspective that minimizes the total cost of electricity generation for one year in hourly resolution. See Zerrahn and Schill [24] for an introduction to the basic model version.

3.1. DIETER

The model's objective function covers operational costs, which comprise, among others, fuel and CO_2 emission costs, and annualized investment costs of electricity generation and storage technologies. A market clearing condition, also referred to as energy balance, ensures that electricity supply satisfies inelastic electricity demand in each hour. Generation technologies comprise thermal generators, such as coal- and natural gas-fired plants, and the renewable technologies bioenergy, run-of-river hydro, onshore and offshore wind, and solar PV. Flexibility options to temporally align supply and demand include different types of energy storage, several demand-side management (DSM) options, differentiated by load shedding and load shifting, as well as the curtailment of renewables. Further constraints ensure that hourly generation by a technology does not exceed installed capacities and that installed capacities do not exceed the potential of a technology. Moreover, the model features intertemporal restrictions for storage and DSM operations as well as constraints related to the provision and activation of balancing reserves.

Model inputs comprise costs and availabilities of technologies as well as hourly demand and renewables feed-in profiles. Endogenous variables are investments into generation and flexibility technologies and their hourly use, including the provision of balancing reserves. Model outputs cover the total cost of providing electricity, installed capacity, the hourly dispatch of all technologies, and various derived indicators on the utilization of different technologies.

The model version used here focuses on the German electricity sector and abstracts from an explicit spatial resolution as well as modeling interactions with neighboring countries. The model assumes perfect foresight and is solved once for an entire year. DIETER is implemented in the General Algebraic Modeling System (GAMS). Code, data, and a comprehensive model documentation are available open-source under a permissive license.[2]

3.2. Representation of the residential power-to-heat segment in DIETER

For this analysis, we augment the DIETER version presented in [24] by a representation of the residential power-to-heat segment, featuring direct resistive heaters, electric storage heaters, and water-based heating systems. In the latter case, ground-sourced or air-sourced heat pumps or fossil-fueled boilers with an auxiliary electric heating rod supply heat to a buffer storage. In this paper, our main focus in on electric storage heaters. For brevity, we denote them by NETS (night-time electric thermal storage heaters) for customary devices that charge electricity inflexibly during the night, and SETS (smart electric thermal storage heaters) for upgraded devices that can charge flexibly around the clock. The residential heat module also features the provision of domestic hot water (DHW), either from the buffer storage, from a separate module complementing SETS, or from direct resistive heaters. All electric space heating and DHW technologies, except direct resistive heating, can also provide secondary and tertiary balancing reserves, both positive and negative.

In Appendix A, we present the model equations relating to residential heat. They interact with the overarching electricity sector model at three instances: first, electricity demand by heating technologies enters the electricity balance of DIETER; second, reserve provision by heating technologies enters the reserves balance of DIETER; and third, costs of fossil fuel consumption for hybrid heating technologies enter the objective function. Investment costs of power-to-heat options do not enter the objective function of the model version used here, as we vary their capacities exogenously. Yet investments related to SETS are considered when evaluating overall results.

4. Data and scenarios

We carry out our analysis for the year 2030. This time horizon allows for a range of plausible scenarios with different assumptions on costs and availabilities of various technologies. At the same time, 2030 is still close enough to plausibly abstract from major uncertainties with respect to technology developments, breakthroughs of alternative sector coupling options or costs.

[2] We use DIETER version 1.3.0 for this paper. See http://www.diw.de/dieter for a complete documentation of the model, all input data, and the executable code files.

4.1. Input data

As for input data, we lean on the EU Reference Scenario 2016 developed by Capros et al. [25]; the respective dataset is provided by [26]. For the power plant portfolio, we take the figures as given in the Reference Scenario whenever possible. For some technologies, we adopt further assumptions, preferably from other established studies, to align them with the technology types in our model.[3]

4.1.1. Capacities of power plants and flexibility options

We adopt assumptions on lower capacity bounds for solar PV, wind power, and pumped hydro storage as well as assumptions on upper capacity bounds for fossil-fueled plants, bioenergy, and run-of-river hydro, guided by the Reference Scenario. Appendix B provides further details on the derivation of the input data. Fig. 1 shows the specific assumptions.

Concerning flexibility options, we assume 6.5 GW of pumped hydro storage power capacities, with an energy capacity of 45.5 GWh. This figure leans on the pumped hydro capacity installed in Germany in 2018. We assume no further flexibility options such as batteries or demand-side management. If a scenario allows for demand-side management, we base maximum capacities for three load shedding and five load shifting technologies to potentials derived by Frontier and Formaet [27], Gils [28], and Klobasa [29].

4.1.2. Electricity demand and renewable generation time series

Time series inputs follow German data from the default base year 2016 [30], taken from the Open Power System Data platform [31]. For renewable infeed, we take hourly capacity factors, defined as actual hourly generation of onshore wind, offshore wind, and solar PV, divided by the historical capacity of the respective technology. Hourly load time series include electricity demand by existing night-time electric thermal storage heaters. Total annual demand is around 490 Terawatt hours (TWh) of which about 2.5%, or 11.5 TWh, accrue from NETS.

For the SETS upgrade case, we construct a synthetic demand profile of NETS, subtract it from the demand time series, and allocate the 11.5 TWh of heating electricity demand to SETS. To this end, we transform the yearly space heating energy provided by existing night-time storage heaters to an electricity consumption pattern covering night-time hours between 10 p.m. and 6 a.m. Accordingly, the electricity consumed by NETS in any such night-time period equals the heating demand of the respective subsequent day. Within contiguous hours of each night, we assume a uniform distribution of heating energy.

Hourly demand for the provision of balancing reserves also follows German data from the base year, differentiated into primary, secondary, and tertiary reserves, each both positive and negative [32]. Likewise, hourly activation of secondary and tertiary reserves follows the actual German pattern from the base year [33]; for primary reserves, we assume a flat hourly activation of 5%.

4.1.3. Cost assumptions, fuel and CO_2 prices

Assumptions on fuel prices follow the Ten Year Network Development Plan (TYNDP) 2016 [34,35], scenario “Vision 3” (Table 1). The CO_2 price of 33.33 euros per ton follows the EU Reference Scenario. Additionally, we explore a scenario with a high CO_2 price of 71 euros per ton according to the TYNDP 2016. We draw on Schröder et al. [36] for figures on thermal efficiency, overnight investment costs, and the technical lifetime of plants, and Kunz et al. [37] for the carbon content of fossil fuels. For overnight investment costs, efficiency, and technical lifetime of storage technologies, we draw on

[3] We provide spreadsheets containing the input data for this paper under http://www.diw.de/dieter.

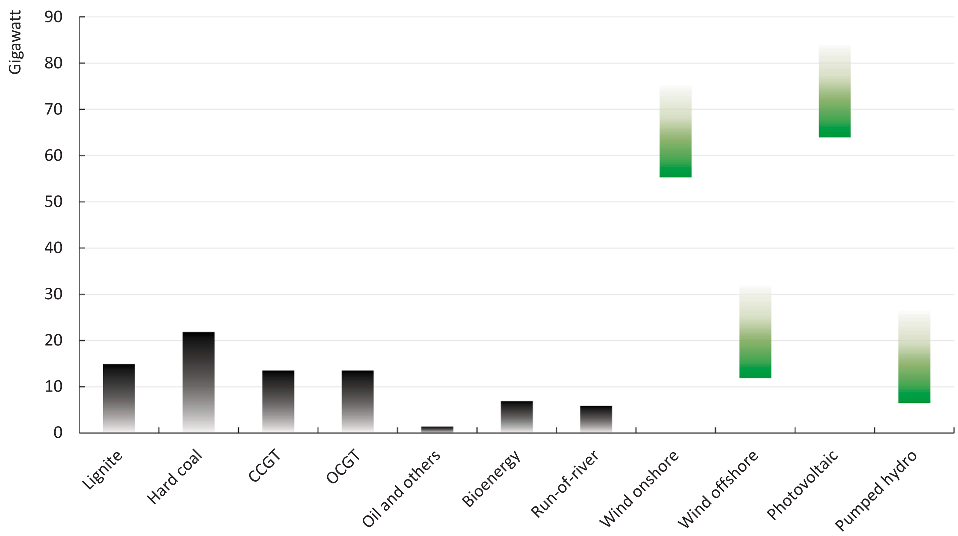

Fig. 1. Assumptions on upper and lower bounds for the generation portfolio. Dispatchable thermal and run-of-river generation capacity (black) can be installed up to the specified upper bound; in contrast, variable renewable and pumped hydro storage capacity (green) face a lower installation bound

Table 1
Fuel and CO_2 price assumptions for 2030.

	Unit	Price assumption
Lignite	Euros per MWh_{th}	3.96
Hard coal	Euros per MWh_{th}	10.08
Natural gas	Euros per MWh_{th}	26.03
Oil	Euros per MWh_{th}	41.65
CO_2 certificates	Euros per ton	33.33 (71.00 in alternative scenario)

Pape et al. [38] and Agora Energiewende [39], complemented by own assumptions on annual fixed costs. Marginal generation, fixed, and overnight investment costs for DSM technologies follow Frontier and Formaet [27].

4.1.4. Power-to-heat technologies

We assume that a large share of the presently existing fleet of customary night-time electric thermal storage heaters devices is still present in Germany by 2030.[4] Turning these NETS into more flexible SETS requires respective control and communication interfaces. According to figures provided by a leading manufacturer, we make the following default assumptions: 270 euros per SETS unit for a communication module plus 140 euros per flat for a gateway.[5] We further assume an average flat size of 150 square meters and 32 kWh storage capacity per SETS device. With a ten years depreciation period and an interest rate of 4%, the upgrade cost annuity amounts to about 1.13 euros per kWh.

With respect to SETS dimensioning, we assume their maximum hourly heat output per square meter to cover the hour with the highest heating load of the year, *i.e.*, we do not assume backup heating options. SETS' electric power rating per square meter is then set to be twice as high, and SETS' energy storage capacity in turn is eight times the maximum hourly electric power consumption. That is, SETS have a storage capacity of eight hours. These parameter choices are guided by technical data sheets of typical SETS devices sold in Germany by 2018.[6]

We further assume a static heat release of 2.5% of stored heating energy per hour. SETS domestic hot water devices (SETS-DHW) are also parameterized such that their maximum hot water output covers the hour with the highest demand of the year. Electric power rating of SETS-DHW devices is equal to maximum hourly DHW output, and energy storage capacity covers 2.2 hours of the maximum hourly electric power consumption.

