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Abstract

As part of the German energy transition, the increasing adoption of electricity-driven technologies in end-use sectors has become a key political priority. Decentralized flexibility from assets such as electric vehicles and heat pumps influences electricity price formation, raising new challenges related to the redistribution of welfare gains, not only between producers and consumers but also across different groups within these two categories. This paper addresses two research questions: How does decentralized flexibility affect the redistribution of total system welfare between producers and consumers in the wholesale electricity market? And how do varying degrees of flexibility impact electricity costs across different user groups in the transport and heating sectors? To explore these questions, we enhance a European high-resolution dispatch model, focusing specifically on Germany, and incorporate a range of flexibility options and heterogeneous end-user groups. We further simulate multiple use cases with varying degrees of flexibility in the road transport and heating sectors. Our findings reveal that while total system welfare improves slightly, increased flexibility redistributes welfare from producers to consumers. This redistribution benefits consumers as an aggregated group by reducing electricity procurement costs, regardless of whether they provide flexibility. Among the flexibility options analyzed, electric vehicles - particularly through bidirectional charging - demonstrates a greater potential for welfare gains compared to heat pumps. However, this dynamic intensifies competition with centralized assets like utility-scale batteries. In the transport sector, flexibility leads to notable variations in electricity costs based on charging behaviors, whereas in the heating sector, increased flexibility promotes cost convergence across different user groups.

Keywords: Flexibility, Welfare effects, Energy System Modeling, Energy Transition, End-use Sectors
JEL classification: C61, D47, O33, Q41, Q48

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1. Introduction

Achieving climate neutrality necessitates a deep transformation of energy systems, particularly through the decarbonization of end-use sectors like transportation, heating, and industry. Electrification has emerged as the primary strategy for this transition, with Germany setting ambitious goals to deploy 15 million electric vehicles (EVs) and 6 million heat pumps by 2030 (BMWK, 2022b,a). While these targets demonstrate ambition towards a low-carbon economy, they also introduce significant challenges due to the increasing integration of decentralized, flexible actors into the electricity market. Their flexible consumption patterns - such as the ability to shift EV charging or heat pump operation to times of lower electricity prices - can alter demand profiles, influencing electricity price formation. Flexibility can potentially reduce the need for costly backup power plants and increase the integration of renewable energy sources (RES) by aligning consumption with periods of high RES generation (Kiviluoma and Meibom, 2010). However, shifting demand can also lead to increased electricity prices due to heightened consumption during periods of negative or low electricity prices.

The deployment of flexibility not only affects the electricity price formation but also leads to significant redistributional consequences in the electricity market. For example, Liski and Vehviläinen (2023) illustrate how increased demand-side flexibility, while reducing overall price volatility, leads to a redistribution of economic surplus from producers to consumers. Producers, especially those relying on price peaks, may see their profits diminish as flexible demand flattens price peaks, reducing their revenues. Furthermore, the interaction of decentralized flexible technologies can create cross-sectoral imbalances. For instance, while EV owners may benefit from lower electricity costs by charging during off-peak hours, this increased demand could raise prices for other groups, such as heat pump owners, who may be operating their systems at the same time. These dynamics complicate the electricity market by creating interactions where one group's flexibility influences the costs borne by others. As such, the introduction of flexibility could exacerbate inequalities, where certain user groups benefit disproportionately while others, including producers or less flexible consumers, face reduced revenues or higher costs.

This paper addresses these redistributional consequences by providing a detailed analysis of the economic implications of deploying flexibility from end-use sectors in the wholesale electricity market. By incorporating heterogeneous end-user groups from the road transport and decentralized heating sectors, this study sheds light on the system-wide, sectoral, and user-level impacts of decentralized flexibility. Specifically, we assess system-level effects, including changes in electricity prices and CO_2 emissions, examine the redistribution of economic gains and losses across different producer and consumer groups, and explore the economic impact of different degrees of flexibility on various user groups. By focusing on these diverse impacts, the paper contributes to a more nuanced understanding of how flexibility deployment affects economic outcomes across different actors in the wholesale electricity market.

Extensive research has been conducted on the effects of flexibility provision, primarily focusing on two main objectives: analyzing system-wide impacts, such as market clearing and electricity price formation, and evaluating welfare effects, including technology-specific market values and the redistribution of economic gains among market participants.

The first body of literature focusing on system-wide effects of flexibility tends to adopt a top-down perspective, often analyzing the impact of flexibility on total system costs. For example, the Big-5 Energy System Studies (dena, 2022) explore the system-wide implications of decentralized flexibility deployment in cost-efficient pathways to achieve climate goals. Other works, such as those by Härtel and Korpås (2021) and Böttger and Härtel (2022), emphasize the importance of capturing cross-sectoral interactions in energy system models to better understand market dynamics. They show that technologies like EVs and heat pumps, which act as flexible, price-setting actors, can significantly influence electricity price formation and market clearing in low-carbon energy systems. Similarly, Nagel et al. (2022) examine the competition between different flexibility options in systems with high RES shares, focusing on how these technologies interact under varying climate targets. Felling and Fortenbacher (2022) further highlight the importance of sector coupling - integrating electricity, heating, and transport sectors - when analyzing price formation. Their research stresses the need for flexibility to be studied in an integrated way, considering multiple energy sectors simultaneously. Despite these advancements, the current literature on market clearing and price formation tends to focus on the overall system, neglecting the heterogeneous impacts of flexibility on different end-user groups, which is crucial for understanding the redistributional effects of flexibility deployment.

The second body of literature shifts the focus towards the welfare effects of flexibility deployment and the impact of specific technologies on market values. Studies like Hirth (2013) have analyzed how the variability of solar and wind power affects the market values of renewables, while others, such as Bernath et al. (2021), have examined sector coupling's impact on these market values. Ruhnau (2022) expands this discussion by exploring the role of electrolyzers in influencing wind and solar market values. Böttger and Härtel (2022) and Nagel et al. (2022) have studied the welfare effects of flexibility deployment, specifically focusing on the economic benefits for flexibility providers. While the existing studies provide valuable insights into the broader economic impact of flexibility deployment, they tend to aggregate flexibility providers, thus overlooking the impacts on various end-user groups. Neglecting heterogeneous flexibility potentials creates a critical gap in understanding how decentralized flexibility affects not only total system welfare but also the redistribution of economic gains and losses across different actors in the energy market. This study aims to fill this gap by providing a granular analysis of decentralized flexibility deployment and exploring how flexibility affects the economic outcomes at the system, sector, and user levels.

This study addresses two key research questions: First, how does decentralized flexibility affect the redistribution of total system welfare across different producer and consumer groups in the wholesale electricity market? Second, how do varying degrees of flexibility deployment affect electricity costs for heterogeneous end-user types, particularly in the road transport and heating sector? To answer these questions, we enhance the existing European energy system model DIMENSION by incorporating a high-resolution dispatch for a range of end-consumer groups and flexibility technologies. This approach allows us to simulate the interaction between decentralized flexible assets - such as EVs and heat pumps - and the energy system. Our analysis is based on a case study for Germany, reflecting the country's technology-specific targets for 2030. By assuming the achievement of these targets, we model varying degrees of flexibility in the road transport and decentralized heating sectors through a range of use cases. This enables us to assess the economic consequences of decentralized flexibility provision across different market actors. Besides this, the paper adds to the existing literature by providing an in-depth analysis of the impacts of various decentralized flexibility use cases across three distinct levels:

- System level: We assess the system-wide impacts of flexibility deployment, including effects on electricity price formation and CO_2 emissions.
- Sector and technology level: We quantify the redistribution of consumer and producer surplus across different sectors and technology groups and estimate the changes in total system welfare.
- User level: We examine the economic impact of flexibility provision for decentralized user groups, accounting for their diverse characteristics and behaviors.

By focusing specifically on the wholesale electricity market, we isolate and quantify the effects of market-oriented provision of decentralized flexibility, while excluding potential gains from balancing and intraday markets and abstracting from distribution grid constraints. Moreover, we limit our analysis to the changes in marginal electricity generation costs, interpreted as wholesale electricity prices, without considering other components of the end-user electricity price such as taxes, levies, and network charges.

Our results show that decentralized flexibility has a negligible impact on the average wholesale electricity price level, consistent with existing literature. However, flexibility significantly reduces price volatility by flattening the residual demand curve, with the magnitude of this effect varying according to the type and degree of flexibility. This dynamic also leads to decreased market-driven RES curtailment and, consequently, lower CO_2 emissions. At the sectoral and technology level, we observe a redistribution of economic surplus from producers to consumers. Additionally, the results highlight the cannibalization between flexible assets with decentralized flexibility exerting competitive pressure on centralized assets such as batteries. Although total system welfare improves only slightly, consumers as an aggregated group benefit from reduced electricity procurement costs, irrespective of whether they provide flexibility. Notably, road transport flexibility demonstrates a greater potential for welfare gains compared to decentralized heating. At the user level, in the transport sector, we find a high and increasing range of average electricity costs across heterogeneous mobility clusters as flexibility grows, driven by differences in charging and parking behaviors that shape their flexibility potential. In contrast, within the heating sector, average electricity costs across various building types tend to converge with increased flexibility, particularly through the use of additional thermal storage. The study also indicates potential cannibalization between decentralized flexible options, such as EVs and heat pumps, as their flexibility strategies intersect and compete for low-cost electricity.

The paper is structured as follows: Section 2 describes the modeling approach, focusing on the flexibility characteristics of decentralized heating systems and EVs. Section 3 presents the case study, outlining the energy system dispatch under various flexibility use cases and detailing the underlying assumptions. Section 4 analyzes the impacts of decentralized flexibility on electricity prices, CO_2 emissions, and the redistribution of welfare between producers and consumers, with particular attention to differences across technology groups and user types. Section 5 addresses the broader implications of our findings, as well as their limitations. Finally, Section 6 summarizes the main findings and suggests directions for future research.

2. Enhanced modeling of decentralized flexibility

To address the research questions posed in this study, we extend the existing DIMENSION modeling framework (Richter, 2011) to incorporate a more detailed representation of flexibility in the decentralized heating and road transport sectors. These enhancements focus specifically on Germany, where the adoption of technologies such as EVs and heat pumps is assumed to be growing. By capturing the behavior of heterogeneous end-user groups in these sectors, the enhanced model allows us to study how varying degrees of flexibility influence electricity price formation and the redistribution of economic gains between producers and consumers. For end-user sectors in other European countries, the model relies on existing methodologies as described in Helgeson and Peter (2020) and Helgeson (2024).

DIMENSION is a European energy system model that integrates multiple energy carriers across various sectors such as energy, transport, industry, and buildings.[1] In the energy sector, the model simulates a wide array of technologies, such as conventional and renewable power plants, energy storage systems like batteries and pumped hydro storage (PHS), electrolyzers, combined heat and power (CHP) plants, and district heating systems. For the industry sector, the model incorporates exogenously defined demand pathways for each industrial branch, corresponding to the energy carriers they consume (EWI/ITG/FIW/ef.Ruhr, 2021). The model also includes a limited degree of demand-side management (DSM), reflecting the potential for flexible energy consumption in certain industrial processes (Virtuelles Institut, 2022). The building sector is divided into two categories. The first category captures exogenously defined demand for district heating and electricity used for lighting, information and communication technologies. The second category models demand for heating, cooling, and cooking, which is particularly relevant for our analysis of decentralized flexibility. The detailed modeling approach for decentralized heating technologies is further elaborated in Section 2.1. In the transport sector, DIMENSION distinguishes between road and non-road transport modes (e.g., rail, aviation, shipping). Non-road transport is represented by exogenously defined demand pathways for each energy carrier. However, road transport is modeled with greater granularity to capture the heterogeneous charging behaviors and flexibility potential of EVs. The detailed methodology for modeling road transport is provided in Section 2.2. In the following sections, we present the specific enhancements made to the DIMENSION model, focusing on the representation of end-user heterogeneity and decentralized flexibility potential, particularly in the decentralized heating and road transport sectors. These improvements enable us to analyze the complex interactions between decentralized technologies and the broader energy system.

2.1. Decentralized heating

This subsection outlines our approach to modeling decentralized heating technologies, specifically focusing on heat pumps in both residential and commercial buildings.[2] The development of the building stock is modeled using the EWI building stock simulation tool (EWI, 2023a), which generates development pathways based

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[1] A graphical overview of the model's structure can be found in Appendix A.

[2] Note that our enhancements in this study are limited to space heating and hot water. For a detailed description of the modeling approach for cooling and cooking, please refer to Helgeson (2024).

on key indicators such as historical building stock data, renovation rates, demolition rates, and technological advancements. The tool categorizes buildings by type, renovation level, and installed heating systems. Simulations are carried out based on annual assumptions for heating system installations, replacements, and construction as well as demolition rates. The output includes metrics such as the projected number of heating systems and final energy demand for each building type.

In this model, five building types are defined, each reflecting different levels of passive building mass storage - a key factor influencing flexibility potential. In the residential sector, buildings are categorized into three groups: unrefurbished, refurbished, and new buildings, based on energy efficiency standards defined by KfW (2024). "Unrefurbished" refers to buildings without any energy efficiency classification, while "new" buildings comply with KfW efficiency classes 40 and 40+. Refurbished buildings represent those with intermediate energy efficiency levels. By 2030, the simulation estimates that approximately 20.5 million residential buildings will exist in Germany, with 33% unrefurbished, 62% refurbished, and 5% newly constructed.[3] For the commercial sector, buildings are categorized by insulation levels into two groups: non-insulated and insulated. By 2030, 71% of the 2.1 million commercial buildings are projected to be non-insulated, while 29% are expected to be insulated.[4]

We further differentiate between two types of heat pumps: air-source heat pumps (ASHPs) and ground-source heat pumps (GSHPs). These distinctions are based on differences in their coefficients of performance (COPs), which affect the relationship between electricity input and heat output and thus their flexibility potential (Rinaldi et al., 2021). By combining the five building stock categories with the two heat pump types, we define ten building types. Based on the simulation outcomes, the total demand for space heating and hot water is projected to reach 471 TWh for residential buildings and 124 TWh for commercial buildings by 2030.[5] The annual heat demand for each building type is distributed hourly using weather- and country-specific demand profiles from the when2heat dataset (Ruhnau, 2022). The share of heat demand, including space heating and warm water, to be met by heat pumps in each building type is calculated based on the number of installed units, as shown in Table 1. In line with the German government's target, we assume approximately 6 million heat pumps to be installed in Germany by 2030 (BMWK, 2022b). Across all building types, ASHPs make up 80% of the total installed capacity, while GSHPs account for the remaining

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[3] The simulation of the residential building stock is based on data from Heitkoetter et al. (2020) and aligned with the WP+|WN scenario from EWI (2023b).

[4] The commercial building stock simulation is based on the ENOB database and covers only heated or cooled buildings. More details can be found at https://www.datanwg.de/home/aktuelles/.

[5] Building sector simulation is conducted in line with the current refurbishment targets (EWI, 2023a) and follows the current literature (Holm et al., 2021; Kemmler et al., 2021; Repenning et al., 2023).

20%. These assumptions are based on a linear interpolation of the observed technology distribution trends in Germany between 2012 and 2022 (BWP, 2023).

