Short Study

The Value of Decentral Flexibility

Or: What is the cost of a delayed flexibilization of heat pumps, electric vehicles, and home storage systems?

This is a machine-translated version of a study originally published in German. The original is available at neon.energy/mehrwert-flex

March 2024

On behalf of the German Verband der Elektro- und Digitalindustrie (ZVEI e.V.)

Authors:
Anselm Eicke (eicke@neon.energy)
Lion Hirth (hirth@neon.energy)
Jonathan Mühlenpfordt (muehlenpfordt@neon.energy)

The Value of Decentral Flexibility

Or: What is the cost of a delayed flexibilization of heat pumps, electric vehicles, and home storage systems?

The original study is available at neon.energy/mehrwert-flex

The machine-translated version of this study is available at neon.energy/decentral_flex

Neon Neue Energieökonomik is an energy industry consultancy based in Berlin. As a boutique, we have specialized in sophisticated quantitative and economic-theoretical analyses of the electricity market since 2014. With consulting projects, studies and training courses, we support decision-makers with the current challenges and future issues of the energy transition. Our clients include governments, regulatory authorities, grid operators, energy suppliers and electricity traders from Germany and Europe.

Contact:

Neon Neue Energieökonomik GmbH
Karl-Marx-Platz 12
12043 Berlin

Prof. Dr. Lion Hirth
hirth@neon.energy
+49 157-55 199 715

Table of contents

Summary

Approach. in Germany, the number of heat pumps, electric cars, and home storage systems (solar batteries) will increase significantly in the coming years. This will also increase the demand for power plants and distribution grids. However, these new consumption technologies have an inherent flexibility potential, i.e. they can shift electricity consumption to times when power plants and grids are underutilized. Against this backdrop, this study shows the costs that can be saved in the electricity system through such system-beneficial flexibilization without any loss of comfort. Our analyses are based on hourly optimization for a typical household. We also discuss approaches to regulation and market design that create incentives for such flexibilization.

Results. The quantification shows that the system-friendly operation of a heat pump reduces the costs caused in the electricity system by 24% compared to load-driven operation. The costs occurring in the electricity system for charging an electric car are even reduced by more than 70%. An ignorantly charged electric car thus causes three times higher costs in the energy system than an intelligently charged car, not even considering additional revenue potential such as intraday optimization or bidirectional charging. These examples show that delaying the flexibilization of household consumers implies a considerable cost. The importance of meaningful economic incentives is also illustrated by the optimization of self-consumption of home storage systems. Although the optimization of self-consumption that dominates today reduces the electricity bill of the respective households, it achieves almost no benefit for the electricity system. It therefore primarily results in a redistribution of the costs of the electricity system at the expense of other consumers. An intelligently operated solar battery, on the other hand, creates almost seven times more benefit for the energy system in the use case we investigated than with classic self-consumption optimization. Some fear that passing on wholesale prices to household customers, i.e. dynamic electricity tariffs, will put a strain on the distribution grids. Our analyses show that the opposite is true: the market-driven use of flexibility nowadays tends to *relieve* the distribution grid. This means that dynamic tariffs are currently beneficial to the grid and reduce the costs of all other grid customers.

Recommendations. Dynamic electricity tariffs harness the flexibility of household consumers for the electricity market. Although such tariffs are already available today, the slow smart meter rollout is slowing their widespread use. The introduction of grid-friendly signals is much more challenging due to the lack of natural price signals in the distribution grid. In the short term, the introduction of static, time-variable distribution grid fees, i.e. grid fees whose amount is fixed on a calendar basis, seems sensible and feasible to us. Based on our analyses, it is currently unlikely that such charges will create new grid bottlenecks, but they are conceivable in the future. Grid fees should therefore be further developed in the medium term so that they take short-term weather situations into account, have more than just three price levels and, if necessary, be supplemented with additional components, such as situational demand charges.

1 Introduction

New electricity consumers. Heat pumps and electric cars play a decisive role in achieving climate targets in the heating and transport sectors. Home storage systems (solar batteries) are increasingly being installed in combination with solar systems in private households. The connected load of these three types of systems in households is therefore estimated to increase tenfold within this decade: from around 20 GW in 2020 to over 200 GW in 2030 (Illustration 1).