Ground-sourced or air-sourced heat pumps supply heat to a buffer storage, covering three hours of maximum hourly heating load. We set the maximum hourly heat output capacity to cover the hour with the highest heating load of the year, including domestic hot water. We also take into account the coefficient of performance (COP) such that the respective electric power rating is accordingly lower.[7]

4.1.5. Heat demand

To adequately represent the German residential building stock, we assume twelve building archetypes: six for one-family homes and six for multi-family buildings, differentiated by building age and corresponding energy efficiency levels. The archetypes are defined by RWTH Aachen University, based on the findings of two research projects.[8] A thermal simulation model calculates the annual energy demand per square meter. Taking into account the German targets for energy efficiency improvements of the building stock, we next determine a projection of the total square meters, and thus total annual energy demand, for each building archetype in 2030. We assume that the share of electric storage heaters in total square meters of the respective building archetypes does not change by 2030. Beyond SETS, we assume a certain share of the residential floor area to be equipped with heat pumps, with

[4] Heitkoetter et al. [40] make a similar assumption.

[5] Information provided by the manufacturer GlenDimplex in the context of the EU Horizon 2020 project RealValue.

[6] Specifically, the parameter choices are guided by the device “Quantum heater” by the manufacturer GlenDimplex as well as additional information provided in the context of the EU Horizon 2020 project RealValue. Also compare the manufacturer's product website https://www.glendimplexireland.com/brands/dimplex/domestic-heating-systems/quantum-off-peak-heaters

(*footnote continued*)
(accessed November 08, 2019).

[7] For heat pump dimensioning, we assume a time-constant source temperature of 10 °C for ground-sourced heat pumps and minus 5 °C for air-sourced heat pumps. The actual COP entering the model varies with outside air temperatures. See Appendix A.3 for further information. The additional scenarios in Appendix A.4 feature fossil-fueled boilers with an auxiliary electric heating rod that supply heat to a buffer storage, which we also dimension to cover three hours of maximum heating load. We define their power rating for maximum hourly electricity demand such that they could supply the heat load in the hour of highest demand without making use of the buffer storage.

[8] EU projects EPISCOPE (Monitor Progress Towards Climate Targets in European Housing Stocks) and TABULA (Typology Approach for Building Stock Energy Assessment; see Loga et al. [58]). See Appendix A.3 for more information.

Table 2
Building archetypes and their heating energy demand satisfied by electric heating.

	Description		Annual heating energy demand [kWh/m^2]	Floorarea with NETS/SETS [million m^2]	Floor area with heat pumps [million m^2]
b1	One-family house	very high energy demand	276	7.15	2.47
b2	Multi-family house		223	3.58	2.22
b3	One-family house	high energy demand	203	12.50	4.31
b4	Multi-family house		164	6.75	4.18
b5	One-family house	medium energy demand	153	16.49	7.57
b6	Multi-family house		130	5.74	0
b7	One-family house	low energy demand	112	6.87	32.23
b8	Multi-family house		103	0.98	3.35
b9	One-family house	very low energy demand	66	0	103.88
b10	Multi-family house		51	0	28.96
b11	One-family house	passive house	15	0	127.67
b12	Multi-family house		11	0	37.15

an equal split between ground-sourced and air-sourced devices. This share is present in all scenarios. Table 2 shows the central parameters.

Hourly heat demand profiles for each archetype are based on a building simulation model, taking into account the behavior of residents and inner loads.[9] Fig. 2 exemplarily shows hourly space heating demand profiles for a full year for three one-family home archetypes. The typical heating period is clearly visible.

Domestic hot water demand is modeled separately from heating energy demand, mainly depending on the assumed number of residents in each apartment or building. DHW profiles are assumed not to vary between housing types; they are derived from the Swiss SIA 2024 standard [42].

4.2. Scenarios

The capacity bounds of the generation portfolio shown in Fig. 1 serve as a reference for the model runs: we set the capacity assumptions for thermal plants as upper bounds for investments and the capacity assumptions for renewable plants and storage as lower bounds for investments. Accordingly, our scenarios are generally in line with the German energy and climate policy targets, while still leaning on the established European Reference Scenario. Beyond pumped hydro storage, the model can also invest in lithium-ion batteries and, in one scenario, into DSM.

We apply the model to a range of scenarios. In each scenario, we compare two cases: a NETS baseline with inflexible electric night-time storage heaters and a SETS upgrade scenario in which the entire NETS fleet is upgraded to more flexible SETS. Considering Germany's energy and climate policy, we consider the upgrade of existing night-time electric thermal storage heaters to be the most plausible market for installing SETS for several reasons: first, SETS are unlikely to replace centralized heating technologies such as district heating systems. Second, it is unlikely that SETS are installed in buildings in which a water-based heating system already exists, taking into account installation and operating costs as well as thermal comfort. If existing water-based heating systems, powered by fossil-fueled boilers in 2018, were to be replaced by power-to-heat options, it appears more likely that they will be converted to heat pumps, which require considerably less electricity. For the same reason, third, new future dwellings are also more likely to be equipped with heat pumps or some centralized heating system.

In all scenarios, we abstract from endogenous investments into SETS or other electricity-based heating systems. Instead, we vary their presence exogenously while their hourly use is determined endogenously in the model.[10] This allows to readily identify effects of more flexible electric heaters and their drivers within the electricity sector. Thus, assumptions on future investment or upgrade costs for various heating systems in different building types, which are both uncertain and idiosyncratic, are not required. Accordingly, such costs are also not part of the objective function. Nonetheless, we consider the costs for upgrading NETS to SETS when comparing overall model results.

Table 3 lists our central scenarios. Beyond the central SETS upgrade scenario, two scenarios explore the effect of competing flexibility or power-to-heat options: demand-side management and a greater share of heat pumps. Three additional scenarios implement more ambitious environmental policies: a higher CO_2 price, a higher share of renewables in electricity generation, and a coal phase-out. The coal phase-out scenario leans on the generation capacity reduction path proposed by the Commission on Growth, Structural Change and Employment in February 2019. The additional natural gas OCGT capacities reflect the backup capacities currently contracted in the German “grid reserve” between 2018 and 2021.[11]

We also calculate an alternative counterfactual baseline with direct electric heaters in place instead of the actual NETS fleet. While this comparison is not realistic for Germany, it illustrates the benefits of flexible power-to-heat operations more prominently. It also connects to other country studies such as Pensini et al. [22] or Rasku and Kiviluoma [23] in which direct electric heaters are considered to be more relevant. In Appendix D, we show results of further scenarios that vary the share of SETS and other power-to-heat technologies.

5. Results

We examine how a more flexible use of electricity for heating affects costs, investments into different generation capacities, their dispatch, CO_2 emissions, the provision of balancing reserves, and wholesale electricity prices. In doing so, we also investigate important drivers of different effects.

[9] The building simulation is provided by RWTH Aachen, using the open-source model TEASER (Tool for Energy Analysis and Simulation for Efficient Retrofit, https://github.com/RWTH-EBC/TEASER) [41]. The simulation is carried out for an eastern German location; sensitivities for other locations show negligible differences. See Appendix A.3 for more detailed information.

[10] We aim to shed light on the effects of more flexible electric heaters within the power system. In order to study an optimal configuration of the overall heating system, a much broader representation of the heating sector would be required. This would also have to include district heating, combined heat and power, the market for fossil heating fuels, and energy efficiency measures.

[11] The Commission on Growth, Structural Change and Employment (often referred to as Coal Commission) is composed of researchers, civil society representatives, and politicians. During 2018 and 2019, they developed a schedule to phase out electricity generation from lignite and hard coal in Germany until 2038. See https://www.kommission-wsb.de/ for further information (in German) and [43] for the final report.

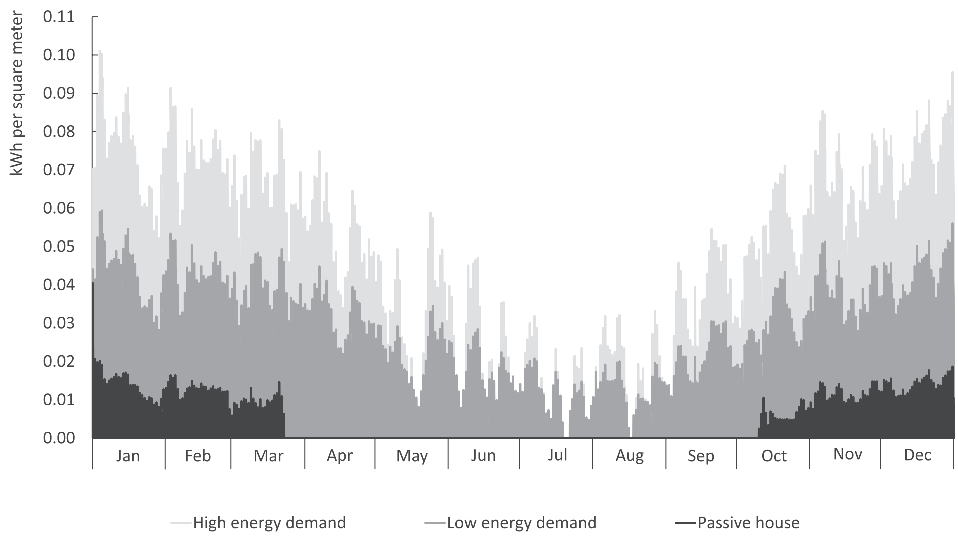

Fig. 2. Hourly heating demand time series for one year for three different building archetypes.

Table 3
Central scenarios.

Scenario	Alternative assumption	Rationale
SETS upgrade	–	Basic scenario with central assumptions
DSM breakthrough	Demand-side management available	Competing flexibility option on the demand side
Heat pump breakthrough	10% of residential space heating provided by ground-sourced and air-sourced heat pumps each	Increased roll-out of competing power-to-heat technology
High CO_2 price	CO_2 price of 71 euros per ton according to the TYNDP 2016	More stringent climate policy scenario
65% renewables	Renewables supply at least 65% of electricity demand	Implements higher target for 2030 laid out in the German 2018 government coalition agreement
Coal phase-out	Maximum lignite and hard coal capacities reduced to 9 GW and 8 GW, additional 6.6 GW OCGT capacities, at least 65% renewables in electricity demand	More progressive energy and climate policy scenario in line with current German policy goals

5.1. Electricity sector costs and total system costs

Total system costs are calculated as overall costs of providing electricity within one year, consisting of investment and dispatch costs. They are given as the sum of electricity sector costs, *i.e.*, the value of the objective function plus SETS investment costs.[12]

In the central SETS upgrade scenario, where SETS fully replace the existing NETS fleet, their temporally more flexible electricity demand enables yearly electricity sector costs savings of around 20 euros per unit. This corresponds to about 0.15% of electricity sector costs, or about 50 million euros in absolute terms. Yet considering SETS investments of around 36 euros per unit, total system costs increase by nearly 16 euros per unit (Fig. 3). Thus, the investment costs for making SETS more flexible exceed the electricity sector benefits of flexibility.