Table 1: Number of heat pumps and share of total heat demand by building type

Building type	**Building group**	**Heat pump type**	**Building condition**	**Number of heat pumps**	**Share of heat demand**
Res1 ASHP	Residential	ASHP	Unrefurbished	1364062	4%
Res2 ASHP	Residential	ASHP	Refurbished	2740057	8%
Res3 ASHP	Residential	ASHP	New	550977	2%
Res1 GSHP	Residential	GSHP	Unrefurbished	341016	1%
Res2 GSHP	Residential	GSHP	Refurbished	685014	2%
Res3 GSHP	Residential	GSHP	New	137744	0%
Total				5818870	16%
Com1 ASHP	Commercial	ASHP	Non-insulated	470434	5%
Com2 ASHP	Commercial	ASHP	Insulated	188530	14%
Com1 GSHP	Commercial	GSHP	Non-insulated	117609	1%
Com2 GSHP	Commercial	GSHP	Insulated	47133	4%
Total				823706	24%

Note: The shares of heat demand shown in this table include the total demand for both space heating and warm water across all building types.

In addition to the passive storage potential, insulation levels affect the COPs of installed heat pumps. Heat pumps serve both space and water heating needs, with water heating accounting for around 20% of the total heat output in older buildings and 40% in newer buildings due to better insulation. Depending on the refurbishment status, heat pumps are paired with either floor/surface heating or radiators. As a result, the COPs vary across building types, as shown in Table 2, which outlines the annual average COPs for each heat pump and building type combination.

Table 2: Annual average COP by heat pump technology and building type

Building type	**Space heating**		**Warm water**	**Annual average COP**	
	Floor/surface	**Radiator**	**-**	**ASHP**	**GSHP**
Res1	0%	80%	20%	3.3	4.5
Res2	40%	40%	20%	3.4	4.7
Res3	45%	5%	50%	3.5	4.9
Com1	15%	70%	15%	3.4	4.7
Com2	15%	70%	15%	3.4	4.7

Note: The hourly, weather-dependent COPs of the heat pumps are based on the when2heat dataset (Ruhnau and Muessel, 2022). The average annual COPs are derived for the weather year 2015, based on the assumptions regarding the heat sinks.

Equations

To model decentralized heating in the buildings sector, we assume that each of the ten defined building types, $b \in B$, meets a fixed share of the overall heating demand. This is represented by a constant parameter α_b, which assigns a specific share of the total demand to each building type.[6] Decentralized heating technologies, $a \in A_{Heating}$, are matched to the appropriate building types using the matching set $a \in B_a$, and, in each case, heat pumps are supplemented by an electric heating rod as backup and thermal storage, which includes both active water tanks and passive building mass storage.[7] Depending on its size, thermal storage can also accommodate additional water tanks, enabling more flexible operation of the heat pumps.

The equilibrium constraint, as formulated in Equation (1), ensures that the heating supply, $P^{th,out}_{d,h,a}$, from heating technologies a, matches the exogenous heat demand profile at all times. This also accounts for the endogenously optimized storage input, $P^{th,in}_{d,h,a}$. The heat demand profile is calculated by multiplying the annual heat demand of each building type, I^{th}_b, with the corresponding normalized heat demand profile $dp^{th}_{d,h,b}$.

$$\sum_{a \in B_a} (P^{th,out}_{d,h,a} - P^{th,in}_{d,h,a}) = I^{th}_b * dp^{th}_{d,h,b} = I^{th} * \alpha_b * dp^{th}_{d,h,b} \qquad \forall d \in D \wedge h \in H \wedge b \in B \tag{1}$$

The electricity input required for heat generation via heat pumps, $P^{el,in}_{d,h,a}$, is calculated by factoring in the temperature-dependent COP, represented as $\eta_{d,h,a}$. Each heat pump technology is linked to its own time series for the COP, as shown in Equation (2).

$$P^{el,in}_{d,h,a} = \frac{P^{th,out}_{d,h,a}}{\eta_{d,h,a}} \qquad \forall d \in D \wedge h \in H \wedge a \in A_{HP} \tag{2}$$

The thermal storage level is determined by summing the previous hour's storage level (adjusted for storage losses, γ) with the net thermal storage feed-in, which is multiplied by the efficiency $\eta_{d,h,a}$, as shown in Equation (3). The storage levels between the last hour of one day and the first hour of the next are connected as per Equation (4). Storage capacity is capped by the installed capacity, C^{th}_a, adjusted by the volume factor, vf_a, as formulated in Equation (5). The daily balance of thermal storage is calculated by summing the endogenous storage feed-in and feed-out.

$$E^{th,level}_{d,h+1,a} = E^{th,level}_{d,h,a} * (1-\gamma) + P^{th,in}_{d,h+1,a} * \eta_{d,h,a} - P^{th,out}_{d,h+1,a} \qquad \forall d \in D \wedge h \in H \wedge a \in A_{thStorage} \tag{3}$$

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[6] The total heating demand is distributed across various installed heating technologies, including gas, oil, biomass, and electricity, as detailed in Appendix B, with the electricity demand further divided among the building types equipped with heat pumps, as shown in Table 1.

[7] The heat pumps are sized to satisfy 80% of the peak heat demand, with the remaining 20% handled by electric heating rods serving as auxiliary capacity.

$$E^{th,level}_{d+1,h,a} = E^{th,level}_{d,h,a} * (1-\gamma) + P^{th,in}_{d+1,h,a} * \eta_{d,h,a} - P^{th,out}_{d+1,h,a} \qquad \forall d \in D \land h = H \land a \in A_{thStorage} \tag{4}$$

$$E^{th,level}_{d,h,a} \leq C^{th}_{a} * vf_{a} \qquad \forall d \in D \land h \in H \land a \in A_{thStorage} \tag{5}$$

To evaluate the effects of varying degrees of flexibility, the volume factor for thermal storage is adjusted across different use cases as described in Section 3.2.

2.2. Road transport

This subsection outlines our modeling approach to account for the charging behavior of EVs within the dispatch model. We focus exclusively on passenger EVs, while light-duty and heavy-duty EVs are modeled using simplified, aggregated demand profiles. The central objective of this modeling approach is to account for heterogeneous charging patterns. Rather than applying average charging costs to all vehicles, we propose that unique cost structures should be applied exclusively to vehicles capable of responding to price signals, enabled by smart meters and user participation in demand-side flexibility. Flexibility in this context refers to the ability of vehicles to adjust their charging in response to wholesale electricity price fluctuations, offering potential cost-saving opportunities. A critical factor influencing this flexibility potential is the variation in driving and parking patterns among EV users. These patterns create varying opportunities for vehicles to shift their charging times, directly affecting their capacity to provide system-oriented flexibility. For instance, EVs with longer parking durations can offer more flexibility than those with shorter or more sporadic parking periods. Thus, our model enhancement aims at incorporating this heterogeneity to accurately capture the diverse flexibility contributions of different EVs. A fundamental challenge arises between the bottom-up approach, which models each vehicle individually, and the top-down approach, which uses aggregated demand profiles. To bridge this gap, we introduce ten distinct mobility clusters that capture different charging behaviors and flexibility patterns. These clusters vary based on the proportion of home, public, and workplace charging, as well as the flexibility to shift demand according to parking durations. This clustering approach enables us to capture diverse mobility behaviors while maintaining computational efficiency.

Modeling of different mobility clusters and flexibility potentials

Electricity demand and potential flexibility of electric vehicles are driven by their driving patterns. For Germany, two primary surveys capture mobility behavior of households: *Mobility in Germany (MiD)* (infas et al., 2018) and the *German Mobility Panel (MOP)* (KIT - Institut für Verkehrswesen, 2021). Leveraging this data, we build upon the methodologies presented by Arnold et al. (2023) and Kröger et al. (2023). First, we employ data from around 300,000 daily trip chains, incorporating information about the arrival time, duration of stays, specific parking locations, settlement type, and electricity consumption during the driving time. Based on this data, individual charging profiles are computed for different combinations of workplace, home or public charging of each daily trip chain. We assume that the charging process begins upon parking and ends either when a new trip begins or the battery is fully charged. Depending on seven different settlement types (urban, rural, semi-urban etc.), different possible charging profiles are weighted and combined to one single profile.[8] As a result, each trip chain is transformed into charging profiles considering the different possibilities to start a charging process at different locations.

To capture the heterogeneity of home charging, we perform a k-medoids clustering based on home parking profiles. Thus, each charging profile is assigned to one mobility cluster. A total of ten mobility clusters are defined, with all individual charging profiles aggregated for each cluster. The charging profiles are then scaled to match the electricity demand of the number of EVs in the use cases presented in Section 3.2.

We further compute both positive and negative flexibility potentials for each cluster. Positive flexibility refers to the ability to reduce charging power (i.e., shifting or delaying charging). This potential is defined as the portion of home charging within the scaled charging profile of each cluster. In contrast, negative flexibility refers to the possibility of shifting charging to another time compared to the initial charging profile, allowing an increase in charging power at specific times. The potential is computed by aggregating the potential charging power of all cars parked at home and subtracting the initial charging profile. Both positive and negative flexibility profiles are intersected with the home parking time series of the cluster center following Arnold et al. (2023).

The results, illustrated in Figure 1, show that the ten distinct mobility clusters exhibit significant heterogeneity in their charging times, charging intensity, and flexibility potentials. For instance, mobility cluster 6 shows a dispersed charging pattern throughout the weekend, while mobility cluster 4 has concentrated midday charging. Conversely, mobility clusters 5 and 10 predominantly charge during the evening hours. Table 3 shows the distribution of the total number of EVs across the defined mobility clusters.

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[8] Based on infas et al. (2018), we assume that profiles containing home charging are weighted with 90% and 42% in urban cities and rural areas respectively. Other settlement types are assigned intermediate weighting factors.

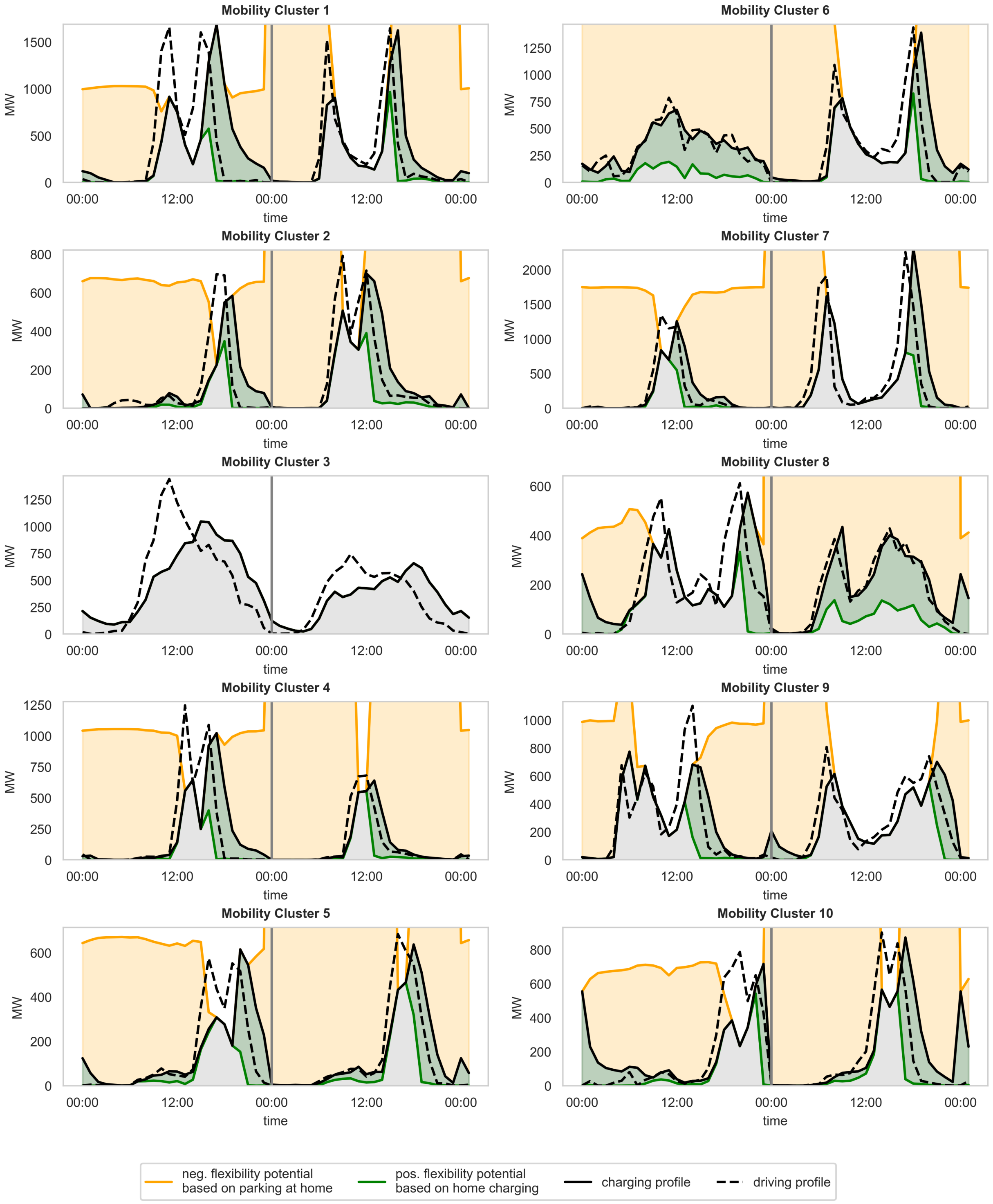

Figure 1: Charging and flexibility profiles for different mobility cluster

Note: Each mobility cluster is characterized by distinct driving and charging patterns, as well as flexibility potentials. One weekend day and one weekday are shown at an hourly resolution, separated by a gray line, with the y-axis representing the total electricity demand.

For 2030, we assume that the total number of passenger EVs reaches 15 million according to BMWK (2022b), with a total annual electricity demand of approximately 34 TWh[9]. This electricity demand remains constant across all use cases. EVs are assigned to the different clusters in proportion to their annual charging demand.

Table 3: Distribution of EVs across mobility clusters MC1 to MC10

	MC1	**MC2**	**MC3**	**MC4**	**MC5**	**MC6**	**MC7**	**MC8**	**MC9**	**MC10**
Absolute [million]	1.97	0.87	2.31	0.86	0.83	1.93	2.24	1.14	1.71	1.10
Relative [%]	13.2	5.8	15.4	5.7	5.5	12.9	15.0	7.6	11.4	7.4

When addressing future flexibility potential, we recognize that only a fraction of home chargers may be equipped with smart meter technology, and only a limited number of users may be willing to provide flexibility, as noted by Agora and FfE (2023). Additionally, Muessel et al. (2022) emphasizes the risk of overestimating the flexibility potential of EVs if one relies solely on overall charging profiles and aggregated flexibility potentials. Considering these factors, we apply a conservative reduction to both the positive and negative flexibility potentials, using a factor of 0.56. Furthermore, we assume that only 25% of all EVs in 2030 will be equipped for bidirectional charging, consistent with the assumptions in Agora and FfE (2023).

Equations

In the following, we present the key equations for the road transport module. Depending on the use case (see Chapter 3), an EV, denoted by a, is classified as either passive ($a \in A_{noFlexCars}$), flexible ($a \in A_{FlexCars}$), or capable of bidirectional charging ($a \in A_{v2gCars}$). Furthermore, EVs are distributed across ten different mobility clusters u, corresponding to the set U_a.