Installierte flexible Leistung

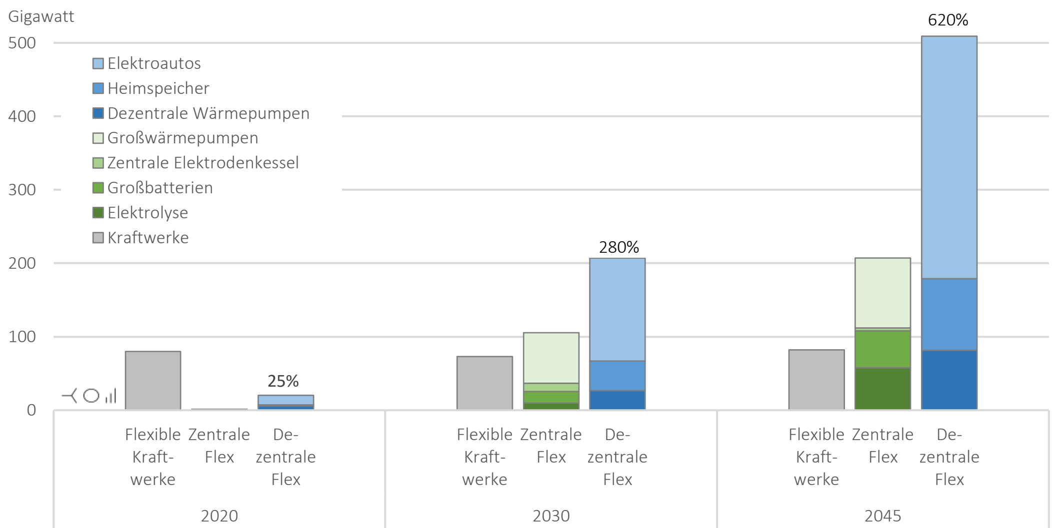

Illustration 1. Expected change in the installed capacity of flexible generators and consumers from 2020 to 2045. Percentages indicate the share of decentralized flexibility in flexible power plant capacity. Own illustration based on the BMWK long-term scenario and own supplementary assumptions.

Concern about peak loads. The rapid expansion of heat pumps, electric cars and home storage systems is having a significant impact on the electricity system. In particular, if the systems are not operated in a way that serves the system, there is a fear of an immense strain on the grids and power plant fleet. For example, if electric cars always charge directly as soon as they are connected to the grid. Particularly in hours when the electricity system is already under the greatest strain - cold winter evenings with low wind generation, when both the power plant fleet and many distribution grids are working at full capacity - heat pumps and electric cars are likely to further increase electricity consumption significantly, while hardly any relief is to be expected from home storage systems. This threatens a large increase in demand for grids and flexible power plants. The associated investments would cause grid fees, electricity prices and financing costs for capacity mechanisms to rise. The scale of the challenge becomes particularly clear when looking at the ratio of decentralized consumers to flexible power plant capacity: while the connected load of heat pumps, electric cars and home storage systems only corresponded to around a quarter of the generation capacity of flexible power plants in

2020, it is likely to exceed power plant capacity by a factor of almost three by 2030 and increase more than sixfold by 2045 (Illustration 1).

Role of decentralized flexibility. However, heat pumps, electric cars and home storage systems in particular have an inherent, i.e. already existing, flexibility potential.

- Solar batteries can draw electricity when grids and power plants have free capacity and feed in electricity when this is advantageous for relieving the electricity system. The same applies, with restrictions, to electric vehicles.
- On average, electric vehicles are driven for less than an hour a day (Nobis & Kuhnimhof, 2018) and only need a fraction of the remaining time to recharge. This makes it possible to schedule charging at a time when the electricity system is under less strain, for example by delaying charging from the evening hours until later at night. In the event of an extreme load on grids or power plants, it is even conceivable to reinject stored electricity (bidirectional charging).
- Heat pumps also have the potential to shift electricity consumption over time. The converted heat can be stored in buffer tanks and by the thermal inertia of the building itself. It is therefore often possible to heat the building by a few (tenths) of a degree in the afternoon and then switch off the heat pump for a few hours in the evening at peak load times without any loss of comfort.

By operating in a way that supports the electricity system, heat pumps, electric cars and home storage systems can make a significant contribution to the integration of wind and solar energy, reduce the need for new power plants and large batteries and reduce the need to expand the distribution grid. For other household electricity consumers such as refrigerators, washing machines and ovens, however, there is little (if any) opportunity to shift electricity consumption over time without a significant loss of comfort.