If competing flexibility options are available, the cost-benefit tradeoff from flexibilizing NETS worsens further. Electricity sector benefits are lower and, accordingly, total system costs increase by around 17 euros per unit in the DSM breakthrough scenario and around 22 euros per unit in the heat pump breakthrough scenario. Also in the scenario with a higher CO_2 price, the upgrade costs exceed the flexibility benefits, yet by only around 7 euros per unit. Benefits over-compensate costs only in the 65% renewables and coal phase-out scenarios, with total system cost savings of about 19 and 22 euros per unit, respectively.

Four implications emerge. First, investments into SETS flexibility are less valuable to the electricity sector if it features more other sources of flexibility such as DSM or heat pumps. These flexibility options compete with SETS for for low-cost renewable electricity in periods of high renewable availability. Accordingly, the marginal benefits of additional flexibility diminish. Second, the flexibility of SETS, in turn, proves more valuable if there are more variable renewable energy sources in the system. The share of renewable energy sources is 59% in the high CO_2 price scenario and 65% in both the 65% renewables and coal phase-out scenarios, compared to 52% in the basic SETS upgrade scenario. Third, the flexibility of SETS proves more valuable if the merit order is steeper, as comparing the 65% renewables and the coal phase-out scenarios shows. While the renewable shares are equal, the marginal costs of the remaining conventional natural gas generators are higher in the coal phase-out scenario. Accordingly, more flexible electricity demand can gain a somewhat larger advantage of directing demand to hours with low-cost generation. Fourth, improving the charging patterns of night-time storage heaters through upgrading them to SETS does not necessarily lead to overall efficiency gains, depending on the configuration of the electricity sector.[13]

To capture uncertainty in future cost developments, we vary the default cost assumption for upgrading NETS to SETS by halving or doubling it. Except for the heat pump breakthrough scenario, total system costs decrease at least slightly if SETS upgrade costs are only half the default assumption (Fig. 4). Conversely, the costs of respective investments exceed the electricity sector benefits in all scenarios under the assumption of double upgrade costs. Therefore, low upgrade costs

[12] SETS investment costs have to be added because they are not included in the objective function, compare Sections 3.1 and 3.2.

[13] In a sensitivity with a pure dispatch model, turning NETS into more flexible SETS would be even less attractive. Here, total system costs would increase by about 25 euros per unit in the central SETS upgrade scenario. Intuitively, more flexible demand enables a greater use of low-cost generation technologies, but a pure dispatch model does not allow for adjusting the generation portfolio accordingly.

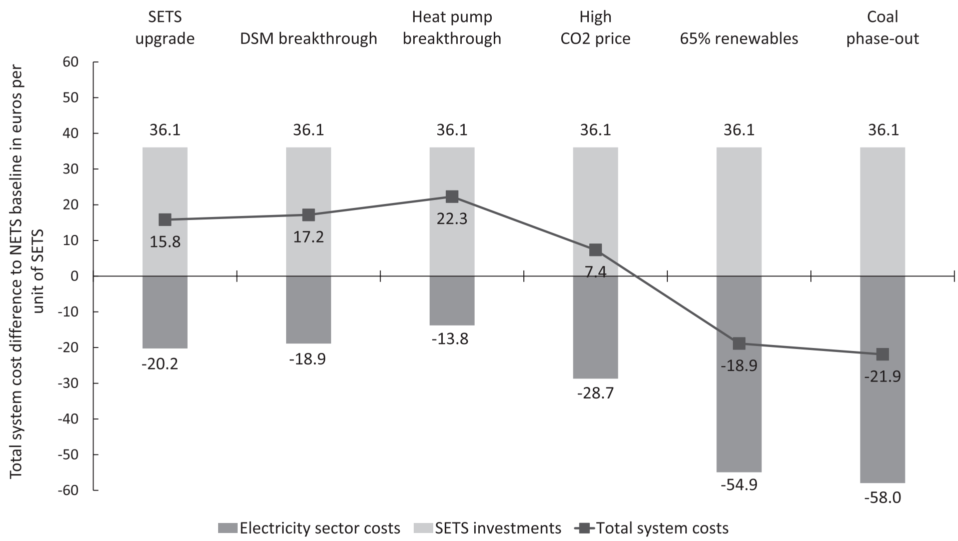

Fig. 3. Effects on electricity sector costs, SETS investment costs, and resulting total system cost effects per SETS unit from upgrading NETS to SETS in the central scenarios.

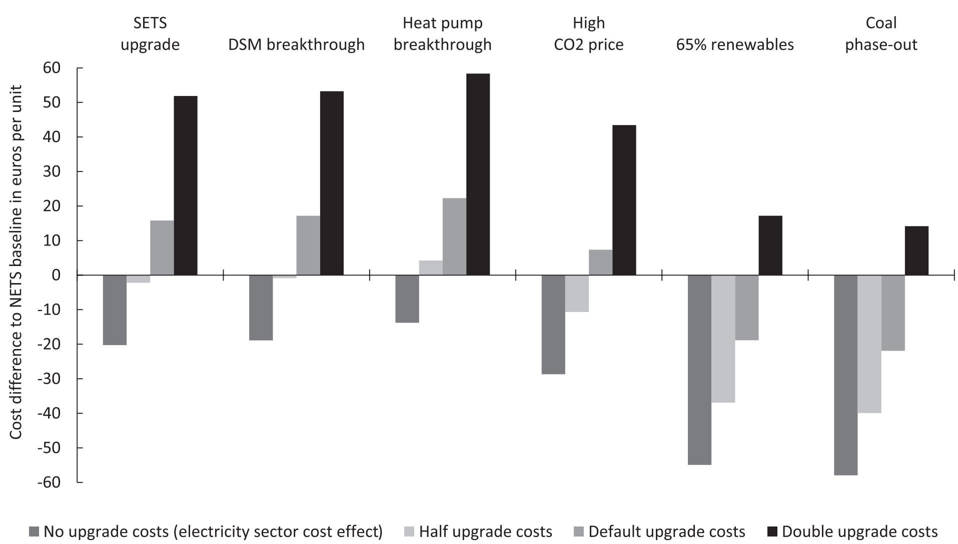

Fig. 4. Specific total system cost savings per SETS unit in the central scenarios for different investment cost assumptions for upgrading NETS to SETS.

are a vital condition for enabling total system costs savings from making electric storage heaters more flexible.

When we compare SETS against the hypothetical baseline scenario with fully inflexible direct resistive heaters instead of NETS, electricity sector effects are considerably more pronounced. Benefits to the electricity sector amount to about 112 euros per unit – compared to about 20 euros per unit when compared to the NETS reference. In absolute terms, this corresponds to 280 million euros, or 0.8% of electricity sector costs. Yet investment costs for replacing direct resistive heaters with SETS would also be higher, so total system cost effect would depend on respective investment cost assumptions.[14] Albeit direct resistive heating is not a practically relevant reference case for Germany, it provides a general insight. Demand patterns of existing night-time storage heaters in Germany are already well aligned with periods of low wholesale electricity prices. In historic markets, in which price patterns were generally demand-driven, low electricity prices occurred at night. In the future, rising shares of variable wind and solar PV energy add supply-driven price variability, not necessary related to the time of day. However, this shows that the general pattern of low night-time electricity prices remains relevant during the heating season.

5.2. Investment, dispatch, and CO_2 emissions

Next, we investigate investment and dispatch effects as drivers of total system cost changes. Flexibilizing NETS leads to only minor adjustments in the power plant fleet in the central SETS upgrade scenario. Notably, the additional flexibility related to SETS allows reducing the electrical storage capacity in the system by 250 MW (Fig. 5). A similar finding holds also for the other scenarios.[15] Sizeable additional renewable investments are only triggered if we assume a high CO_2 price. Under higher carbon prices, SETS flexibility allows integrating additional 3.1 GW of photovoltaics and 0.8 GW of wind power, which goes along with an increasing share of renewables.

The impacts of SETS on generation capacities go along with

[14] Compare also O'Dwyer et al. [44], Section 7.1, for complementary illustrations for different countries with varying cost assumptions.

[15] This is an instance of a more general finding: additional flexibility can strongly mitigate electrical storage requirements as long as the share of variable renewable energy sources is well below 100% (for a more generic analysis, see [45].

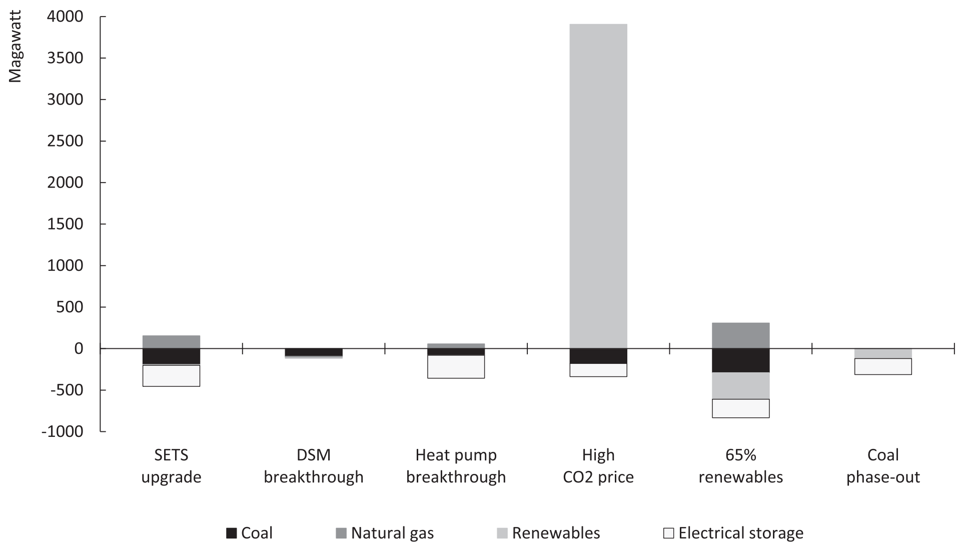

Fig. 5. Differences in installed generation and storage capacities compared to the respective NETS baselines.