The fundamental constraint, expressed in Equation (6), necessitates that the power consumption by EVs, $P^{el,in}_{d,h,a}$, for each day d and hour h, equals the product of exogenous road transport demand I_a (in km), fuel consumption fc_a (in kWh/km), and the exogenous, normalized demand profile $dp_{d,h,u}$ for each mobility cluster.

$$P^{el,in}_{d,h,a} = I_a * fc_a * \sum_{u \in U_a} dp_{d,h,u} \qquad \forall d \in D \wedge h \in H \wedge a \in A_{noFlexCars} \tag{6}$$

To account for a system-oriented flexible charging, we formulate Equations (7) to (10). These constraints ensure that while an EV can be charged flexibly, the total daily amount of charging must remain constant, assuming users are unlikely to alter their driving habits across multiple days. The first two equations establish the balance of EV's battery storage. First, the daily storage balance is computed as the difference

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[9] Based on Helgeson and Peter (2020), we assume an annual driving distance of 11,200 km per EV and an average energy consumption of 0.2 kWh/km

between the energy inflow and outflow, with the outflow - associated with Vehicle-to-Grid (V2G) - adjusted by the round-trip efficiency η_a of the battery. Second, the balance must equal the product of the exogenous road transport demand, fuel consumption, and the exogenously determined daily demand share, $ds_{d,a}$ (in %), ensuring that EV's storage is balanced within a day.

$$E_{d,a}^{el,daysaldo} = \sum_h (P_{d,h,a}^{el,in} - P_{d,h,a}^{el,out} * \eta_a) \qquad \forall d \in D \land a \in (A_{FlexCars} \lor A_{v2gCars}) \tag{7}$$

$$E_{d,a}^{el,daysaldo} = I_a * fc_a * ds_{d,a} \qquad \forall d \in D \land a \in (A_{FlexCars} \lor A_{v2gCars}) \tag{8}$$

Flexible charging is constrained within positive and negative flexibility limits, computed for each mobility cluster. Although flexible cars generally follow the demand profile $dp_{d,h,u}$, they are allowed to deviate within the upper and lower bounds $flex_{d,h,u}^{neg}$ and $flex_{d,h,u}^{pos}$, respectively.

$$P_{d,h,a}^{el,in} \geq I_a * fc_a * \sum_{u \in U_a} (dp_{d,h,u} - flex_{d,h,u}^{pos}) \qquad \forall d \in D \land h \in H \land a \in (A_{FlexCars} \lor A_{v2gCars}) \tag{9}$$

$$P_{d,h,a}^{el,in} \leq I_a * fc_a * \sum_{u \in U_a} (dp_{d,h,u} + flex_{d,h,u}^{neg}) \qquad \forall d \in D \land h \in H \land a \in (A_{FlexCars} \lor A_{v2gCars}) \tag{10}$$

For use cases involving bidirectional charging, bidirectional charging is only allowed for cars assigned to the corresponding set $A_{v2gCars}$. The V2G potential $flex_{d,h,u}^{v2g}$ in Equation (12) is defined for each mobility cluster as the sum of the positive and negative flexibility potential.

$$P_{d,h,a}^{el,out} = 0 \qquad \forall d \in D \land h \in H \land a \in (A_{FlexCars} \lor A_{v2gCars}) \tag{11}$$

$$P_{d,h,a}^{el,out} \leq I_a * fc_a * \sum_{u \in U_a} flex_{d,h,u}^{v2g} \qquad \forall d \in D \land h \in H \land a \in A_{v2gCars} \tag{12}$$

Additional constraints link the road transport sector to the energy system, accounting for factors such as CO_2 emissions, total energy consumption or variable costs, following the methodology described in Helgeson and Peter (2020).

3. Case study - Energy system dispatch under different flexibility use cases

This section describes the data and use cases employed to assess the impact of varying degrees of decentralized flexibility on electricity prices, producer and consumer rents and total system welfare. Our analysis focuses on the year 2030 and is based on a comprehensive model of the European energy system that captures cross-sectoral interdependencies. While the model covers the entire European electricity system, our primary focus is on Germany, where we introduce a high level of granularity in end-use sectors such as heating and transport. By analyzing different use cases of decentralized flexibility deployment, we aim to provide a comprehensive understanding of how the changes in the degree of flexibility affect different producers and end consumers. Subsection 3.1 describes the underlying modeling data, while subsection 3.2 details the flexibility use cases developed for the heating and transport sectors.

3.1. Data

Our analysis relies on a broad range of data sources to accurately model the European energy system. Sector and fuel specific energy demand is primarily drawn from the Ten-Year Network Development Plan (TYNDP) 2022, published by the European Network of Transmission System Operators of Electricity (ENTSO-E) and European Network of Transmission System Operators for Gas (ENTSOG) (ENTSO-E and ENTSOG, 2022). While optimizing the investment in electricity generation technologies across Europe, our assessment aligns with nuclear capacity trajectories outlined in the TYNDP 2024 report (ENTSO-E and ENTSOG, 2024). Minimum RES targets are also in line with the TYNDP 2024 projections. For cross-border electricity trading, we incorporate net transfer capacities (NTCs) provided in TYNDP 2024. The RES profiles, including wind and solar generation, are based on the ERAA dataset for the weather year 2015 (ENTSO-E, 2022).

For Germany, our primary data source is the dena lead study (EWI/ITG/FIW/ef.Ruhr, 2021), which has been updated to reflect the latest policies and regulations, such as those outlined in the Easter Package (BMWK, 2022b). Additionally, we account for the ongoing dynamics surrounding the coal phase-out, as outlined in the German legislative framework (BMJ, 2022). District heating shares for Germany are derived from the dena lead study, with further details provided in Appendix F. The targeted number of EVs is drawn from the Eastern Package (BMWK, 2022a), while the number of heat pumps is based on announced capacity goals for the year 2030 (BMWK, 2022b). Additional input parameters, such as fuel prices, installed capacities and electricity demand, are presented in Appendices C to E.

3.2. Different use cases for end-use sectors

This subsection outlines various flexibility use cases for the heating and transport sectors. These use cases cover a range of potential flexibility degrees for EVs and heat pumps. We define three levels of flexibility for transport and two for the heating sector, resulting in six distinct flexibility use cases, as illustrated in Figure 2. By examining these combinations, we aim to gain insights into the impacts of flexibility on the overall energy system, various sectors, technologies, and the end-user groups involved.

		Heating sector	
		passive (H0) only with buildings' inertia	**flexible (H1)** with additional heat storage
Transport sector	**passive (M0)** Charging processes follow exogenous profiles	M0/H0 (Reference)	M0/H1 (Heating)
	flexible (M1) charging processes can be shifted according to flexibility potentials	M1/H0 (Transport)	M1/H1 (Interaction)
	flexible + V2G (M2) Like M1, but additionally considering bidirectional charging	M2/H0 (Transport)	M2/H1 (Interaction)

Figure 2: Definition of flexibility use cases

Note: The figure illustrates the defined flexibility use cases for both transport and heating sectors. The rows represent flexibility levels for EVs, while the columns represent different flexibility assumptions for decentralized heating. The names for the use cases are displayed in the gray cells.

The following sections describe the flexibility use cases for the heating and transport sectors in more detail.

3.2.1. Heating sector

In the passive use case (H0), the only flexibility considered is the thermal inertia of buildings, which varies depending on the building type. This thermal inertia is represented by the volume factor of thermal storage, indicating how long the heat pump can supply heat based on the stored energy. For example, a volume factor of two means that fully charged storage can meet the heating demand for two continuous hours. The volume factors for different building types are defined as follows: one hour for unrefurbished buildings, two hours for refurbished buildings, and three hours for newly constructed buildings. In the flexible use case (H1), we introduce additional heat storage to enable more flexible operation of a heat pump. This is achieved by increasing the above described volume factors by one hour for each building type. For example, in new constructed buildings, the volume factor increases from three to four hours, meaning the heat pump can continuously meet demand for up to four hours with fully charged storage.

3.2.2. Transport sector

In the transport sector, we define three distinct use cases based on varying degrees of flexibility in charging behavior: passive charging, flexible charging, and bidirectional charging. In the passive use case (M0), EVs follow a predetermined charging profile with no flexibility in the timing of charging. In the flexible use case (M1), EVs are allowed to shift their charging within the limits of their positive and negative flexibility potentials, as described in Section 2.2. The final use case (M2) incorporates bidirectional charging, allowing vehicles not only to draw electricity from the grid but also to supply it back, thereby providing additional flexibility to the system. Across all flexible use cases, the energy balance must be maintained within each day.

4. Results

To evaluate the impact of varying degrees of flexibility provided by EVs and heat pumps on consumer and producer surplus, we apply the enhanced model to the defined use cases. By analyzing the changes in both surpluses, we aim to assess the overall impact on total system welfare, reflecting the economic benefits of market-driven flexibility provision at the wholesale level. This section is structured as follows: first, in Section 4.1, we present the results for the reference use case, which assumes no flexibility from heat pumps and EVs. In Section 4.2, we explore the changes in market outcomes resulting from different levels of flexibility provision.

4.1. Results without decentralized flexibility

In the absence of flexibility from EVs and heat pumps, the average electricity price - defined as the marginal cost of electricity generation - equals 51.39 EUR/MWh, as depicted in the cyan-colored box plot in Figure 3.[10] The electricity price for each hour serves as a key metric for determining the market values and surpluses for different producer groups, as well as the average electricity costs for consumers, all visualized in Figure 3. The distribution of market values, producer surpluses, and electricity costs is illustrated using box plots for each respective producer and consumer group. Market values for electricity producers - visualized by the blue dots in Figure 3 (top) - are calculated as the average revenue per unit of electricity sold, following the approach of Brown and Reichenberg (2021). Within the dispatch modeling framework, which assumes perfect competition, perfect foresight, and perfect information, short-term producer surplus can be achieved due to sunk investment costs. We define short-term producer surplus as the difference between the total market value (i.e., total revenue from electricity sold) and the sum of variable electricity generation costs over the analyzed period. The average producer surplus - represented by red dots - is calculated by dividing the absolute surplus (in EUR) by the respective production volumes. On the consumer side, we estimate average electricity costs, represented by the blue dots in Figure 3 (bottom).

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[10] Refer to Appendix C for the assumptions regarding fuel prices and EU carbon permits. The model's results remain structurally robust against variations in fuel and emission allowance prices.

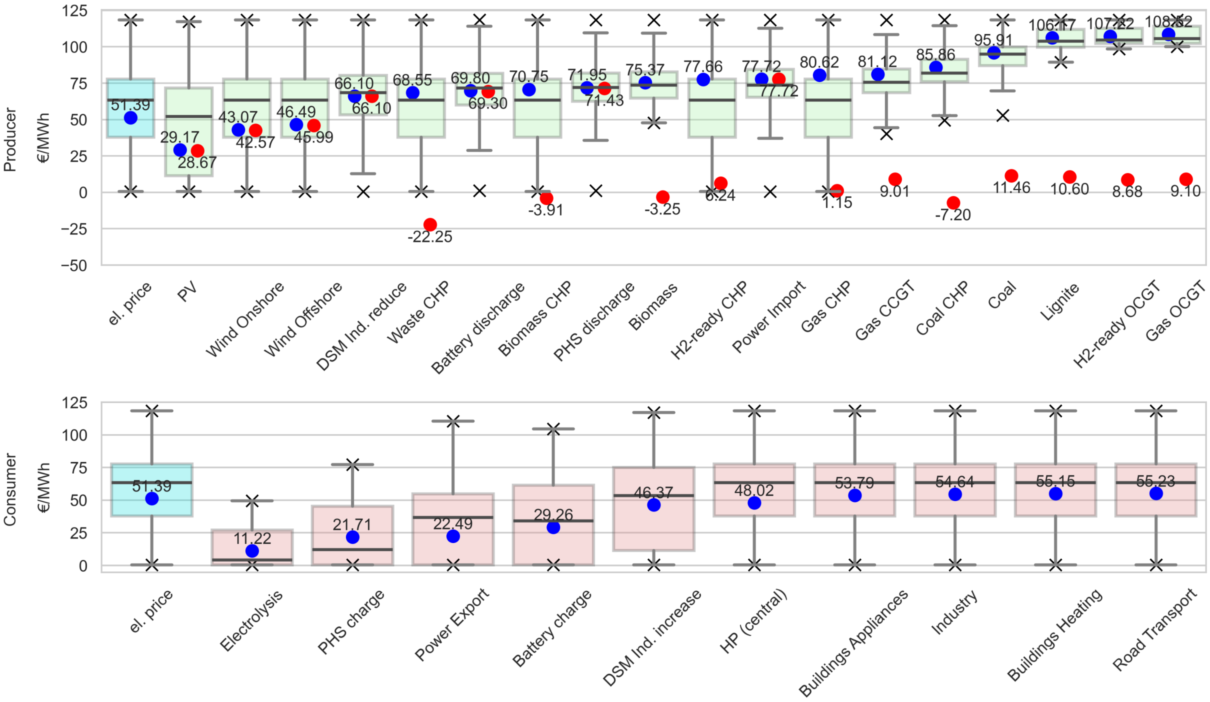

Figure 3: Electricity price, average market values and producer surplus for producer groups as well as average electricity costs for consumer groups in the use case M0/H0

Note: Blue dots reflect the volume weighted market values for producer (top) and average electricity costs for consumer (bottom). Red dots denote the volume weighted short-term producer surplus (top). The box plots visualize the distribution of data points without volume weights. The minimum and maximum values are represented by crosses. The median is depicted by the gray line, while the colored box between the lower and upper quantiles represents 50% of all values. The maximum whiskers are equal or lower to 1.5 times the Inter-Quartile Range.

On the producer side, average market values indicate the merit order function. We observe that PV technologies exhibit the lowest market values, followed by onshore and offshore wind. This is primarily due to the influence of high renewable energy supply or low demand, which can push electricity prices downward. PV technologies tend to have lower market values as peak electricity demand often occurs in the afternoon or after sundown, especially in winter, when solar energy is unavailable. During periods of scarce renewable energy generation, NTCs and energy storage are used to meet electricity demand. In contrast, when renewable generation is low and demand is high, conventional power plants are deployed. Due to high fuel costs and comparably low efficiency, open-cycle gas turbines (OCGTs) have the highest average market values.

In the reference use case without decentralized flexibility, we observe a wide range of producer surpluses across the different technologies used for electricity production. Negative producer surplus values are particularly evident for CHP technologies, which are constrained by heat provision requirements. Biomass facilities also experience negative surplus values due to their assumed baseload generation, although in reality, subsidies prevent negative rents for these plants. Conventional power producers, such as coal, lignite, and gas plants, show comparatively low surplus values, reflecting their marginal position in the merit order and the impact of variable electricity generation costs.

On the consumer side, the order of average electricity prices paid by end-consumers reflects their load flexibility. Consumers with greater flexibility, such as electrolysis plants and batteries, tend to face lower electricity costs. Electrolysis plants can adjust their operations to take advantage of hours with high renewable energy supply or low demand, thereby reducing their costs. Compared to electrolysis plants, batteries exhibit higher average electricity costs due to technical constraints. In contrast, inflexible consumers, such as industrial users and households, face higher electricity costs. In the reference use case without decentralized flexibility, their electricity consumption remains relatively rigid, meaning less ability to avoid periods of high prices.[11] As a result, similar electricity costs are observed across various electricity-based applications for these end-consumers.

Average electricity costs exhibit variation both across and within different consumer groups, particularly in the transport and heating sectors, as illustrated in Figure 4.