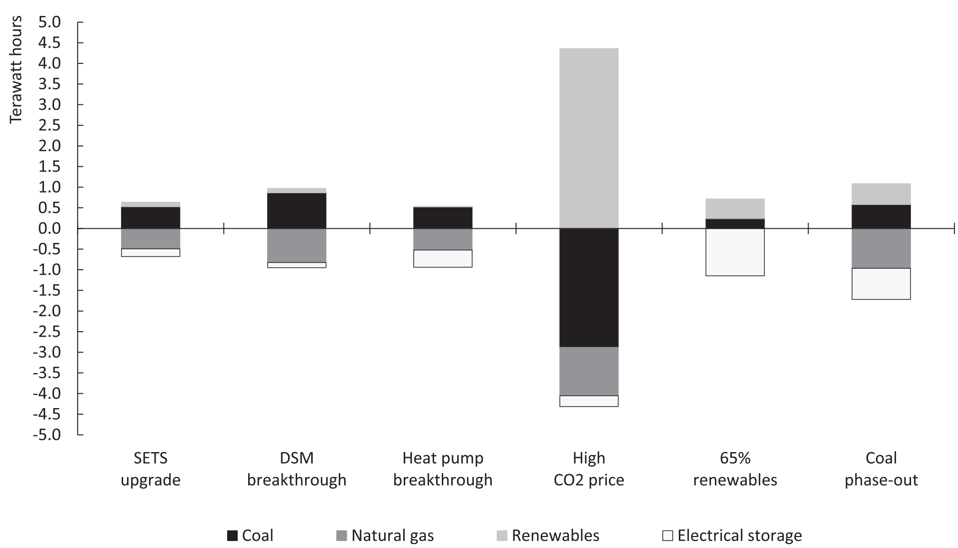

Fig. 6. Differences in annual electricity generation compared to the respective NETS baselines.

corresponding changes in annual electricity provision when comparing the SETS upgrade case with the NETS baseline for the central scenarios (Fig. 6). SETS help to make better use of available generation resources through intertemporal arbitrage. On the one hand, this lowers generation from electrical storage in all scenarios. On the other, SETS crowd out technologies with high marginal costs and help to integrate more electricity from generators with low marginal costs. However, this only slightly increases the use of renewables in the central SETS upgrade, DSM breakthrough, and heat pump breakthrough scenarios because renewable surpluses in the respective NETS baselines are already very low. So there is hardly any potential for integrating additional renewable energy through increased demand-side flexibility. Instead, SETS displace natural gas and integrate more electricity from coal plants. The same also holds for the coal phase-out scenario, and partly for the 65% renewables scenario, but less pronounced.[16]

Only when assuming a high CO_2 price of 71 euros per ton, SETS help to integrate variable renewables to a sizeable extent. Renewables replace around 4 GWh of electricity generation by fossil plants, which corresponds to about half of SETS electricity demand. The renewable share accordingly increases from 57.8% to 58.7% in this scenario. Thus, the shape of the merit order determines which technologies benefit from additional flexibility. With a high CO_2 price, the absolute advantage in marginal costs of renewables compared to fossil-fueled technologies is greater, and it is optimal to invest into additional renewables that can be more easily integrated by flexibility from SETS, despite higher fixed costs. For the default CO_2 price, the absolute advantage of renewables in marginal costs hardly justifies further investments into renewables, even though more flexibility from SETS is available.

The changing dispatch pattern has implications for CO_2 emissions. Independent of SETS, emissions are lowest in the high CO_2 price and coal phase-out scenarios (Fig. 7). In all scenarios with baseline assumptions on the CO_2 price, SETS trigger additional electricity generation from coal, and CO_2 emissions of the electricity sector accordingly increase. In the central SETS upgrade scenario, emissions grow by about 0.3 Megatons (0.13%). SETS help to decrease CO_2 emissions only in the high CO_2 price scenario, by around 2.9 Megatons (2.4%).

[16] While the renewables share in electricity demand is at 65% in the NETS baseline and SETS upgrade cases, electricity generation from renewables slightly increases in the 65% renewables and coal phase-out scenarios. There are two indirect explanations: (i) reduced provision of balancing reserves by renewables, and (ii) possible over-heating of SETS (compare equation (1) in Appendix A.1).

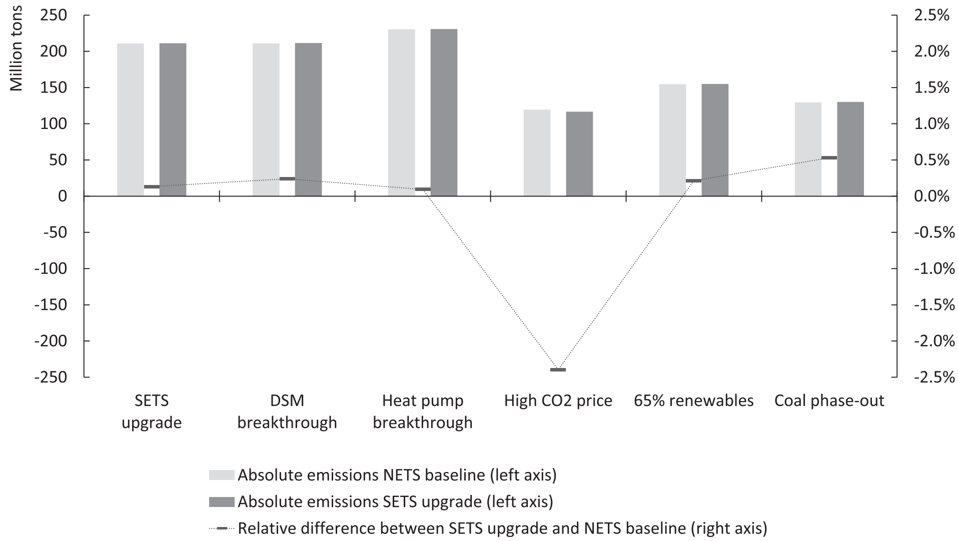

Fig. 7. CO_2 emissions in the NETS baseline and SETS upgrade cases in the central scenarios.

5.3. Drivers of system cost savings

To disentangle dispatch and investment effects on the reduction of total system costs, we devise a "waterfall" separation. We first run the baseline specification with NETS, fix all generation capacities to their optimal values, and then re-run the model in a pure dispatch mode with SETS to isolate the system value of SETS arbitrage. Next, we allow reserves provision by SETS to pin down the reserves value. Finally, we carry out the full-fledged investment run to infer the capacity-related value of SETS. The latter reflects the value of an adjusted power plant portfolio, which also includes additional dispatch changes.[17] Fig. 8 shows the results.

Three quarters of electricity sector cost savings arise from arbitrage, that is, the temporally more flexible demand opposed to NETS. The reserves value, in turn, is negligible despite the fact that SETS considerably contribute to the provision of balancing reserves. In the central SETS upgrade scenario, they provide over 13% of all positive secondary positive reserves and over 10% of all secondary negative reserves.[18] However, this is hardly valuable in the electricity sector because other technologies can provide reserves at similar costs, for instance thermal and renewable plants or electricity storage.[19] Finally, around one quarter of the electricity sector cost savings stems from the capacity, or portfolio, value attributable to SETS.

5.4. Wholesale electricity prices

If SETS substitute NETS, this has an impact on wholesale electricity prices. In the model, they are given as the marginal on the electricity market balance. In the NETS baseline, the unweighted mean electricity price is around 60 euros per MWh (Fig. 9). The mean price for NETS electricity is about 53 euros per MWh, around 12% below the system mean price. The mean price for SETS electricity in the central SETS upgrade scenario is about 48 euros per MWh, 20% below the system mean price. This reflects the greater flexibility of SETS to better schedule consumption to low-price hours, *i.e.*, hours with higher availability of generation technologies with low marginal costs. In line with that, the mean electricity price for inflexible direct resistive heating in the counterfactual baseline is markedly higher, at 71 euros per MWh, more than 18% above the system mean price.

If competing flexibility options are available, average prices for SETS electricity demand are slightly higher. This "cannibalization" increases the mean price for SETS to around 49 euros per MWh in the DSM breakthrough scenario. Conversely, the electricity price advantage of SETS is more pronounced in the 65% renewables and coal phase-out scenarios, both in absolute and relative terms. With more renewables, the temporal flexibility of SETS allows to make better use of low-price periods compared to the respective NETS baselines.

The price advantage of SETS is also reflected in the annual heating electricity bill of households, which can be obtained by summing up all hourly electricity payments for residential space heating and DHW and subtracting revenues from the provision of balancing reserves.[20] In the central SETS substitution scenario, the annual heating electricity bill for SETS is 9.35 euros per square meter, compared to 10.21 euros per square meter in the NETS baseline. Analogous to the mean heating electricity prices, the reduction in the electricity bill is lower if there is more competing flexibility in the electricity sector, and it is larger if the share of renewable energy sources increases.

5.5. Why are electricity sector cost effects of flexible storage heaters not more beneficial?

While SETS flexibility helps to make use of cheaper generation resources, total system cost effects are not necessarily beneficial and in any case rather moderate. This is due to the temporal pattern of electricity demand for heating. Fig. 10 shows the daily distribution of heating electricity demand, averaged over the year, for the NETS baseline, the central SETS upgrade scenario, and the 65% renewables scenarios. The curves largely follow a diurnal pattern. By default, NETS charge only at night-time (dotted line), but also SETS charge more than three quarters of their annual electricity demand at night in the central SETS upgrade scenario (solid black line). Thus, except for a kink around noon, the charging pattern is comparable under basic assumptions albeit SETS electricity demand is temporally more flexible. In turn, in the 65% renewables scenario, less than 60% of charging occurs at night (solid gray line). Due to a greater share of renewables, especially solar

[17] This type of portfolio-oriented capacity value should not be confused with the narrower, peak-oriented capacity value definition typically used in reliability studies.

[18] Positive reserves are activated when supply is lower than demand in the electricity sector. In case of SETS, they reduce their scheduled demand.

[19] This finding holds in a robustness check in which we restrict reserve provision by variable renewables; while reserve provision shares of SETS are somewhat greater, the system value is almost identical.

[20] That is, this "heating bill" only includes wholesale electricity expenditures and no other retail price components.

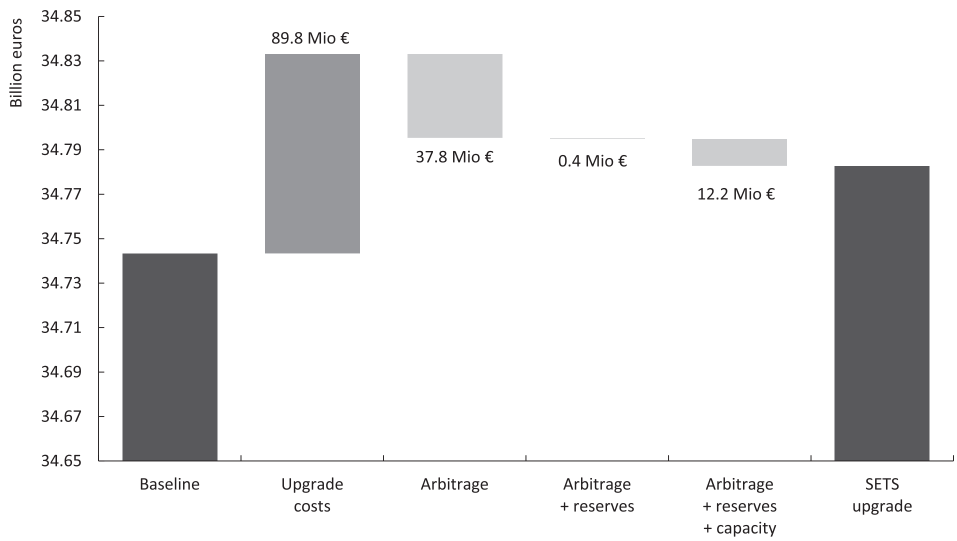

Fig. 8. Waterfall separation of SETS system values in the central SETS upgrade scenario.

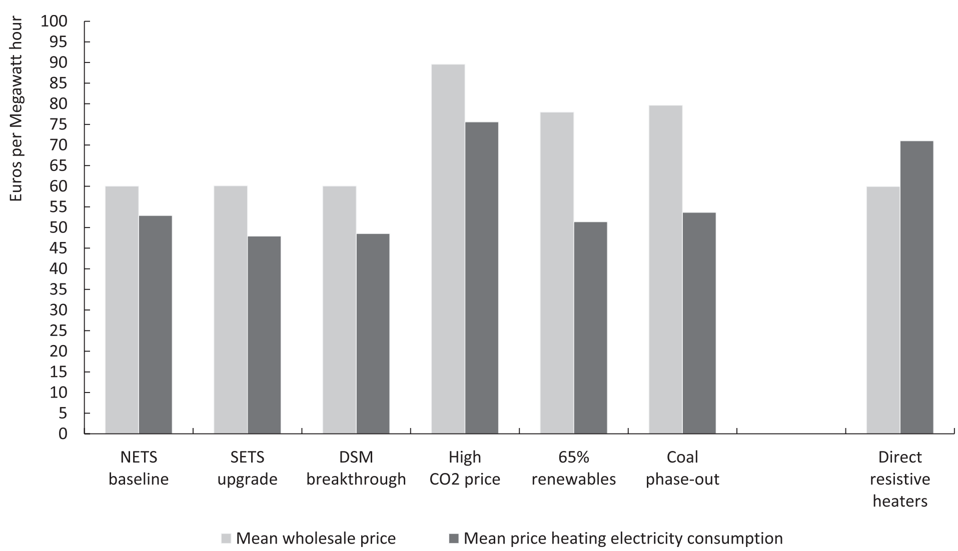

Fig. 9. Unweighted average wholesale electricity prices and prices of heating electricity consumption of NETS, SETS, and inflexible direct resistive heaters.

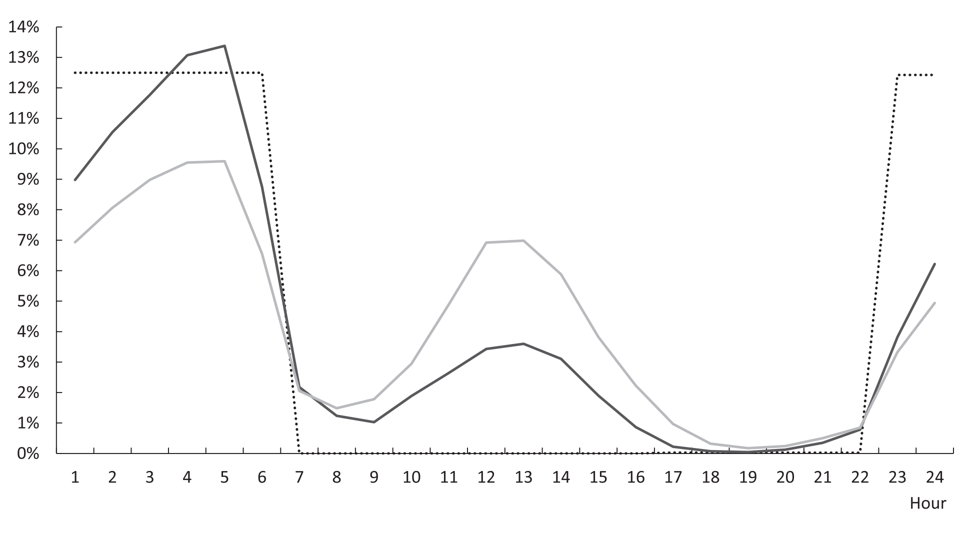

Fig. 10. Average daily charging pattern of NETS and SETS.

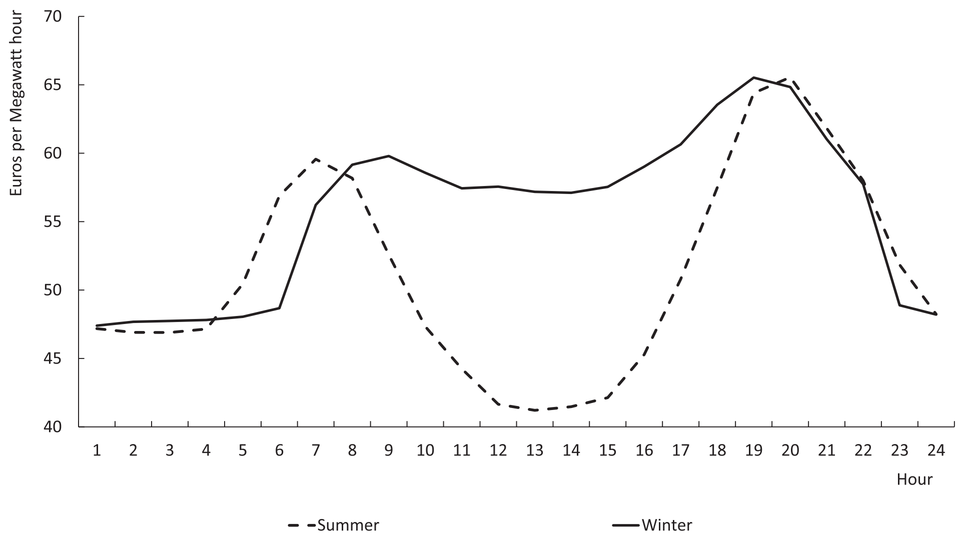

Fig. 11. Seasonal average hourly electricity prices in the central SETS upgrade scenario.

PV, more charging is shifted to daytime.

Almost 80% of annual heating demand arises in winter of fall. During the heating season, prices are, on average, still absolutely lowest at night in the central SETS upgrade scenario (Fig. 11). Therefore, SETS have an incentive to mainly charge at night and their flexibility does not offer a substantial price advantage compared to NETS. Conversely, PV feed-in is highest during summer and spring days around noon, and prices are lower than at night-time. However, only about 20% of heating demand falls into that seasons, and SETS heat storage capacity does not allow for seasonal storage. These special characteristics of electricity demand for heat render benefits rather moderate.[21]

If the renewable share rises to 65%, daily price patterns change (Fig. 12). While average prices are still absolutely lowest at night, the PV dip is more pronounced also in winter. Accordingly, more charging occurs during daytime and the temporal flexibility of SETS proves more valuable to the electricity sector.

6. Discussion of limitations and scope for future research

The model we use in this paper is subject to several limitations relevant for interpreting results. First, we analyze the German electricity sector in isolation without explicitly taking into account exchange with neighboring countries. Spatial balancing with other European countries would provide additional flexibility to the German electricity sector. Moreover, we do not incorporate further potential flexibility options such as electric vehicles or power-to-X, for instance hydrogen. Assuming that these technologies can be operated in a sufficiently flexible way, we tend to under-estimate the supply of flexibility of electric storage heaters and thus over-estimate its value. The results of the DSM and heat pump breakthrough scenarios point into this direction. This conclusion is not unanimous though. It is also conceivable that a future electric vehicle fleet charges predominantly in an inflexible, user-driven fashion[47]. Likewise, power-to-X could constitute a rather inflexible base load. Future research is needed to assess the interplay between electric heating and spatial balancing with other countries as well as interactions with other – more or less flexible – sector coupling technologies.

Second, we do not incorporate the electricity network and thus network congestion. Especially in regions with high demand or high renewable supply, temporal demand-side flexibility could prove more valuable to the electricity sector. In this regard, our results could underestimate the demand for flexibility and thus its value. However, in a study on heat pumps, Felten et al. [46] conclude that locally differentiated prices only have a modest beneficial effect on the electricity system while entailing large distributional repercussions. Future research could provide more evidence on the spatial dimension of temporal (demand-side) flexibility.[22]

Third, we do not take into account all conceivable power-to-heat options. Based on this analysis, especially those technologies that come with longer-term heat storage are likely to provide a greater benefit to the electricity sector. They are better able to align the mismatching temporal long-term patterns of renewable electricity supply and heat demand. McKenna et al. [49] analyze seasonal heat storage on a residential district level and provide a literature overview of studies on the building and district levels. Whether and under which conditions the electricity sector benefit exceeds their respective investment requires further research.

We also assume that the demand side faces wholesale real-time electricity prices and thus abstract from a range of regulatory price components. Residential retail prices are normally time-invariant and include a range of taxes and surcharges, for instance, to finance the electricity network or renewable support schemes. However, this common simplification helps to isolate relevant tradeoffs within an optimal power system. Future research could identify how incentives and behavior on the demand side depend on the design of regulated price components, for instance, whether they are energy-based or capacity-based. This could also incur a specific focus on prosumage, that is, the self-consumption of solar electricity.