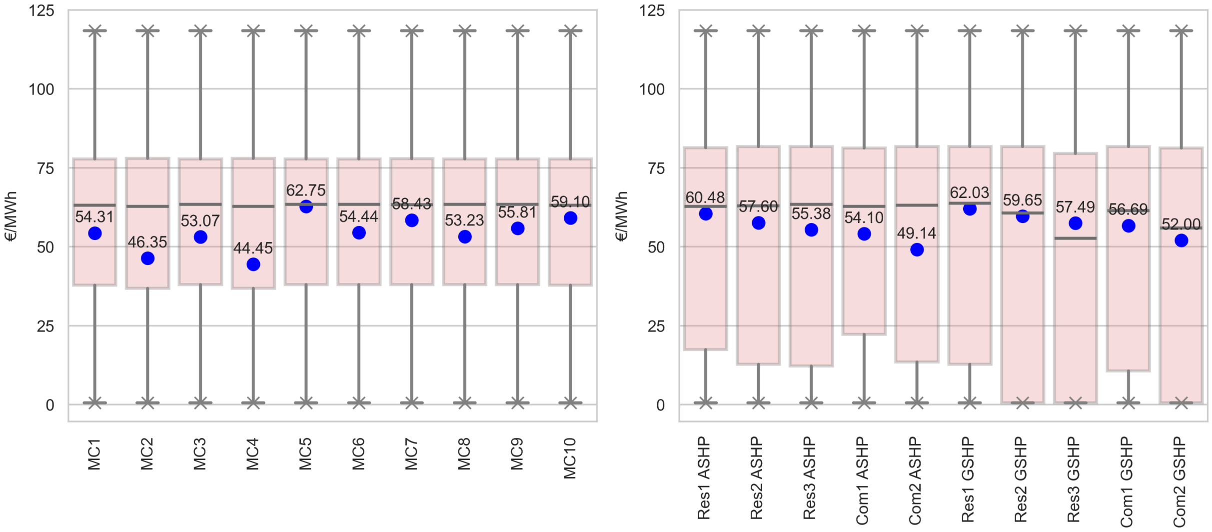

Figure 4: Average electricity costs across the defined mobility clusters and buildings types

Note: The blue dots reflect the volume weighted average electricity costs whereas the box plots visualize the distribution of data points without volume weights. The minimum and maximum values are represented by crosses. The median is depicted by the grey line, while the colored box between the lower and upper quantiles represents 50% of all values. The maximum whiskers are equal or lower to 1.5 times the Inter-Quartile Range (range of the colored box).

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[11] For certain industrial processes, demand-side management (DSM Ind.) is enabled, following Virtuelles Institut (2022).

In the road transport sector (Figure 4, left), the modeling results reveal significant differences in average electricity costs across the defined mobility clusters, with variations of up to 18.30 EUR/MWh. These differences highlight the economic impact of varying charging behaviors. For example, mobility clusters with evening peak charging - such as MC5, MC7, and MC10 - face higher costs due to lower renewable energy availability and increased demand during those hours. In contrast, clusters that charge during midday - such as MC2 and MC4 - benefit from significantly reduced electricity costs, thanks to the comparatively higher availability of renewable energy. Mobility clusters that distribute charging more evenly throughout the day - such as MC6 and MC8 - experience average electricity costs around 54 EUR/MWh.

In contrast, the decentralized heating sector (Figure 4, right) shows less variation in average electricity costs across the defined building types. The differences between residential and commercial buildings are primarily due to their distinct demand profiles. Commercial buildings typically have a smoother daytime demand, leading to lower maximum electricity costs and, consequently, lower average electricity costs compared to residential buildings, where substantial peak demand occurs in the morning and evening. In addition to demand profiles, building-specific factors such as insulation levels, which act as passive thermal storage, also influence electricity costs. The results indicate a slight decrease in average electricity costs with improving building efficiency, suggesting that refurbishments can modestly reduce the operational costs of heat pumps. Furthermore, the type of heat pump installed affects electricity costs. GSHPs tend to face higher average electricity costs compared to ASHPs. However, GSHPs require less electricity for heat generation due to their higher COP, resulting in lower overall annual electricity costs.

4.2. Results with decentralized flexibility

The introduction of decentralized flexibility affects electricity prices, leading to cascading effects on the economic outcomes of various producer and consumer groups. In this subsection, we first examine the effects of the defined flexibility use cases on electricity prices and CO_2 emissions. Next, we present welfare analysis results, focusing on the changes in producer and consumer surplus. Lastly, we assess welfare shifts within the heating and road transport sectors. This subsection, therefore, provides a comprehensive view of decentralized flexibility's impact on system-wide performance, sector- and technology group-specific dynamics, and user group-specific outcomes in the heating and road transport sectors.

4.2.1. Impact of decentralized flexibility on electricity prices and CO_2 emissions

Decentralized flexibility has only a limited impact on wholesale electricity price levels, as shown by the blue dots representing the average level and by the box plots illustrating the distribution in Figure 5. However, while price levels remain relatively stable, decentralized flexibility helps reduce electricity price volatility. The mean 1-hour electricity price volatility, represented by the red dots in Figure 5, is defined as the average absolute price change from one hour to the next (Martinez-Anido et al., 2016).

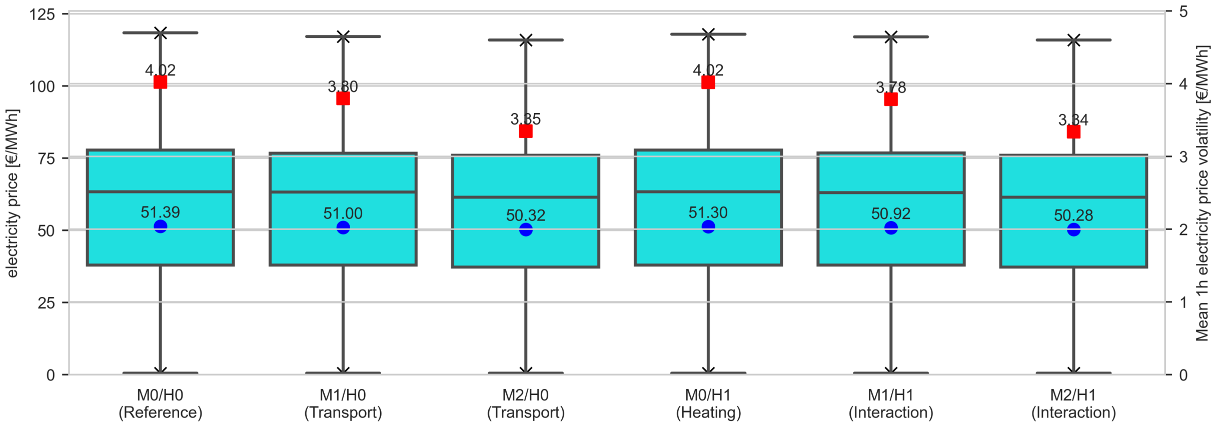

Figure 5: Variation of electricity prices across different flexibility use cases

Note: The blue dots reflect the volume weighted marginal electricity generation costs, while the box plots visualize the distribution of data points without volume weights. The minimum and maximum values are represented by crosses. The median is depicted by the gray line, while the colored box between the lower and upper quantiles represents 50% of all values. The maximum whiskers are equal or lower to 1.5 times the Inter-Quartile Range (range of the colored box).

The system-oriented deployment of decentralized flexibility helps smooth demand fluctuations, flattening the hourly price curve and reducing price volatility. One way flexibility achieves this is through peak load reduction, which decreases the reliance on dispatchable generation. As a result, peak prices are lower across flexibility use cases compared to M0/H0. Although the number and magnitude of peak load hours decline with increased flexibility[12], the maximum prices shown in Figure 5 exhibit only slight changes between the use cases. Another mechanism for reducing price volatility is demand shifting, where increased electricity consumption during hours with zero or negative prices helps smooth price curves further by reducing the frequency of such low-price hours. The overall small decline in average electricity prices suggests that the effects of peak shaving and demand shifting are nearly balanced. Together, these two effects contribute to a smoother residual load function, as illustrated in Figure K.8 in the Appendix. When comparing flexible assets, the results show that EVs, with their higher flexibility potential and longer flexibility windows,

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[12] This can be observed in Figure K.8 in the Appendix, which shows deviation in the residual load curve for each analyzed use case.

have a more substantial effect on price formation than heat pumps. The additional positive flexibility provided by EVs significantly reduces electricity price volatility and lowers the need for dispatchable generation.

Beyond mitigating electricity price volatility, decentralized flexibility also contributes to reducing CO_2 emissions in the energy sector, as shown in Table 4.

Table 4: Changes in national CO_2 emissions under different flexibility use cases, in million tons of CO_2eq

Sector	**M1/H0** (Transport)	**M2/H0** (Transport)	**M0/H1** (Heating)	**M1/H1** (Interact.)	**M2/H1** (Interact.)
Energy	-0.22	-0.37	-0.06	-0.27	-0.40

Note: Only changes in the CO_2 emission in the energy sector are included, while CO_2 emissions in sectors other than the energy sector remain constant across the flexibility use cases.

By lowering peak load hours and shifting demand, flexibility reduces the need for backup power plants and decreases RES curtailment, leading to lower overall CO_2 emissions. As evident from the deviations in the residual load curve from the reference use case (Figure K.8), the most significant impact on CO_2 emissions comes from flexible, and particularly bidirectional charging of EVs. EVs help reduce reliance on fossil-fuel-based backup generation and enable better utilization of renewable energy. In contrast, heat pumps - due to their lower flexibility potential and their tendency to operate during cold afternoon hours where RES availability is lower - show comparatively smaller potential to reduce RES curtailment. Consequently, their impact on CO_2 emission reductions is less pronounced than that of EVs. However, both technologies contribute to improving RES integration.

4.2.2. Welfare analysis for different sectors and technology groups

The introduction of decentralized flexibility through EVs and heat pumps results in a significant redistribution of economic welfare across various producer and consumer groups. The impact of the analyzed flexibility use cases varies greatly depending on the technology and end-use sector. While increased flexibility smooths the electricity price curve, it also leads to substantial reductions in producer surplus for dispatchable power plants, along with corresponding increases in consumer surplus, especially for EV owners. This consumer surplus is defined as the reduction in average electricity costs compared to the reference use case without decentralized flexibility (M0/H0). Figure 6 highlights these shifts across producer and consumer groups for the defined flexibility use cases compared to the reference use case (M0/H0), visually demonstrating how welfare redistribution varies with different levels of flexibility using a detailed heat map.

		M1/H0 (Transport)	M2/H0 (Transport)	M0/H1 (Heating)	M1/H1 (Interaction)	M2/H1 (Interaction)
Producer	Waste CHP	-0.35	-1.70	-0.08	-0.41	-1.76
	Coal CHP	-0.50	-2.43	-0.07	-0.55	-2.58
	Biomass CHP	-0.24	-1.00	-0.04	-0.27	-1.04
	Biomass	-0.35	-1.60	-0.05	-0.42	-1.65
	Gas CHP	-0.46	-2.35	-0.12	-0.55	-2.44
	H2-ready CHP	-0.50	-2.88	-0.10	-0.58	-2.96
	H2-ready OCGT	-0.29	-0.54	0.01	-0.39	-0.56
	Gas CCGT	-0.52	-2.72	-0.10	-0.65	-2.80
	Gas OCGT	-0.42	-0.68	-0.03	-0.58	-0.56
	Lignite	0.02	-0.90	0.05	-0.04	-0.91
	Coal	-0.13	-0.21	-0.03	-0.16	-0.25
	PV	0.14	1.32	0.04	0.16	1.38
	Wind Onshore	-0.24	-0.69	-0.04	-0.24	-0.68
	Wind Offshore	-0.25	-1.02	-0.06	-0.28	-1.04
	Hydro	-0.28	-1.30	-0.06	-0.33	-1.33
	DSM Ind. reduce	-0.65	-1.99	-0.13	-0.53	-1.90
	Battery discharge	-1.10	-4.28	-0.16	-1.26	-4.38
	PHS discharge	-0.84	-3.60	-0.19	-1.00	-3.73
	Power Import	-0.40	-1.54	-0.09	-0.50	-1.64
Consumer	Electrolysis	-0.21	-1.45	-0.01	-0.28	-1.47
	PHS charge	0.13	-0.28	0.01	0.12	-0.25
	Power Export	-0.38	-2.43	-0.11	-0.50	-2.55
	Battery charge	0.40	0.61	0.03	0.38	0.56
	DSM Ind. increase	-0.04	-1.16	-0.05	-0.27	-1.33
	HP (central)	-0.02	-0.71	-0.02	-0.08	-0.77
	Buildings Appliances	0.25	0.59	0.03	0.29	0.59
	Industry	0.20	0.79	0.04	0.23	0.81
	Non Roadtransport	0.20	0.82	0.04	0.23	0.84
	Buildings Heating	0.18	0.38	0.76	0.90	1.01
	Road Transport	3.14	13.68	0.04	3.16	13.61

Figure 6: Changes in average producer and consumer surplus under different flexibility use cases, measured in EUR/MWh

Note: The first column shows average producer surplus of electricity production (or provision) and average consumer costs of electricity consumption (including storage feed-in or exports) in EUR/MWh for the reference use case without decentralized flexibility (M0/H0) in ascending order. The subsequent columns represent the absolute changes in average producer and consumer surplus across different technology and end-user groups for the defined flexibility use cases, compared to the reference use case (M0/H0). The estimated deviations in relative terms are visualized via heatmap.

The road transport sector, with the introduction of flexible (M1/H0) and bidirectional (M2/H0) charging, has the most significant impact on short-term producer surplus. Gas-fired power plants are particularly affected, with producer surplus changes reaching -2.72 EUR/MWh for gas CCGT (Combined Cycle Gas Turbine) plants and -2.35 EUR/MWh for gas CHP plants. In some cases, this represents a 70% reduction, highlighting the detrimental effect of EV flexibility on dispatchable assets. As EVs shift demand away from high-priced peak hours, gas power plants lose out on their ability to generate revenue during these times. This is visually illustrated in Figure 6, where the darkest shades correspond to the largest declines in producer surplus. Increasing flexibility further leads to cannibalization effects on other flexible assets, such as batteries, NTCs, and DSM, which face decreasing surplus. The flattening of the residual load curve due to flexible charging reduces price volatility, thereby limiting the profitability of technologies that store and/or shift electricity. Specifically, battery discharge experiences a significant decrease in producer surplus, declining by 4.28 EUR/MWh with increasing EV flexibility (M2/H1). The reduction in price peaks limits arbitrage opportunities for batteries. Similarly, power imports decrease by 1.54 EUR/MWh as domestic flexibility reduces the need for external electricity during peak demand hours. DSM in industrial processes also suffers a reduction in producer surplus, with decreases of 1.99 EUR/MWh in the M1/H0 use case. This is primarily due to the flattening of electricity prices, which reduces the effectiveness of DSM strategies. On the consumer side, the flexibility provided by EVs results in notable increases in consumer surplus. EV users see surplus gains of up to 13.68 EUR/MWh, reflecting a 30% increase in surplus when bidirectional charging is introduced. In contrast, other (non-flexible) end-use sectors such as non-road transport, industry, and buildings, show more modest increases in consumer surplus, ranging from 0.82 EUR/MWh and 0.59 EUR/MWh. These increases are driven by slightly lower electricity prices due to the additional system-oriented flexibility.

In comparison, the impact of heating sector flexibility (M0/H1) on welfare redistribution is less pronounced. For instance, gas CCGT plants experience a reduction in producer surplus of solely 0.10 EUR/MWh, which is significantly smaller than the impact of transport sector flexibility. Similarly, gas CHP plants see smaller but still notable reductions, with a 0.12 EUR/MWh decline in producer surplus, as shown in Figure 6. Decentralized flexibility from heat pumps also affects other flexible assets. However, due to the seasonal nature of heating demand, the overall impact is less severe compared to the transport sector. For example, PHS and battery discharge reduction only reaches -0.19 EUR/MWh and -0.16 EUR/MWh, respectively. Imports decrease by 0.09 EUR/MWh as domestic flexibility slightly reduces reliance on imported electricity during colder periods. DSM in industrial processes experiences a producer surplus reduction of 0.13 EUR/MWh compared to 1.99 EUR/MWh observed in the bidirectional charging use case (M2/H0). Heat pumps, which mainly provide flexibility during colder periods, have a limited ability to shift demand away from peak hours, resulting in smaller overall welfare gains for consumers. However, the highest gains, reaching 0.76 EUR/MWh, are observed in the heating sector with more flexible heating demand. Gains in other end-user sectors amount to 0.04 EUR/MWh, underscoring the limited potential of heating sector flexibility to substantially reduce electricity price volatility.