Finally, and related, we tacitly assume that households are able and willing to allow a flexible use of their electric storage heaters. As Boait et al. [50] and Darby [51] conclude from field trials with smart electric thermal storage devices in several countries, critical success factors for a demand-response system comprise a well-designed interface and effective user activation. Households may also be unwilling to change the status quo of their heating system [52] or shy away from upfront investments for potential later savings [53]. An obstacle for the realization of system-friendly behavior by households may be their concern about data protection and security [54]. Broberg and Persson [55] as well as Wilson et al. [56] raise strong concerns about the unwillingness of households to cede autonomy and accept remote control of parts of

[21] Felten et al. [46] provide comparable evidence for the case of heat pumps in Germany.

[22] Runge et al. [48] devise an analysis for different electric fuels that sheds some light on the impact of locally differentiated prices on electricity demand of this sector coupling option.

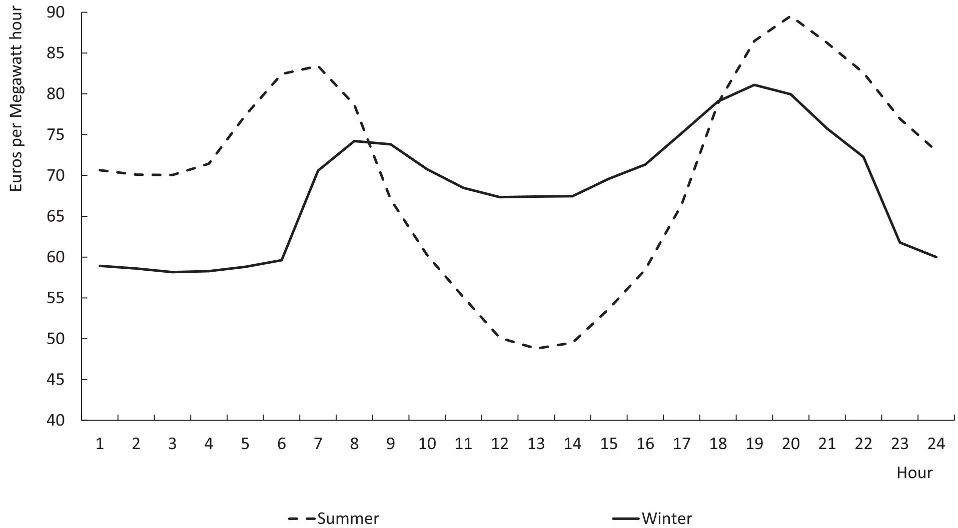

Fig. 12. Seasonal average hourly electricity prices in the 65% renewables scenario.

their electricity use. However, both large-scale empirical evidence on acceptance and the incorporation of such "soft" factors into numerical models is missing.

7. Conclusions

Decarbonizing the energy system requires a shift to renewable energy sources, not only for current electricity uses. Electric storage heaters for space heating are one option for the flexible use of renewable electricity from wind and photovoltaics in the heating sector. These devices convert electricity to heat that can be stored and released when needed. Using an open-source electricity sector model, we analyze electricity sector effects in a German 2030 setting if customary night-time storage heaters are upgraded to flexibly charge electricity around the clock. Beyond evidence on electric storage heaters, results also provide more general insights on residential demand-side flexibility in renewables-based electricity markets.

First, temporal flexibility on the demand side is agnostic about the electricity it helps to integrate. It benefits generation technologies with low marginal costs. This is also the main channel for the (moderate) electricity sector benefits from upgrading electric storage heaters; the benefit from adjustments in the generation portfolio is lower, the benefit from providing reserves negligible. Which generation technologies benefit most depends on the shape of the merit order. Beyond renewables, this may be also coal or natural gas. For flexibility options to trigger a further expansion of renewables, other measures may be required like, for instance, higher CO_2 prices.

Second, low investment costs for upgrading customary night-time storage heaters are vital for savings in total system costs. Unless the required upgrade investments are very low, they may exceed the benefits to the electricity sector. To this end, further cost reductions in information and communication technology as well as stable regulatory conditions that enable profitable business models would be favorable.

Third, overall cost savings are moderate because the temporal patterns of renewable availability and heat demand are not well aligned in Germany, as an example of temperate climate countries. During the heating season in fall and winter, when energy demand is high, electricity wholesale prices are likely to be lowest at night-time, even for a renewables penetration above 50%. More flexible electric heaters thus do not gain a large advantage compared to customary night-time storage heaters. Only if the share of renewables increases to 65%, low-price phases more frequently occur at daytime, and flexible electricity demand for heating gains a larger advantage. Thus, temporal flexibility for electric heating appliances appears to be less valuable to the power system in the medium run than other demand-side flexibility options such as electric vehicles, which have a less seasonal demand pattern. Those may provide short-term flexibility also during periods of the year in which it is more beneficial, for instance, during summertime with high diurnal PV supply. Alternatively, power-to-heat technologies with a long-term heat storage may help to exploit high availability of renewables outside the heating season.

Electric storage heaters entail several further drawbacks not explicitly analyzed in this paper. Compared to heat pumps, they come with a relatively low electrical efficiency. Especially in the long-run, the level of electricity consumption is likely to become a more critical factor when it comes to a comprehensive decarbonization of energy supply based on renewable energy sources. Also, their heat storage capacity is not sufficient to bridge longer periods of low electricity supply and high electricity demand. In this respect, accelerated building retrofitting toward greater energy efficiency and heat pumps appear to be a more promising option. However, if upgrades can be realized at very low costs, flexible electric storage heaters may also play a small yet beneficial role in decarbonizing the energy system.

CRediT authorship contribution statement

Wolf-Peter Schill: Conceptualization, Methodology, Project administration, Software. **Alexander Zerrahn:** Conceptualization, Methodology, Software, Visualization.

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Declarations of Competing Interest

None.

Role of the funding source

The funding source had no involvement in study design, collection, analysis and interpretation of data, in the writing of the report, and in the decision to submit the article.

Appendix A. Model formulation

In this section of the appendix, we document the equations that extend the power sector model DIETER with an electric space heating module.

A.1. Heating technologies

Let indices h denote the hours of the year and $b \in$ B the building archetypes. For power-to-heat technologies. Let Θ^{dir}, Θ^{sets}, and $\Theta^{hp} = \{hp_{as}, hp_{gs}\}$ denote the (singleton) sets of direct, SETS, and heat pump heating technologies, Θ^{elec} and $\Theta^{fos} = \{gas, oil\}$ the (singleton) sets of electric and fossil heating technologies. Accordingly $\Theta^{hy} = \Theta^{elec} \times \Theta^{fos}$ denotes the set of hybrid heating technologies that combine a fossil fuel and an auxiliary electric heating rod, and $\Theta^{sto} = \Theta^{hp} \cup \Theta^{hy}$ the set of all technologies that feed to a hot water buffer tank Finally, let $ch \in \Theta^{ch} = \Theta^{dir} \cup \Theta^{sets} \cup \Theta^{hp} \cup \Theta^{hy}$ denote all theoretically available (combinations) of heating technologies.

Hence, a dwelling may be heated by a stand-alone technology or a (hybrid) water-based heating technology, possibly combining two sources that feed to a hot water buffer tank. Among the hybrid technologies, we only consider the combinations of a heat pump or a fossil boiler with an auxiliary electric heating rod.[23] The general formulation would allow for further combinations. To address the heating technologies covered in the application, we define the binary parameter $\theta^{sto}_{b,ch} = \{0, 1\}$. It is equal to zero if the respective water-based heating technology ch is not in place in building type b. It is equal to one if the heating technology is in place in that building type. Analogous parameters $\theta^{dir}_{b,ch}$, $\theta^{elec}_{b,ch}$, $\theta^{hp}_{b,ch}$, and $\theta^{sets}_{b,ch}$ indicate whether direct resistive heating, an auxiliary electric heating rod, heat pumps or SETS are present in building archetype b. For instance, if $\theta^{sets}_{b2,sets} = 0$, then building archetype 2 is not equipped with SETS; or if $\theta^{sto}_{b6,hp_{gs}\_elec} = 1$, then some proportion of building archetype 6 is equipped with ground-sourced heat pumps with an auxiliary electric boiler.

The specific proportion of the floor area of a building type equipped with the respective heating technology follows an exogenous assumption. It is contained in the hourly heat demand parameters that are derived separately for all building type-heating technology combinations at hand. On that note, a proportion of a building type can be equipped with one heating technology, and another proportion of the same building type with another heating technology.

A.2. Heat energy balance

The heating energy balance (1) prescribes that, for each hour, heat output by the respective technologies installed in the building archetypes must satisfy residential heat demand.

$$\theta^{dir}_{b,ch} H^{dir}_{b,ch,h} + \theta^{sto}_{b,ch} H^{sto,out}_{b,ch,h} + \theta^{sets}_{b,ch} [H^{sets,out}_{b,ch,h} + (1 - \eta^{sets}) H^{sets,l}_{b,ch,h}] \geq d^{h}_{b,ch,h} \quad \forall\, b,\, ch,\, h \tag{1}$$

where hourly heating demand $d^{h}_{b,ch,h}$ can be met by direct resistive electric heating, $H^{dir}_{b,ch,h}$, heat output from water-based storage heaters, $H^{sto,out}_{b,ch,h}$, or SETS, $H^{sets,out}_{b,ch,h}$, in case the respective technology exists in b. The hourly heating demand enters the model as data and is specified for each technology-building combination. For SETS, static heat losses $1 - \eta^{sets}$ also contribute to residential heating, yet in an uncontrolled fashion. To give the model leeway of tolerating over-heating, we set up the heating energy balance as inequality. Accordingly, we assume that residents either tolerate such over-heating or cause heat losses by opening the window. Throughout the paper, capital Roman letters denote variables and lower case letters parameters.

A.3. SETS

Eq. (2a) links the energy level of the SETS heat storage, $H^{sets,l}_{b,ch,h}$, in each hour to the storage level in the previous period – deteriorated by static efficiency losses – the heat output, and the intake of electricity, $E^{sets}_{b,ch,h}$, corrected by activated balancing reserves.

$$H^{sets,l}_{b,ch,h} = \eta^{sets} H^{sets,l}_{b,ch,h-1} + E^{sets}_{b,ch,h} - H^{sets,out}_{b,ch,h} - \left(\sum_{r^+} RP^{sets}_{r^+,b,ch} \phi^{act}_{r^+,h} - \sum_{r^-} RP^{sets}_{r^-,b,ch} \phi^{act}_{r^-,h} \right) \quad \forall\, b,\, ch \in \Theta^{sets},\, h \tag{2a}$$

where $RP^{sets}_{r^+,b,ch}$ is the endogenously determined hourly provision of positive balancing reserves, r^+, by SETS and $\phi^{act}_{r^+,h}$ the exogenous hourly share of reserves activated following actual data from the base year. Analogously, r^- represents negative reserve qualities. For positive balancing reserves, SETS reduce their electricity demand to a lower level than initially scheduled; for negative balancing reserves, SETS increase their electricity demand beyond the original schedule.

Four constraints take account of SETS' capacity limits. The power rating, $n^{sets,in}_{b,ch}$, restricts hourly SETS electricity demand, also taking account of the provision of negative reserves (2b). The SETS heating power capacity, $n^{sets,out}_{b,ch}$, restricts hourly SETS heat output (2c). If SETS provide positive reserves, the reserve provision may be no larger than the hourly scheduled electricity intake (2d). Finally, the SETS storage energy level may not exceed its energy capacity, $n^{sets,e}_{b,ch}$ (2e).

$$E^{sets}_{b,ch,h} + \sum_{r^-} RP^{sets}_{r^-,b,ch} \leq n^{sets,in}_{b,ch} \quad \forall\, b,\, ch \in \Theta^{sets},\, h \tag{2b}$$

$$H^{sets,out}_{b,ch,h} \leq n^{sets,out}_{b,ch} \quad \forall\, b,\, ch \in \Theta^{sets},\, h \tag{2c}$$

[23] The combination of heat pumps with auxiliary electric heating rods is implemented in the model formulation, but not used in the present analysis.

$$\sum_{r^+} RP^{sets}_{r^+,b,ch} \leq E^{sets}_{b,ch,h} \qquad \forall\ b,\ ch \in \Theta^{sets},\ h \tag{2d}$$

$$H^{sets,lev}_{b,ch,h} \leq n^{sets,e}_{b,ch} \qquad \forall\ b,\ ch \in \Theta^{sets},\ h \tag{2e}$$

A.4. Direct resistive heaters

Alternatively to SETS, residential heat may be provided by direct resistive heaters. Their heat output is part of the heat energy balance (1) above. Their electricity input enters the energy balance of the electricity sector in the same hour (not shown here).

A.5. Water-based storage heating: heat pumps

Heat pumps convert electricity input, $E^{hp}_{b,ch,h}$, to heat output to the water storage tank, $H^{hp}_{b,ch,h}$. This conversion is subject to the coefficient of performance (COP).

$$cop_{b,ch,h} \equiv \eta^{hp,dyn} \frac{temp^{sink}_{b,ch} + 273.\,15^{\circ}C}{temp^{sink}_{b,ch} - temp^{source}_{b,ch,h}} \qquad \forall\ b,\ ch \in \Theta^{hp},\ h \tag{3a}$$

The COP relates the sink temperature, $temp^{sink}_{b,ch}$, to the source temperature, $temp^{source}_{b,ch,h}$, both in degrees Celsius. It is augmented by the efficiency of the heat pump, $\eta^{hp,dyn}$. For ground-sourced heat pumps, we assume a time-constant source temperature, and a time-varying source temperature for air-sourced heat pumps. The time series of the air temperature enters the model as data. As for SETS, the electricity demand is netted by the activation of balancing reserves.

$$H^{hp}_{b,ch,h} = \left[E^{hp}_{b,ch,h} - \left(\sum_{r^+} RP^{hp}_{r^+,b,ch} \phi^{act}_{r^+,h} - \sum_{r^-} RP^{hp}_{r^-,b,ch} \phi^{act}_{r^-,h} \right) \right] cop_{b,ch} \qquad \forall\ b,\ ch \in \Theta^{hp},\ h \tag{3b}$$

Heat pump electricity demand is restricted by the electrical power rating, $n^{hp,in}_{b,ch}$, (3c) as well as a required minimum scheduled electricity demand in case of positive reserve provision (3d).

$$E^{hp}_{b,ch,h} + \sum_{r^-} RP^{hp}_{r^-,b,ch} \leq n^{hp,in}_{b,ch} \qquad \forall\ b,\ ch \in \Theta^{hp},\ h \tag{3c}$$

$$\sum_{r^+} RP^{hp}_{r^+,b,ch} \leq E^{hp}_{b,ch,h} \qquad \forall\ b,\ ch \in \Theta^{hp},\ h \tag{3d}$$

A.6. Water-based storage heating: auxiliary electric heating rods

Water-based storage heating systems may complementarily be powered by an auxiliary electric heating rod, for which analogous equations as for heat pumps apply. Specifically, the heat output to the hot water storage tank, $H^{elec}_{b,ch,h}$, equals the electricity intake in the same hour, $E^{elec}_{b,ch,h}$, corrected by activated reserves.

$$H^{elec}_{b,ch,h} = E^{elec}_{b,ch,h} - \left(\sum_{r^+} RP^{elec}_{r^+,b,ch} \phi^{act}_{r^+,h} - \sum_{r^-} RP^{elec}_{r^-,b,ch} \phi^{act}_{r^-,h} \right) \qquad \forall\ b,\ ch \in \Theta^{elec},\ h \tag{4a}$$

Eqs. (4b) and (4c) restrict the maximum and minimum electricity demand according to the power rating, $n^{elec}_{b,ch}$, and the provision of reserves, respectively.

$$E^{elec}_{b,ch,h} + \sum_{r^-} RP^{elec}_{r^-,b,ch} \leq n^{elec}_{b,ch} \qquad \forall\ b,\ ch \in \Theta^{elec},\ h \tag{4b}$$

$$\sum_{r^+} RP^{elec}_{r^+,b,ch} \leq E^{elec}_{b,ch,h} \qquad \forall\ b,\ ch \in \Theta^{elec},\ h \tag{4c}$$

A.7. Water-based storage heating: storage tank

The heat supply of heat pumps, electric heating rods, and fossil boilers feeds to the hot water storage tank. Its energy level in each hour, $H^{sto,l}_{b,ch,h}$, is determined by the level in the previous hour – corrected by static efficiency losses, $\eta^{heat,sto}$ – plus the net of heat inputs by the technologies that feed to the heat storage and the heat output for space heating, $H^{sto,out}_{b,ch,h}$, and domestic hot water, $H^{DHW,out}_{b,ch,h}$. $H^{fos}_{b,ch,h}$ denotes the heat input from fossil-fueled boilers to the hot water heat storage tank. (5a). The storage energy capacity, $n^{sto,e}_{b,ch}$, restricts the maximum storage energy level (5b).

$$H^{sto\_l}_{b,ch,h} = \eta^{heat,sto} H^{sto,l}_{b,ch,h-1} + \theta^{hp}_{b,ch} H^{hp}_{b,ch,h} + \theta^{elec}_{b,ch} H^{elec}_{b,ch,h} + \theta^{fos}_{b,ch} H^{fos}_{b,ch,h} - H^{sto,out}_{b,ch,h} - H^{DHW,out}_{b,ch,h}\ \forall\ b,\ ch \in \Theta^{sto},\ h \tag{5a}$$

$$H^{sto,l}_{b,ch,h} \leq n^{sto,e}_{b,ch} \qquad \forall\ b,\ ch \in \Theta^{sto},\ h \tag{5b}$$

A.8. Domestic hot water

In each hour, domestic hot water (DHW) demand, $d^{DHW}_{b,ch,h}$, must be satisfied from the heating system's buffer storage, a direct hot water provision element complementing direct resistive space heaters, $H^{DHWdir}_{b,ch,h}$, or an auxiliary hot water storage tank complementing SETS, $H^{DHWsets,out}_{b,ch,h}$. We refer to the latter as DHW-SETS in the following.[24]

$$\theta^{dir}_{b,ch} H^{DHWdir}_{b,ch,h} + \theta^{sto}_{b,ch} H^{DHW,out}_{b,ch,h} + \theta^{sets}_{b,ch} H^{DHWsets,out}_{b,ch,h} = d^{DHW}_{b,ch,h} \quad \forall\, b,\, ch,\, h \tag{6a}$$

where heat output, $H^{DHWdir}_{b,ch,h}$, equals the required electricity demand and enters the electricity energy balance in the respective hour (not shown here). The energy level of the auxiliary DHW tank complementing SETS space heating, $H^{DHWsets,l}_{b,ch,h}$, is subject to the following intertemporal equation:

$$H^{DHWsets,l}_{b,ch,h} = \eta^{DHWsets} H^{DHWsets,l}_{b,ch,h-1} + E^{DHWsets}_{b,ch,h} - H^{DHWsets,out}_{b,ch,h} - \left(\sum_{r^+} RP^{DHWsets}_{r^+,b,ch} \phi^{act}_{r^+,h} - \sum_{r^-} RP^{DHWsets}_{r^-,b,ch} \phi^{act}_{r^-,h} \right) \quad \forall\, b,\, ch \in \Theta^{sets},\, h \tag{6b}$$

which links the storage level in each period to the level in the previous period – corrected by static efficiency losses, $\eta^{DHWsets}$ – plus the net of energy inflow, $E^{DHWsets}_{b,ch,h}$, and outflows, also accounting for reserves provision. Electricity inflows (6c) and the tank's energy level (6e) are restricted by the the respective capacities, $n^{DHWsets,in}_{b,ch}$ and $n^{DHWsets,l}_{b,ch}$, respectively, also taking balancing reserves provision into account (6d).

$$E^{DHWsets}_{b,ch,h} + \sum_{r^-} RP^{DHWsets}_{r^-,b,ch} \leq n^{DHWsets,in}_{b,ch} \quad \forall\, b,\, ch \in \Theta^{sets},\, h \tag{6c}$$

$$\sum_{r^+} RP^{DHWsets}_{r^+,b,ch} \leq E^{DHWsets}_{b,ch,h} \quad \forall\, b,\, ch \in \Theta^{sets},\, h \tag{6d}$$

$$H^{DHWsets,l}_{b,ch,h} \leq n^{DHWsets,l}_{b,ch} \quad \forall\, b,\, ch \in \Theta^{sets},\, h \tag{6e}$$

Appendix B. More information on the generation capacity assumptions

Numbers on solids-fired thermal plants specified in the Reference Scenario [25,26] are only given as aggregate figure. To differentiate between lignite and hard coal, we assume a split according to the 2030 scenario Vision 3 ("National Green Transition") of the Ten Year Network Development Plan (TYNDP) 2016 [34,35]. We attribute natural gas-fired capacities evenly to combined cycle gas turbines (CCGT) and open cycle gas turbines (OCGT). For the split between onshore and offshore wind, we assume about 18% offshore and about 82% onshore. This follows the most recent proposal for the central scenario B from the German Network Development Plan for 2030 [57]. Lastly, we summarize the remaining, minor technologies "other renewables," "hydrogen plants," and "geothermal heat" as the type "other" for our model application.