When flexibility from both sectors is combined (M1/H1 and M2/H1), the effects on welfare redistribution become more significant. Producer surplus for gas power plants continues to decrease, reaching up to 2.80 EUR/MWh for gas CCGT plants, further reducing profitability as both flexible EVs and heat pumps contribute to a stronger flattening of the residual load curve. Combined flexibility also affects batteries, imports, and DSM. Battery discharge experiences a reduction of 4.38 EUR/MWh, indicating that opportunities for batteries to capitalize on price fluctuations are further diminished in a highly flexible system. Gains from imports decrease by 1.64 EUR/MWh, reflecting the reduced need for external power as domestic flexibility improves the balancing of demand and supply. DSM in industrial processes sees a drop of 1.90 EUR/MWh in producer surplus, underscoring the diminishing returns from DSM strategies in a market with decreasing price volatility. In contrast, consumer surplus increases significantly. The heating sector sees its largest welfare gains when flexibility from both heating and transport is combined, with consumer surplus increasing by up to 1.01 EUR/MWh for buildings heating. However, these gains remain modest compared to the road transport sector, which faces up to 13.64 EUR/MWh in consumer surplus.

Redistribution of total system welfare

Decentralized flexibility significantly reshapes total system welfare, redistributing economic benefits between producers and consumers. Table 5 summarizes the changes in total producer surplus and consumer surplus, categorized by three different technology groups. The last row shows the changes in the total system welfare.

Table 5: Absolute welfare changes for specific producer and consumer groups, in million EUR

Welfare changes	**M1/H0** (Transport)	**M2/H0** (Transport)	**M0/H1** (Heating)	**M1/H1** (Interact.)	**M2/H1** (Interact.)
Total producer surplus	-259.5	-968.5	-43.3	-298.2	-993.9
- Renewable generation	-22.9	159.8	2.7	-13.9	180.0
- Conventional generation	-46.3	-226.9	-10.8	-55.3	-234.3
- Flexible assets	-190.3	-901.4	-35.4	-229.0	-939.6
Total consumer surplus	304.4	1031.0	57.4	353.9	1062.6
- End-use sectors	289.9	1057.0	56.7	340.5	1088.3
- Flexible assets	14.5	-26.0	0.7	13.3	-25.8
Total system welfare	44.9	62.5	14.0	55.7	68.7

Note: The estimated changes in total producer and consumer surplus are derived as the sum of technology and user-specific changes in total producer and consumer surplus for each analyzed flexibility use case compared to the reference use case without decentralized flexibility (M0/H0). Biomass and biomass CHP, hydro, PV, wind onshore, and wind offshore are included in the category renewable generation. Flexible assets encompass technologies used to shift, store, and/or provide electricity, such as DSM through industrial processes, batteries, PHS, and electricity imports/exports via NTCs from neighboring countries. Positive flexibility of these technologies (such as electricity provision or demand reduction) is denoted within the producer group, while negative flexibility (such as electricity infeed, export, or demand increase) is accounted for within the consumer group.

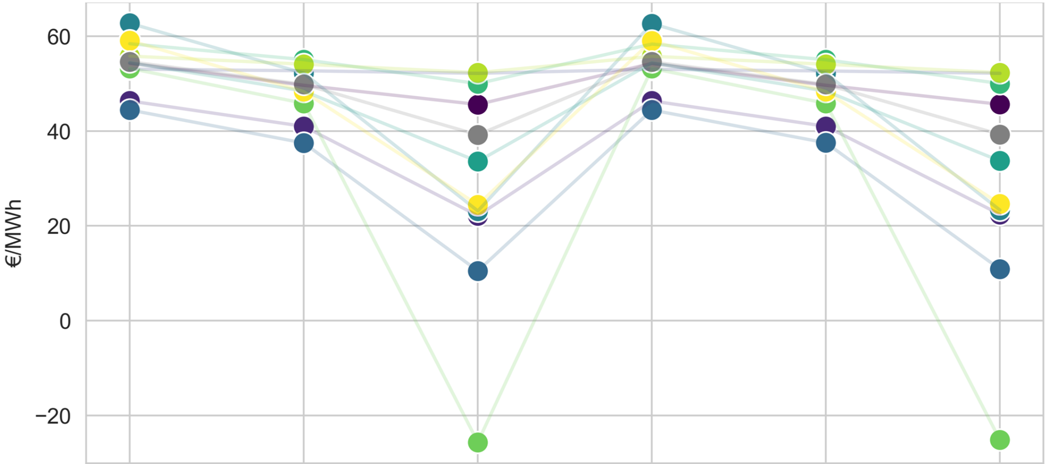
On the producer side, renewable generators benefit from increased flexibility with the introduction of V2G technology, which raises their surplus by up to 180 million EUR. In contrast, conventional power plants face substantial losses, with reductions in producer surplus reaching up to 234 million EUR. These losses are primarily due to fewer price peaks and the reduced need for dispatchable generation during high-demand periods. Flexible assets, such as batteries and DSM, experience mixed results. While these assets provide crucial flexibility, they suffer significant cannibalization as decentralized technologies like V2G erode their profitability. As a result, producer surplus for flexible assets decreases by up to 939.6 million EUR, reflecting the competition between centralized and decentralized flexible technologies for price arbitrage opportunities.
On the consumer side, the introduction of decentralized flexibility leads to notable welfare gains, particularly in the transport and heating sectors. The most significant increases occur when both flexible EV charging and heating flexibility are combined, with consumer surplus rising by up to 1,088.3 million EUR. These gains are driven by consumers' ability to shift their electricity consumption to lower-cost hours, benefiting from reduced price volatility. However, as more flexibility is added to the system, it becomes increasingly difficult for flexible assets to capture value, as their ability to profit from price arbitrage diminishes.
When comparing the impacts across different use cases, decentralized flexibility in the transport sector - through flexible charging and V2G - has a far greater influence on system welfare than decentralized heating. While flexible charging (M2/H0) increases total system welfare by up to 62.5 million EUR, the impact of decentralized heating alone (M0/H1) is modest, with a welfare increase of just 14 million EUR. Even in combined use case (M2/H1), transport flexibility remains the dominant factor, contributing significantly to consumer surplus and system-wide efficiency improvements, while decentralized heating shows a much smaller incremental effect. This highlights the greater potential of transport sector flexibility to drive welfare gains compared to heating, which has a limited ability to shift demand.

4.2.3. Impact of decentralized flexibility on electricity costs for distinct end-user groups

We further analyze the effects of the defined flexibility use cases on average electricity costs for decentralized heating in various building types, as well as on the average electricity costs for different mobility clusters in the road transport sector.

Road transport

In the road transport sector, average electricity costs differ significantly across mobility clusters, as shown in Figure 7.[13]



Mobility Cluster	M0/H0 (Reference)	M1/H0 (Transport)	M2/H0 (Transport)	M0/H1 (Heating)	M1/H1 (Interaction)	M2/H1 (Interaction)
● MC1	54.31	49.65	45.61	54.28	49.66	45.64
● MC2	46.35	40.99	22.15	46.35	41.0	22.42
● MC3	53.07	52.71	52.18	53.04	52.67	52.19
● MC4	44.45	37.49	10.5	44.44	37.53	10.87
● MC5	62.75	52.2	23.14	62.66	52.16	23.32
● MC6	54.44	48.43	33.59	54.4	48.42	33.7
● MC7	58.43	55.07	50.0	58.36	55.04	50.03
● MC8	53.23	45.85	-25.64	53.21	45.85	-25.17
● MC9	55.81	54.11	52.33	55.77	54.09	52.33
● MC10	59.1	48.34	24.44	59.05	48.33	24.62
● All	54.64	49.85	39.19	54.6	49.83	39.28

Figure 7: Changes in average electricity costs across mobility cluster under different flexibility use cases, in EUR/MWh

Note: 'All' denotes the weighted average electricity costs across analyzed mobility clusters.

In the reference use case without decentralized flexibility (M0/H0), average electricity costs range from 44.45 EUR/MWh in MC4 to as high as 62.75 EUR/MWh in MC5, reflecting variations in consumption and charging behavior patterns. When flexible charging is introduced (M1/H0), average electricity costs decrease across all clusters. On average, costs fall to 49.85 EUR/MWh, with the largest reduction seen in MC10, where costs drop from 59.1 EUR/MWh to 48.34 EUR/MWh. By contrast, MC4 shows a smaller reduction, declining from 44.45 EUR/MWh to 37.49 EUR/MWh. The introduction of demand flexibility leads

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[13] Refer to Figure H.4 for supplementary data on the total electricity costs, and Figures J.6 and J.7 for calculated hourly deviations in EV charging compared to the reference use case (M0/H0) for each mobility cluster.

to significant cost reductions, with an average decrease of around 8.7%. When bidirectional charging is employed (M2/H0), the impact on costs varies significantly among clusters. On average, electricity costs drop further to 39.19 EUR/MWh. MC8 shows a substantial deviation, with negative electricity costs of -25.64 EUR/MWh due to the cluster's ability to shift nearly all charging demand across the day. Conversely, MC4, with less flexibility, experiences a much smaller reduction, with costs declining only to 10.5 EUR/MWh. The addition of heat pump flexibility in the M0/H1 use case leads to a slight increase in electricity costs, with average costs increasing to 54.6 EUR/MWh. Similarly, in the M1/H1 and M2/H1 use cases - where both electric vehicle and heat pump flexibility are incorporated - results are mixed. Average costs stabilize around 49.83 EUR/MWh in M1/H1 and 39.28 EUR/MWh in M2/H1. These findings underscore the substantial savings associated with charging flexibility, particularly when V2G is implemented, although the benefits vary greatly across different mobility clusters.

Decentralized heating

In the heating sector, average electricity costs for heat pump operation vary significantly across building types, as shown in Figure 8.[14] While the direction of the effects of additional flexibility from both heat pumps and electric vehicles is consistent across building types, the magnitude of these effects differs. The introduction of thermal storage (M0/H1) results in a general reduction in electricity costs across all building types, with the average cost decreasing from 56.44 EUR/MWh to 54.22 EUR/MWh. Commercial buildings experience a sharper decline, reflecting their high degree of flexibility with additional thermal storage, whereas residential buildings see a more moderate impact. Notably, unrefurbished buildings benefit the most from thermal storage, while more efficient buildings see smaller reductions in costs. When road transport flexibility is introduced (M1/H0), it puts upward pressure on electricity costs, raising the average to 56.58 EUR/MWh. However, this increase is not uniform across building types. Residential buildings show moderate cost increases, while commercial buildings are more strongly affected. The difference in magnitude suggests that commercial entities are more sensitive to the increased competition for low-cost electricity. The impact of added load becomes even more pronounced with the integration of V2G technology (M2/H0), further driving up costs to an average of 57.64 EUR/MWh. Commercial buildings face steeper increases compared to residential buildings, indicating a stronger sensitivity to the added load and potential cannibalization effects between electric vehicles with V2G and heat pump operation. Commercial buildings, which typically benefit from lower electricity costs due to higher daytime consumption, are more heavily

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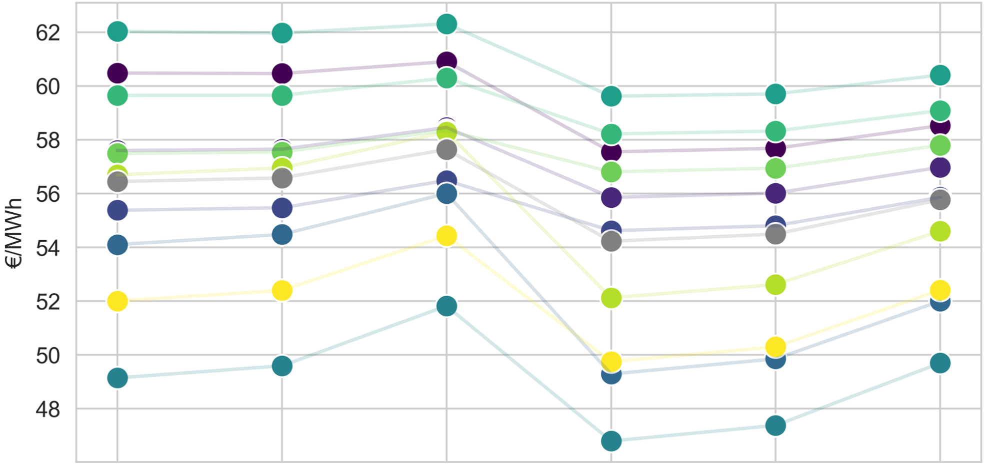
[14] Refer to Figure H.3 for supplementary data on the total electricity costs, and Figure I.5 for hourly deviations in heat pump operation compared to the reference use case (M0/H0) for each building type.

impacted by the competition for low-cost electricity, while residential buildings see a more moderate cost increase. Finally, when both V2G and thermal storage are utilized (M2/H1), electricity costs stabilize somewhat, with the average cost reducing to 55.77 EUR/MWh.



Buildings	M0/H0 (Reference)	M1/H0 (Transport)	M2/H0 (Transport)	M0/H1 (Heating)	M1/H1 (Interaction)	M2/H1 (Interaction)
● Res1 ASHP	60.48	60.46	60.9	57.55	57.68	58.53
● Res2 ASHP	57.6	57.65	58.46	55.85	56.01	56.98
● Res3 ASHP	55.38	55.47	56.48	54.62	54.8	55.86
● Com1 ASHP	54.1	54.48	56.0	49.28	49.85	52.0
● Com2 ASHP	49.14	49.59	51.82	46.79	47.37	49.69
● Res1 GSHP	62.03	61.97	62.31	59.62	59.7	60.41
● Res2 GSHP	59.65	59.65	60.3	58.22	58.32	59.09
● Res3 GSHP	57.49	57.54	58.35	56.8	56.94	57.8
● Com1 GSHP	56.69	56.95	58.29	52.12	52.62	54.6
● Com2 GSHP	52.0	52.39	54.43	49.74	50.29	52.41
● All	56.44	56.58	57.64	54.22	54.49	55.77

Figure 8: Changes in average electricity costs across buildings types under different flexibility use cases, in EUR/MWh

Note: 'All' denotes the weighted average electricity costs across analyzed building types.

This use case shows a greater convergence in prices across building types. For instance, residential buildings using GSHPs (Res1 GSHP) see a cost reduction from 62.31 EUR/MWh in M2/H0 to 60.41 EUR/MWh in M2/H1, illustrating how the additional flexibility from thermal storage offsets the upward pressure from V2G. Commercial buildings, although still affected by V2G, also experience some relief from the cost increases, though to a lesser extent than residential buildings.

5. Discussion

The discussion of the findings spans multiple perspectives, encompassing system-level impacts, sectoral and technological dimensions, and user-specific implications. On the system level, the results indicate that decentralized flexibility has a minimal effect on average wholesale electricity prices but significantly reduces price volatility by smoothing the residual load curve. This aligns with findings by Härtel and Korpås (2021) and Böttger and Härtel (2022), which emphasize flexibility's stabilizing effects on wholesale prices. Flexibility from EVs, especially those with V2G capabilities, reduces both the frequency and intensity of peak demand hours and helps smooth demand fluctuations, with negligible stabilizing effects observed for heat pumps. Although this study focuses on 2030, a year in which electricity price volatility is still moderate, the expected rise in RES penetration could amplify volatility, making decentralized flexibility increasingly valuable.

Our findings also suggest that flexibility contributes to reducing national CO_2 emissions by aligning demand with variable renewable generation and mitigating market-driven RES curtailment. This effect is particularly pronounced in Germany, where fossil fuels are expected to remain a substantial part of the energy mix in 2030. However, as RES shares continue to increase, the potential for flexibility to reduce emissions may lessen, as e.g. seen in the study by Kirkerud et al. (2021) on Norway's RES-dominant energy system.

Although decentralized flexibility improves total system welfare, the welfare gains are relatively modest and vary significantly across the analyzed flexibility use cases. Under high-flexibility assumptions for both EVs and heat pumps, welfare improvements reach up to 68.7 million EUR, suggesting only a moderate system-wide impact. Modeling results further indicate that higher flexibility potential due to longer flexibility windows, such as those of flexible and especially bidirectional EV charging, play a critical role, with the resulting welfare benefits being over three times greater than those achievable with flexible heat pumps only. The observed price stickiness in electricity costs for heat production via heat pumps arises due to low or absent RES generation during cold, dark winter hours, when heat demand is high.

Nevertheless, the quantified impact of flexibility on total welfare may be overestimated, as this study assumes sufficient distribution grid capacity to support market-oriented flexibility provision. In cases where distribution grid congestion occurs, the ability to provide flexibility, and thus achieve related welfare gains, may be restricted. This constraint could vary for EVs and heat pumps depending on regional load profiles and grid infrastructure. Given the findings in Lilienkamp and Namockel (2025), our results may still approximate welfare gains accurately, particularly for a moderate penetration of RES, EVs, and heat pumps in 2030, where distribution grid constraints are less pronounced, even with herding behavior. Nonetheless, such constraints could become increasingly critical with higher penetration rates.

Moreover, by focusing exclusively on the wholesale (day-ahead) market, this analysis omits the welfare gains that decentralized flexibility might yield in balancing and intraday markets. These markets typically exhibit higher price volatility than the day-ahead market due to real-time supply-demand imbalances and the need to compensate for unpredicted RES generation changes. Addressing different markets with decentralized flexibility would introduce opportunity costs, potentially reducing the effects on the day-ahead market.

The introduction of decentralized flexibility redistributes welfare across market participants, shifting surplus from conventional producers to consumers. This shift primarily affects gas-fired power plants, which see reduced surplus due to lower frequency and intensity of peak demand hours. The observed decrease in peak load suggests that flexibility could lower the need for investments in costly backup generation. However, as this analysis relies on a dispatch model that assumes sunk investment costs, it does not capture the potential influence of decentralized flexibility on optimal investment decisions.

Furthermore, our results suggest a potential cannibalization effect among flexible assets, with decentralized flexibility significantly reducing the surplus for centralized assets like batteries. This occurs as decentralized flexibility reduces the demand for off-peak electricity, limiting centralized assets' profitability. Although our analysis highlights potential cannibalization effects, it does not address trade-offs between centralized and decentralized flexibility investments. Here, co-optimization of investment and dispatch decisions would provide a long-term equilibrium, ensuring optimal capacity configuration with profitability of all assets.

For RES generators, the impact on producer surplus is minor, consistent with findings by Bernath et al. (2021), who identified limited impacts on the market values of renewable power plants. Notably, PV producers experience increased surplus across all flexible use cases, particularly with V2G-enabled EVs, which shift demand to better align with daytime solar generation. However, potential network congestion, particularly at the distribution level, could constrain the observed increasing PV integration.

Our modeling results highlight that all user groups benefit from lower electricity costs due to decentralized flexibility, regardless of their participation in flexibility provision. However, this analysis only addresses the procurement component of the end-user electricity price, approximated by marginal electricity generation costs, and excludes taxes, levies, and network fees, which together constitute a significant portion of end-user electricity price (Kienscherf et al., 2023). This omission limits the analysis, as these additional price components may alter the economic gains of flexibility for various end-user groups.

The benefits from decentralized flexibility provision vary significantly by user group, with flexibility potential largely determining cost savings. In the road transport sector, the range of the observed average electricity costs across mobility clusters increases with increasing flexibility. Charging flexibility - especially with V2G capabilities - yields more substantial savings for EV owners with more frequent and longer parking periods. Within the building sector, we observe that introduction of additional flexibility through thermal storage leads to a convergence of electricity costs across building types. Commercial buildings, due to their load profiles with less pronounced evening peaks, benefit more from additional thermal storage. However, they are also more affected by the introduction of V2G, as the additional flexibility from EVs increases competition for low-cost electricity during off-peak hours. This analysis, however, does not account for the costs of providing flexibility, such as e.g. investments in smart meters or bidirectional charging. Some consumers may benefit from flexibility investments without bearing associated costs, while others can bear costs but realize minimal benefits. For user groups with minor cost savings, the net gains from flexibility may be negligible after factoring in these expenses. The profitability of flexibility provision is therefore highly dependent on specific consumption patterns and the flexibility windows. For certain user groups, flexibility may be unprofitable once these costs are considered. Our findings highlight the advantage of broader flexibility windows, particularly for EVs, and underline the limitations that heat restrictions and price stickiness in electricity costs for heat production impose on the flexibility potential of heat pumps.

6. Conclusion

As part of the energy transition, the electrification of end-use sectors is essential to achieving climate neutrality. In this context, EVs and heat pumps can play a pivotal role in the future energy system, significantly influencing electricity price formation. The deployment of end-user flexibility not only shapes price dynamics but also brings about considerable redistributional effects within the electricity market. This flexibility could potentially exacerbate inequalities, as certain user groups may benefit disproportionately, while others - particularly producers or less flexible consumers - may experience reduced revenues or higher costs. This paper has analyzed the impact of decentralized flexibility provision across three levels: system, sector and technology, and user-level. Each level provides distinct insights into how flexibility affects the broader electricity system and the redistribution of economic outcomes among various market participants in the wholesale electricity market. This was achieved by enhancing the existing European energy system model DIMENSION with specific focus on Germany, incorporating a high-resolution dispatch for a range of end-consumer groups and flexibility technologies.

6.1. Main results

At the system level, our results show that while decentralized flexibility has a limited impact on average wholesale price levels, it significantly reduces price volatility by smoothing demand peaks and aligning load with renewable energy generation. EVs, due to their larger flexibility windows, contribute more prominently to volatility reduction than heat pumps. This flexibility also facilitates CO_2 emissions reductions by decreasing RES curtailment, underscoring its potential to support a low-carbon energy system as renewable energy shares increase.

At the sectoral and technology-specific levels, decentralized flexibility enhances overall system welfare, generating gains of up to 68.7 million EUR. However, these benefits are unevenly distributed. Conventional generation technologies, particularly natural gas plants, experience reduced revenues due to lower peak prices. RES, particularly solar PV, see modest gains from better demand alignment, while battery storage faces competitive pressure from EV flexibility, leading to a cannibalization effect in the market. The transport sector, with its higher flexibility potential, delivers greater welfare gains than the heating sector, highlighting EVs' significant role in system cost savings. Overall, by lowering peak prices through increased flexibility, the average electricity costs for consumers decrease. However, the magnitude of this effect varies depending on the specific flexibility use case.

At the user level, while consumers as a whole benefit from lower electricity procurement costs, the extent of these benefits differs significantly across user groups and the flexibility use case. These variations are highly dependent on the consumption characteristics and flexibility time windows. In the transport sector, EV owners with greater flexibility potential, such as those who park for extended periods, experience the largest cost savings, especially with V2G capabilities. In the heating sector, commercial buildings with flatter load profiles benefit most from flexibility, while residential buildings see moderate cost changes. The competition introduced by EV flexibility impacts commercial users especially, raising off-peak prices and indicating the potential cannibalization across decentralized flexible assets.

6.2. Future research

Based on our findings, we identify several relevant areas for further investigation. While this work focuses on the market-oriented provision of flexibility, future research should incorporate network constraints - particularly at the distribution level - to capture interactions between decentralized flexibility and grid congestion. The interplay between market-driven flexibility provision and price or volume signals from distribution system operators could create significant challenges in the future, underscoring the need for further investigation. Expanding the scope to include balancing and intraday markets would provide a more comprehensive view of flexibility's overall system benefits, as these markets play a key role in managing renewable variability and maintaining grid reliability. From the end-user perspective, the introduction of multiple markets, along with the associated opportunity costs, would add complexity but also unlocks greater opportunities for profit making. Additionally, exploring the evolution of components in end-user electricity prices - such as taxes, levies, and network charges - would clarify how these factors influence flexibility's financial viability and the savings potential for different user groups. Similarly, while our analysis sheds light on redistribution between end-user sectors and heterogeneous user groups, further research can examine how decentralized flexibility affects different social or income groups, as redistributional impacts could vary significantly across socioeconomic demographics. Lastly, future research can examine whether increasing decentralized flexibility may reduce the need for investments in backup dispatchable capacity, as suggested by the observed decrease in peak prices. In this context, future studies that co-optimize investment and dispatch decisions could provide further insights into optimal flexibility configurations and potential pathways for achieving welfare gains at lower costs.

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Nomenclature

Abbreviations

Table 6: Table of abbreviations

ASHP	Air-Source Heat Pump	MC	Mobility Cluster
CCGT	Combined Cycle Gas Turbine	MiD	Mobility in Germany
CHP	Combined Heat and Power	MOP	German Mobility Panel
Com	Commercial Building	NTC	Net Transfer Capacity
COP	Coefficient of Performance	OCGT	Open Cycle Gas Turbine
DSM	Demand Side Management	PHS	Pumped Hydro Storage
EV	Electric Vehicle	PtH	Power-to-Heat
GSHP	Ground-Source Heat Pump	Res	Residential Building
HP	Heat Pump	RES	Renewable Energy Source
KSG	Climate Protection Act	TYNDP	Ten Year Network Development Plan
LULUCF	Land Use, Land Use change and Forestry	V2G	Vehicle-to-Grid

Sets, parameters and decision variables

Table 7: Sets

Set	Unit	Description
$a \in A$	-	All technologies
$a \in A_{Cars}$	-	All electric vehicles
$a \in A_{noFlexCars}$	-	Electric vehicles that are not flexible
$a \in A_{FlexCars}$	-	Electric vehicles that are flexible
$a \in A_{v2gCars}$	-	Electric vehicles that flexible and capable of bidirectional charging
$a \in A_{Heating}$	-	All decentralized heating technologies
$a \in A_{thStorage}$	-	Thermal storage technologies
$a \in A_{HP}$	-	Heat pump technologies
$a \in B_a$	-	Mapping heating technologies to building types
$a \in U_a$	-	Mapping mobility clusters to electric vehicles
$b \in B$	-	Building types
$d \in D$	-	Days
$h \in H$	-	Hours
$u \in U$	-	Mobility clusters

Table 8: Decision variables

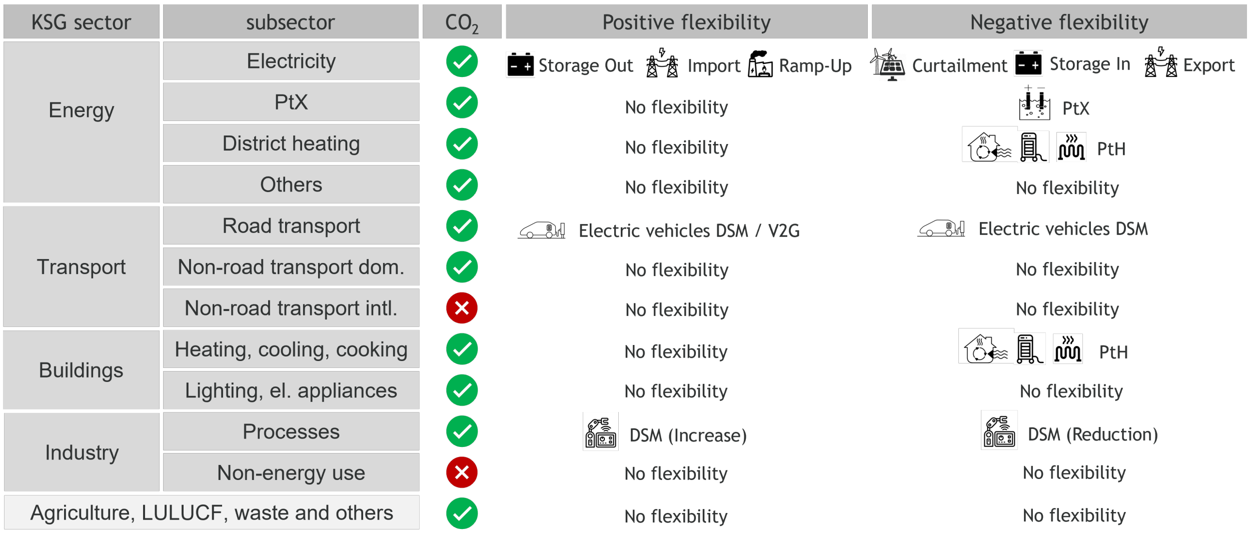
Variable	**Unit**	**Description**
$E_{d,a}^{el,daysaldo}$	MWh_{el}	Net electrical energy consumed by each electric vehicle $a \in A_{Cars}$ on day $d \in D$
$E_{d,a}^{th,daysaldo}$	MWh_{th}	Net thermal energy consumed by each thermal storage technology $a \in A_{thStorage}$ on day $d \in D$
$E_{d,h,a}^{th,level}$	MWh_{th}	Thermal energy stored in thermal storage $a \in A_{thStorage}$ in hour $h \in H$ on day $d \in D$
$P_{d,h,a}^{el,in}$	MW_{el}	Electrical power consumed by each technology $a \in A$ in hour $h \in H$ on day $d \in D$
$P_{d,h,a}^{el,out}$	MW_{el}	Electrical power generated by each technology $a \in A$ in hour $h \in H$ on day $d \in D$
$P_{d,h,a}^{th,in}$	MW_{el}	Thermal power consumed by each technology $a \in A_{Heatin}$ in hour $h \in H$ on day $d \in D$
$P_{d,h,a}^{th,out}$	MW_{el}	Thermal power generated by each technology $a \in A_{Heating}$ in hour $h \in H$ on day $d \in D$

Table 9: Parameters

Parameter	**Unit**	**Description**
α_b	%	Share of heating demand for each building type $b \in B$
C_a^{th}	MW	Installed thermal capacity for each technology $a \in A_{Heating}$
$dp_{d,h,u}$	-	Normalized demand structure for each mobility cluster $u \in U$, hour $h \in H$ and day $d \in D$
$dp_{d,h,b}^{th}$	-	Normalized heat demand structure for each building type $b \in B$, hour $h \in H$ and day $d \in D$
$ds_{d,a}$	%	Relative electricity demand of each electric vehicle $A \in A_{Cars}$ on day $d \in D$
η_a	%	Time-independent efficiency of technology $a \in A$
$\eta_{d,h,a}$	%	Efficiency of technology $a \in A$ on day $d \in D$ in hour $h \in H$
fc_a	kWh/km	Fuel consumption of each electric vehicle $a \in A_{Cars}$
$flex_{d,h,u}^{neg}$	-	Normalized negative flexibility potential for each mobility cluster $u \in U$ in hour $h \in H$ on day $d \in D$
$flex_{d,h,u}^{pos}$	-	Normalized positive flexibility potential for each mobility cluster $u \in U$ in hour $h \in H$ on day $d \in D$
$flex_{d,h,u}^{v2g}$	-	Normalized bidirectional flexibility potential for each mobility cluster $u \in U$ in hour $h \in H$ on day $d \in D$
γ	%	Storage losses for thermal storage
I_a	km	Road transport demand of each electric vehicle $a \in A_{Cars}$
I^{th}	TWh	Total heat demand
I_b^{th}	TWh	Heat demand of each building type $b \in B$
vf_a	$-$	Volume factor (ratio of power and energy) for each thermal storage $a \in A_{thStorage}$

Appendices

A. *DIMENSION sector overview*



KSG sector	subsector	CO_2	Positive flexibility	Negative flexibility
Energy	Electricity	✓	Storage Out Import Ramp-Up	Curtailment Storage In Export
	PtX	✓	No flexibility	PtX
	District heating	✓	No flexibility	PtH
	Others	✓	No flexibility	No flexibility
Transport	Road transport	✓	Electric vehicles DSM / V2G	Electric vehicles DSM
	Non-road transport dom.	✓	No flexibility	No flexibility
	Non-road transport intl.	✗	No flexibility	No flexibility
Buildings	Heating, cooling, cooking	✓	No flexibility	PtH
	Lighting, el. appliances	✓	No flexibility	No flexibility
Industry	Processes	✓	DSM (Increase)	DSM (Reduction)
	Non-energy use	✗	No flexibility	No flexibility
Agriculture, LULUCF, waste and others		✓	No flexibility	No flexibility

Figure A.1: DIMENSION sector overview

Note that the column 'CO_2' reflects weather CO_2-emissions of the specific subsector are accounted for total CO_2 emissions of the corresponding sector, as defined in the Climate Protection Act (KSG).