Appendix C. More information on heating demand

Hourly time series of space heat and DHW demand per square meter enter the model as data, differentiated between twelve building archetypes. Further exogenous inputs comprise the electric power rating of heating technologies, their storage energy capacity, the heat output capacity, and the static and dynamic efficiency, which is given as the coefficient of performance (COP) for heat pumps. For ground-sourced heat pumps, the COP is constant; for air-sourced heat pumps, it varies hourly over the year, depending on the outdoor air temperature, which also enters the model as input data in line with the test reference year assumptions of the heating profiles.

Hourly outputs comprise the electricity demand of residential power-to-heat options, their heat and DHW output, the provision and activation of balancing reserves, and the heating electricity price. Derived indicators encompass, among others, yearly heating costs, average electricity prices as well as revenues from providing reserves.

Hourly heating energy demand profiles were calculated by RWTH Aachen University within the EU Horizon 2020 research project RealValue and then serve as input parameters for the power sector model DIETER. To this end, twelve building archetypes were defined to adequately represent the large and heterogeneous German residential building stock. The definition of archetypes is based on results of two European research projects: (i) EPISCOPE, Monitor Progress Towards Climate Targets in European Housing Stocks; and (ii) TABULA, Typology Approach for Building Stock Energy Assessment; also compare Loga et al. [58]. For modern and future buildings, not covered by the projects, relevant characteristics were selected based on the current German Energy Saving Ordinance (EnEV) [59]and other sources.

The twelve archetypes are differentiated by two building sizes (one-family houses, OFH, and multi-family house, MFH) and six different vintage classes: buildings with very high energy demand (VHED), built before 1957; buildings with high energy demand (HED), built in the period 1958–1978; buildings with medium energy demand (MED), built in the period 1979–1994; buildings with low energy demand (LED), built in the period 1995–2009; buildings with very low energy demand (VLED), built in the period 2010–2019; and passive houses (PH), built after 2019. The share of each building type in the year of analysis, 2030, is based on an own forward projection of depreciation and renovation rates, guided by general trends and reflecting the ambitious targets for energy efficiency improvements by the German government.

To derive the hourly heating demand profile, the open-source thermal building model TEASER (Tool for Energy Analysis and Simulation for Efficient Retrofit) was used [41]. Each archetype was modeled separately, drawing on the publicly available AixLib Library [60]. The thermal building model features resistances and capacities to take into account heat flows and thermal inertia of physical components. Heat flows inside the building and toward the ambience were modeled considering heat conduction, convection, and radiation effects. Internal loads were no endogenous part of the simulations. Based on the Swiss SIA 2024 standard [42], they were subtracted from hourly heating energy demand profiles after the simulation. Indoor temperatures reflect a daily set temperature of 22 °C, based on the current standards DIN EN 15251 and DIN EN ISO 7730. To reflect actual heating behavior in Germany, a reduction of night-time indoor temperatures to 18 °C was allowed between 10 p.m. and 5 a.m. A German test reference year (TRY) approach was employed to ensure representative environmental boundary conditions for building simulations, based on weather data calibrated to a central eastern German region. Hourly heat energy demand profiles are defined per square meter. For aggregation to the national level, all values were multiplied with the overall square meters in the respective building class.

Domestic hot water demand in buildings is generally not correlated with the building's size, year of construction or standard of energy efficiency.

[24] In contrast to SETS used for space heating, DHW-SETS store thermal energy directly in the water for domestic use and not in a solid thermal storage medium.

Therefore, DHW demand was modeled separately, depending on the assumed number of residents in each apartment or building. Its hourly profile was also derived from the Swiss SIA 2024 standard [42].

Appendix D. Further scenarios with different shares of SETS and other power-to-heat technologies

In this section, we show results of further scenarios that vary the share of SETS and other power-to-heat technologies. Beyond the complete upgrade of NETS to SETS, we provide intermediate cases in which only 25%, 50%, and 75% of the current German NETS fleet is substituted. Going beyond full upgrades of existing NETS, one scenario exemplarily assumes a SETS capacity double the size of the former NETS fleet. Finally, we devise a scenario in which hybrid electric-natural gas boilers replace existing NETS. Table 4 gives an overview.

If SETS substitute only a part of the current NETS fleet, electricity sector costs, *i.e.*, not accounting for SETS investments, decrease with a diminishing marginal rate: if SETS replace 25% of the current NETS capacity, they are lower by 0.045%; if SETS replace 50% of NETS, they are lower by 0.083%; by 0.116% for 75%, and and by 0.145% for 100% NETS upgrades. Fig. 13 plots this convex curve (solid line) against a hypothetical linear decrease (dotted line).

Table 4
Further scenarios with alternative assumptions on heating technologies.

Scenario	Alternative assumption	Rationale
25%, 50%, 75% SETS upgrade	Only a share of existing NETS is upgraded to SETS	Explore electricity sector effects for lower SETS penetration
Double SETS	Double SETS capacities compared to upgrade case	Explore electricity sector effects of SETS roll-out beyond upgrade of existing NETS
Hybrid substitution	NETS fleet substituted by hybrid electric-natural gas boilers instead of SETS	Explore electricity sector effects of competing power-to-heat technology
Heat pump substitution	NETS fleet substituted by heat pumps instead of SETS	Explore electricity sector effects of competing power-to-heat technology

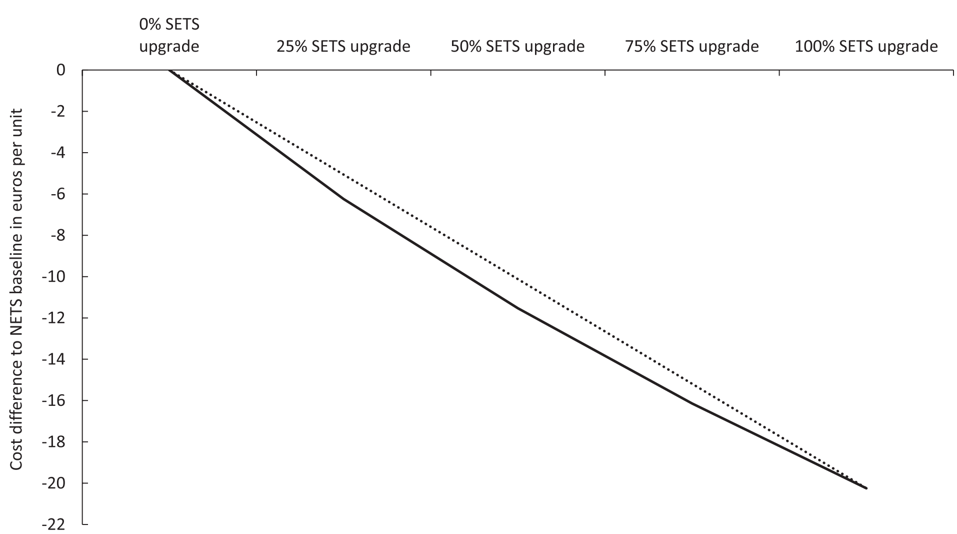

Fig. 13. Specific electricity sector cost savings per SETS unit in case of partial upgrades of NETS to SETS.

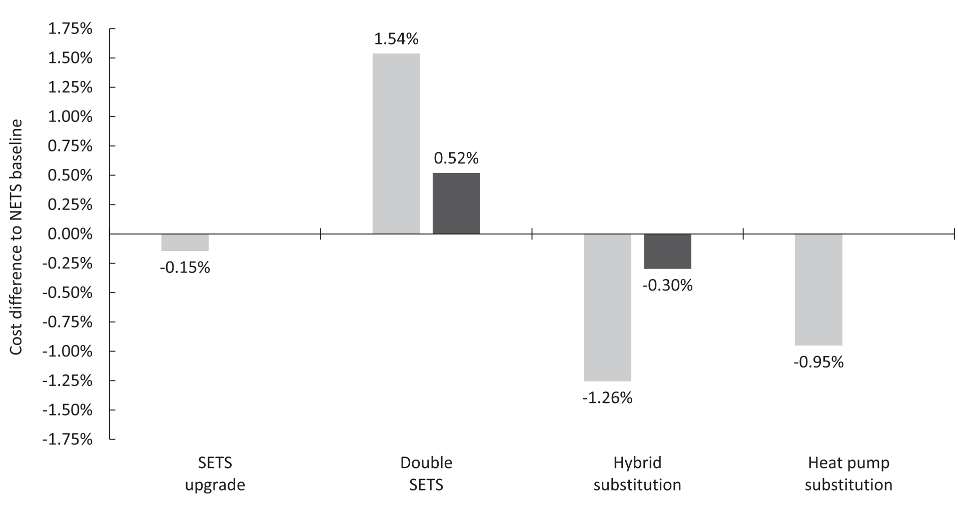

Fig. 14. Electricity sector cost effects for further scenarios with alternative assumptions on heating technologies.

Accordingly, SETS compete against themselves. More precisely, each additional SETS unit not only comes with a decreasing marginal flexibility benefit, but also decreases the average benefits of already existing SETS units. This illustrates a more general point: the more competing sources of flexibility there are in the electricity system, the lower is the value of additional flexibility. The effect parallels the finding for the scenarios with DSM or heat pumps as competing flexibility options.

If we increase the share of the residential floor area heated by SETS beyond upgrading the existing NETS fleet, electricity sector costs no longer decrease (as in the basic SETS upgrade scenario), but rise by around 1.5% (Fig. 14). This is driven by additional electricity demand of storage heaters, which is here twice as large as for the initial NETS fleet. Accounting for SETS investments, the effect of total system costs would be more pronounced. To allow for better comparison, we assume that the additional SETS replace natural gas-based heating systems and include according fuel cost savings in the calculation. Even then, the overall cost effect is still positive. This finding is in line with our assumption that SETS are unlikely to become a widespread heating option beyond the NETS replacement market.

Finally, if we assume that hybrid electric-natural gas heating systems or heat pumps replace NETS, electricity sector costs decrease by a greater extent than if NETS are upgraded to SETS. This cost advantage is particularly pronounced in the heat pump substitution scenario with a cost decrease of −1.0%, reflecting the more efficient electricity use of heat pumps compared to SETS. In the hybrid substitution scenario, the pure electricity sector cost effect is even larger, but savings drop to −0.3% if we also consider additional natural gas expenditures for hybrid heating systems.

While these sensitivities provide complementary insights, more detailed calculations on relative advantages of specific heating technologies would also have to consider the full costs of respective installations. This analysis is out of the scope of this work and left for future research.

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