B. *Heating shares for individual heating*

Table B.1: Heating shares for decentralized heating in Germany in 2030

Gas	Oil	Biomass	Hydrogen	Electricity
53%	18%	7%	0%	22%

Note that each value reflects the share of heat that is covered by a certain fuel type. The assumptions follow EWI/ITG/FIW/ef.Ruhr (2021).

C. *Commodity and CO_2 prices*

Table C.2: Commodity prices and EU Carbon Permits in 2030

Oil	Coal	Lignite	Gas	CO_2
46.8 EUR/MWh	8.6 EUR/MWh	5.5 EUR/MWh	21.5 EUR/MWh	88 €/t

Note that prices for oil, coal and gas are based on the "Stated Policies" scenario in IEA (2023), while the lignite price follows ENTSO-E and ENTSOG (2024). The assumed price of emission allowances refers to the ICIS Modeling group, with its results visualized in Pahle et al. (2022).

D. *Installed capacities*

Table D.3: Installed capacities in Germany per generation group and corresponding efficiencies

Technology group	**Capacity in GW**	**Efficiency in %**
Waste CHP	1.3	17
Lignite	8.7	-
- Lignite no CHP	8.0	32-35
- Lignite CHP	0.7	37-41
Coal	8.0	-
- Coal no CHP	6.0	37-46
- Coal CHP	2.0	39-45
Gas	40.2	-
- Gas OCGT	5.6	28-40
- Gas CCGT	5.0	40-60
- Gas CHP	19.6	42-56
- H2-ready OCGT	6.7	40
- H2-ready CHP	3.3	56
Wind Offshore	30.0	100
Wind Onshore	115.0	100
Photovoltaic	215.0	100
Biomass	8.0	-
- Biomass no CHP	3.5	39
- Biomass CHP	4.5	31-49
Hydropower	5.3	100
DSM (Industry)	1.8	100
Battery	13.1	90
PHS	9.9	76
Electrolysis	10.0	68

The capacities of lignite and coal are determined based on the coal phase-out trajectory outlined in BMJ (2022). Targets for Wind Onshore, Wind Offshore, and PV capacities align with the objectives defined in the Easter Package (Bundesrat, 2022). Initial capacities for gas-fired power plants are sourced from the list of power stations as of April 15th, 2024, as published by the BNetzA (BNetzA, 2024). Subsequently, an additional 10 GW of H2-ready power plants are assumed by 2030, as per the guidelines outlined in The Federal Government (2024). We assume that one third of these capacities is built as CHP.

E. *Electricity demand*

Table E.4: Electricity demand in TWh

KSG sector	**subsector**	**2030**
Energy	PtX*	19.8
	District heating*	12.8
	Others	4.6
Transport	Road transport*	51.6
	Non-road transport (domestic)	19.6
Buildings	Heating, cooling, cooking*	54.2
	Lightning, el. appliances	202.7
Industry	Processes	263.1
Total net demand	-	629.3

Note that endogenously determined electricity demand is labeled with *. The respective demand is depicted based on the reference use case (M0/H0).

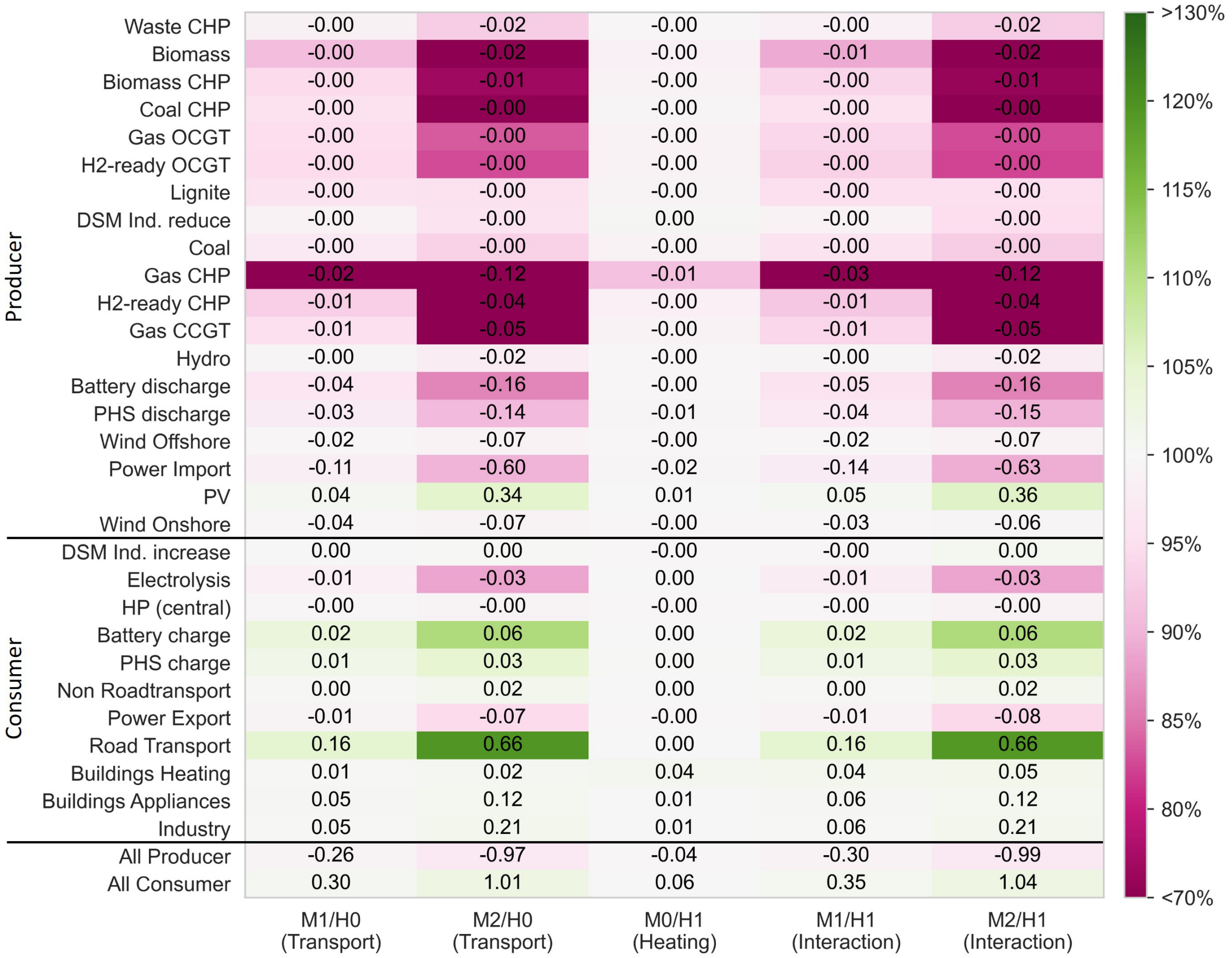
F. ***Heating shares for central heating (district heat)***

Table F.5: Heating shares for central heating (district heat)

Technology/Fuel	**2030**
Biosolid	6.9%
Biogas	1.6%
Waste	13.9%
Industrial heat	6.8%
Solar thermal	1.6%
Geothermal heat	2.4%
Hydrogen	1.0%
Gas	49.7%
Heat pump	4.2%
Coal	8.3%
Lignite	3.5%
Total	100.0%

Note that each value reflects the share of heat that is covered by a certain fuel type. The assumptions follow EWI/ITG/FIW/ef.Ruhr (2021) but are slightly adjusted to account for current developments.

G. *Welfare redistribution*



		M1/H0 (Transport)	M2/H0 (Transport)	M0/H1 (Heating)	M1/H1 (Interaction)	M2/H1 (Interaction)
Producer	Waste CHP	-0.00	-0.02	-0.00	-0.00	-0.02
	Biomass	-0.00	-0.02	-0.00	-0.01	-0.02
	Biomass CHP	-0.00	-0.01	-0.00	-0.00	-0.01
	Coal CHP	-0.00	-0.00	-0.00	-0.00	-0.00
	Gas OCGT	-0.00	-0.00	-0.00	-0.00	-0.00
	H2-ready OCGT	-0.00	-0.00	-0.00	-0.00	-0.00
	Lignite	-0.00	-0.00	-0.00	-0.00	-0.00
	DSM Ind. reduce	-0.00	-0.00	0.00	-0.00	-0.00
	Coal	-0.00	-0.00	-0.00	-0.00	-0.00
	Gas CHP	-0.02	-0.12	-0.01	-0.03	-0.12
	H2-ready CHP	-0.01	-0.04	-0.00	-0.01	-0.04
	Gas CCGT	-0.01	-0.05	-0.00	-0.01	-0.05
	Hydro	-0.00	-0.02	-0.00	-0.00	-0.02
	Battery discharge	-0.04	-0.16	-0.00	-0.05	-0.16
	PHS discharge	-0.03	-0.14	-0.01	-0.04	-0.15
	Wind Offshore	-0.02	-0.07	-0.00	-0.02	-0.07
	Power Import	-0.11	-0.60	-0.02	-0.14	-0.63
	PV	0.04	0.34	0.01	0.05	0.36
	Wind Onshore	-0.04	-0.07	-0.00	-0.03	-0.06
Consumer	DSM Ind. increase	0.00	0.00	-0.00	-0.00	0.00
	Electrolysis	-0.01	-0.03	0.00	-0.01	-0.03
	HP (central)	-0.00	-0.00	-0.00	-0.00	-0.00
	Battery charge	0.02	0.06	0.00	0.02	0.06
	PHS charge	0.01	0.03	0.00	0.01	0.03
	Non Roadtransport	0.00	0.02	0.00	0.00	0.02
	Power Export	-0.01	-0.07	-0.00	-0.01	-0.08
	Road Transport	0.16	0.66	0.00	0.16	0.66
	Buildings Heating	0.01	0.02	0.04	0.04	0.05
	Buildings Appliances	0.05	0.12	0.01	0.06	0.12
	Industry	0.05	0.21	0.01	0.06	0.21
	All Producer	-0.26	-0.97	-0.04	-0.30	-0.99
	All Consumer	0.30	1.01	0.06	0.35	1.04

Figure G.2: Changes in total producer and consumer surplus under different use cases, measured in billion EUR

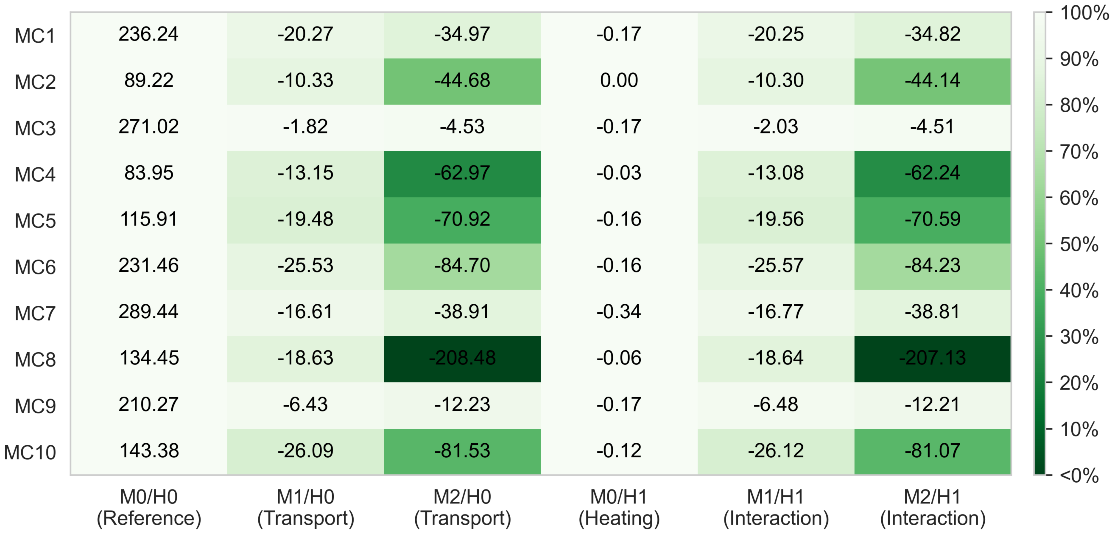
Note: The columns represent the absolute changes in the total producer and consumer surplus across different technology and end-user groups for the defined flexibility use cases, compared to the reference use case (M0/H0). The estimated deviations in relative terms are visualized via heatmap.

H. Changes in total electricity costs

	M0/H0 (Reference)	M1/H0 (Transport)	M2/H0 (Transport)	M0/H1 (Heating)	M1/H1 (Interaction)	M2/H1 (Interaction)
Res1 ASHP	195.51	-0.16	1.04	-8.27	-8.00	-5.61
Res2 ASHP	356.59	0.09	4.36	-8.81	-8.14	-3.05
Res3 ASHP	74.02	0.08	1.22	-0.81	-0.63	0.55
Com1 ASHP	60.09	0.30	1.76	-4.76	-4.27	-2.17
Com2 ASHP	143.95	0.97	6.67	-6.17	-4.86	1.12
Res1 GSHP	40.09	-0.05	0.14	-1.42	-1.39	-1.01
Res2 GSHP	71.61	-0.04	0.61	-1.48	-1.40	-0.63
Res3 GSHP	15.17	0.00	0.18	-0.14	-0.12	0.07
Com1 GSHP	12.39	0.04	0.29	-0.89	-0.81	-0.44
Com2 GSHP	29.94	0.16	1.15	-1.17	-0.92	0.13

Figure H.3: Changes in total electricity costs across building types under different flexibility use cases, in million EUR

Note: The first column represents the total electricity costs for heat pump operation. The subsequent columns represent the absolute changes in total electricity costs across different building types for the defined flexibility use cases, compared to the reference use case (M0/H0). The estimated deviations in relative terms are visualized via heatmap.



	M0/H0 (Reference)	M1/H0 (Transport)	M2/H0 (Transport)	M0/H1 (Heating)	M1/H1 (Interaction)	M2/H1 (Interaction)
MC1	236.24	-20.27	-34.97	-0.17	-20.25	-34.82
MC2	89.22	-10.33	-44.68	0.00	-10.30	-44.14
MC3	271.02	-1.82	-4.53	-0.17	-2.03	-4.51
MC4	83.95	-13.15	-62.97	-0.03	-13.08	-62.24
MC5	115.91	-19.48	-70.92	-0.16	-19.56	-70.59
MC6	231.46	-25.53	-84.70	-0.16	-25.57	-84.23
MC7	289.44	-16.61	-38.91	-0.34	-16.77	-38.81
MC8	134.45	-18.63	-208.48	-0.06	-18.64	-207.13
MC9	210.27	-6.43	-12.23	-0.17	-6.48	-12.21
MC10	143.38	-26.09	-81.53	-0.12	-26.12	-81.07

Figure H.4: Changes in total electricity costs for different mobility clusters under different flexibility use cases, in million EUR

Note: The first column represents the total electricity costs for EV charging. The subsequent columns represent the absolute changes in total electricity costs across different mobility clusters for the defined flexibility use cases, compared to the reference use case (M0/H0). The deviations in relative terms are visualized via heatmap.

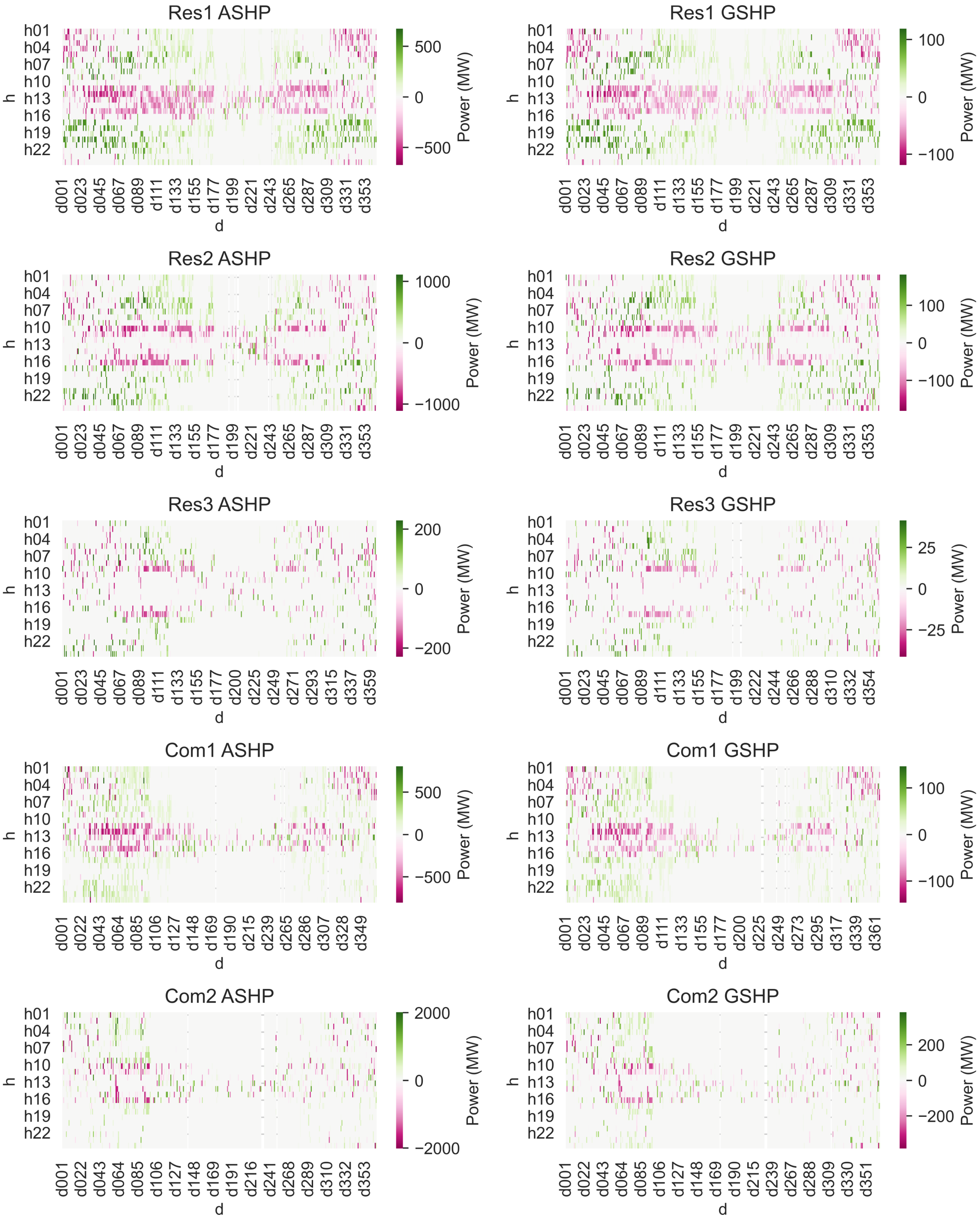


Figure I.5: Flexibility decisions across different building types for the use case M0/H1 compared to M0/H0

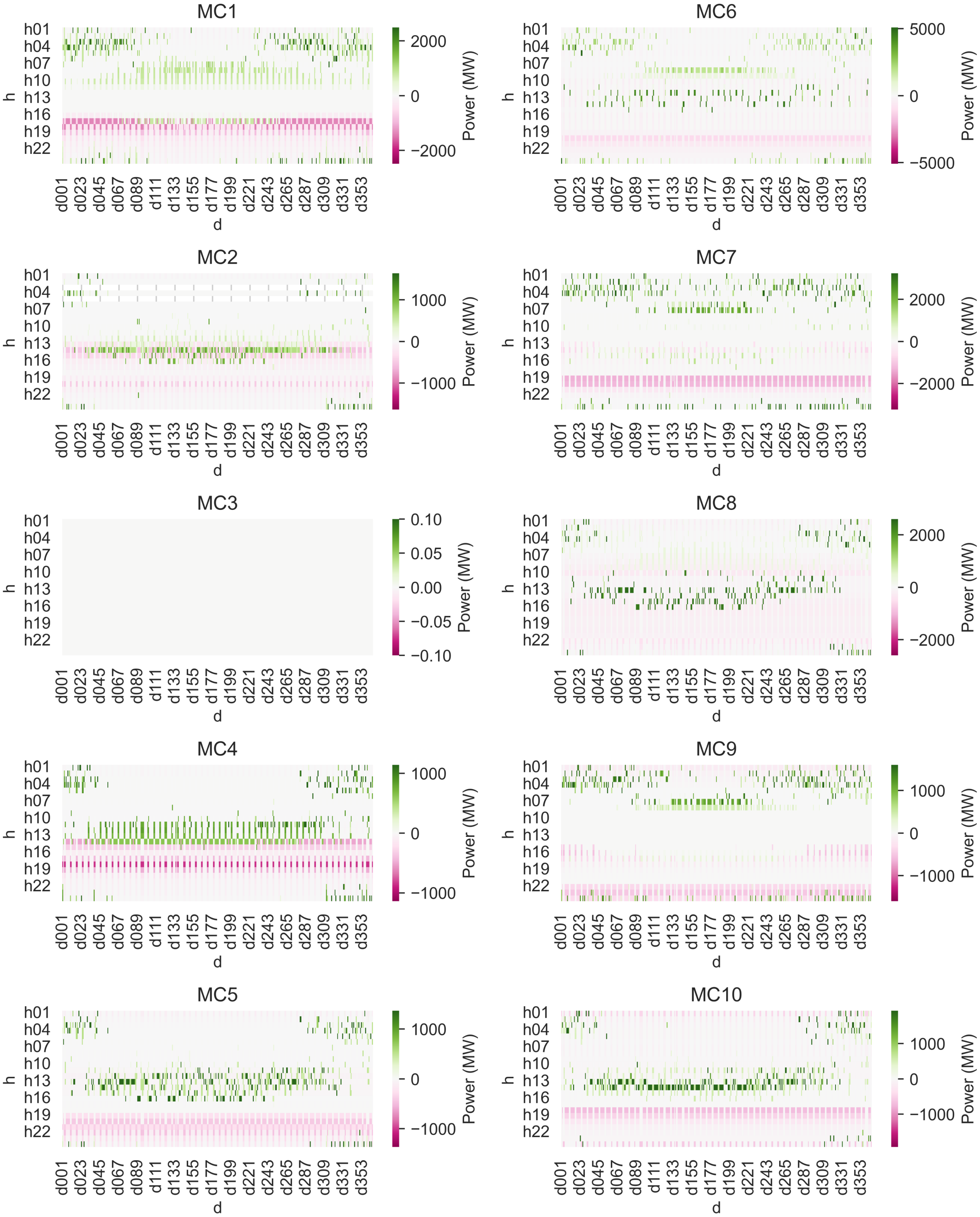
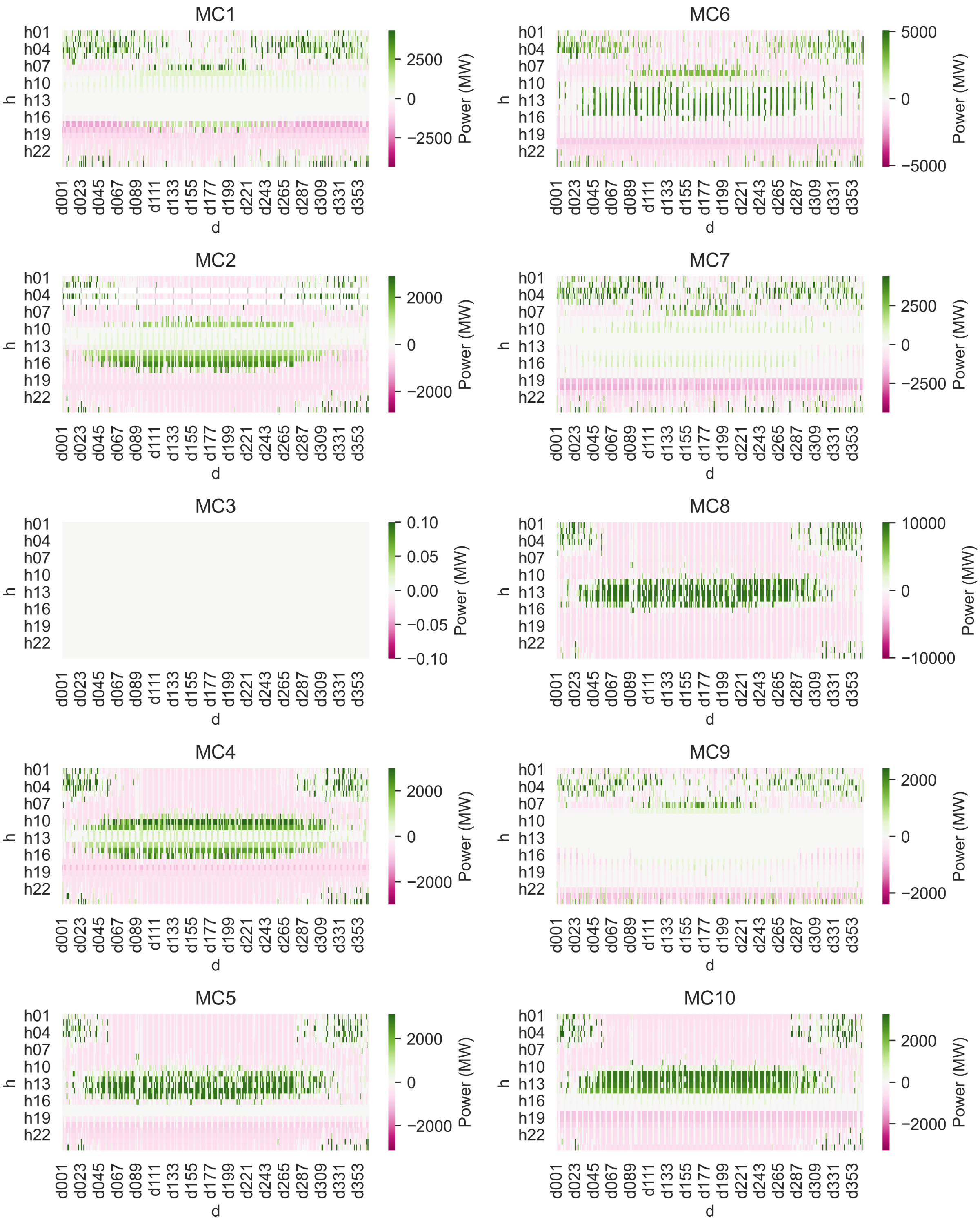


Figure J.6: Flexibility decisions across different mobility clusters for the use case M1/H0 compared to M0/H0



MC1

MC2

MC3

MC4

MC5

MC6

MC7

MC8

MC9

MC10

Figure J.7: Flexibility decisions in the road transport sector for the use case M2/H0 compared to M0/H0

*K. **Residual load duration curve***

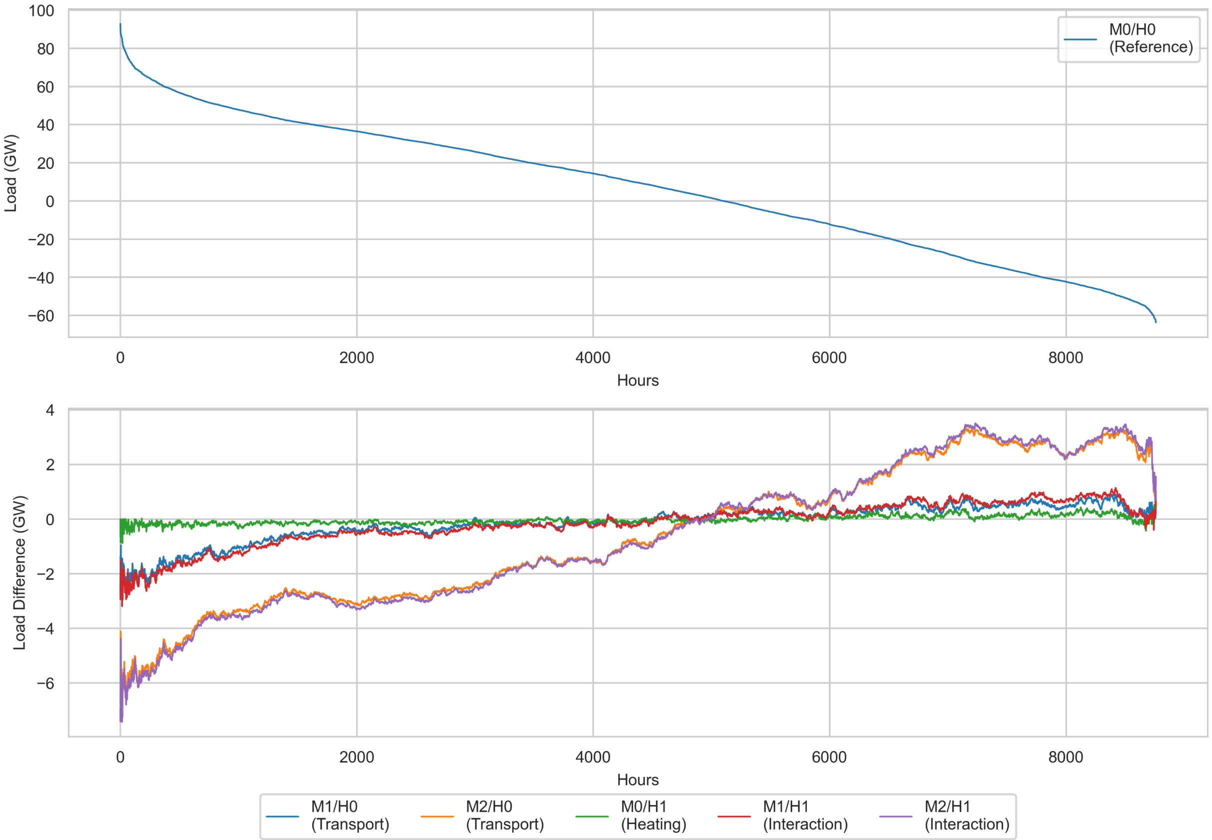


Figure K.8: Residual load duration curve in the reference use case M0/H0 (above) and its deviations in flexibility use cases (below)

Note that we define the residual load by subtracting the renewable electricity generation from the inflexible as well as flexible demand within the heating and transport sectors. We calculate the deviations by subtracting the load duration curve values of the reference use case (M0/H0) from those of the other use cases.