Smart meters. Flexibility of demand always means adjusting electricity consumption at *a certain point in time* - for example by shifting the load from the evening to the night. To leverage the flexibility potential of heat pumps, electric vehicles, and home storage systems, it is necessary to measure and bill the consumption of at least these devices on a quarter-hourly basis. Political support for the corresponding metering infrastructure is therefore an essential prerequisite. The EU Commission's proposal to reform the EU electricity market, which is currently in the trilogue process, would make it possible to use internal meters for billing (EU Commission, 2023). Until then, smart meters are a *conditio sine qua non* for decentralized flexibility. However, Germany is lagging far behind in the expansion of smart meters compared to the rest of Europe: in 2022, less than one percent of households had corresponding metering systems (ACER, 2022).

Incentives. However, metering infrastructure alone is not enough. The right economic incentives are also needed to ensure that flexible systems are operated sensibly. For flexible consumers to purchase electricity when it is cheap from a grid and market perspective, it must be cheap at that time - and conversely more expensive when the grid and/or power plants reach their capacity limits. This is generally not the case today. With end customer tariffs that charge the same price per kWh throughout the year, there is no incentive to use the existing flexibility potential for the benefit of the electricity system. Rather, batteries are often used today to save taxes and fees by maximizing self-consumption, which benefits individual households, but generates hardly any benefits (or even additional costs) for the electricity system. The long-standing discussion about Section 14a of the German Energy Industry Act (EnWG) shows the challenges and resistance to the introduction of regulatory instruments to make system operation more flexible.

This study. Against this background, this hour discusses the added value of the flexible operation of heat pumps, electric vehicles, and home storage systems. It examines the provision of flexibility for the electricity market and for eliminating bottlenecks in the distribution grid; flexibility for the transmission grid, on the other hand, is not taken into account. To this end, we quantitatively estimate the cost reductions in electricity generation and grids that result from the system-friendly operation of household consumers. We differentiate between the private savings potential and the benefits for the electricity system. The analyses are based on the hourly optimization of the operation of typical system configurations. We estimate the distribution grid costs for parameters of the Berlin distribution grid as an example. We also present and evaluate instruments for regulation and market design that create meaningful incentives for the use of decentralized flexibility.

2 Economic fundamentals

Electricity market and grids. Decentralized consumers can provide flexibility for the electricity market and/or the electricity grids, i.e. they can shift their electricity consumption to hours when (wind and solar) generation is cheap or when the grids are underutilized. We discuss the fundamental economic differences and correlations in this section.

Flex in the electricity market. In the electricity market, flexibility can balance out fluctuations in electricity prices by shifting consumption from hours with high electricity prices to hours with low prices. This reduces costly and emission-intensive electricity generation from gas and coal-fired power plants and makes use of wind and solar power that would otherwise have been curtailed due to negative prices. These economic savings in generation costs are reflected in lower electricity costs for all consumers. Flexibility also reduces the need for secure generation capacity and other flexibility resources such as interconnectors or large batteries.

Market segments. In principle, flexibility can be used in all electricity markets. In this study, we focus on spot markets, more specifically the day-ahead auction. Participation in intraday markets and markets for control and balancing energy is also possible in principle and offers further savings potential. However, we have not taken this into account in this study due to the higher technical requirements of these short-term markets.

System-serving signal: electricity market. The wholesale price is fundamentally a robust and meaningful indicator of the economic added value of flexibility on the spot market because it reflects the marginal costs of electricity generation, including the costs of greenhouse gas emissions, the ramping up and ramping down of power plants and the curtailment of renewable energies. An arbitrage gain of €100/MWh through load shifting therefore generally corresponds to an economic cost saving in electricity generation in the order of €100/MWh. Shifting consumption to hours with more favorable prices therefore almost always makes economic sense. To create operating incentives for flexible consumers that are conducive to the electricity market, it is therefore sufficient to pass on the wholesale price.

Flex in the distribution grid. In addition to the electricity market, decentralized flexibility can also be used to relieve the distribution grid. By reducing the load at times when the grid reaches its design limit, grid expansion can be avoided or delayed. Conversely, in distribution grids with a high feed-in of wind and solar energy, shifting electricity consumption to hours with high feed-back can reduce the need for grid expansion. In contrast to the electricity market, the location where flexibility is provided plays a key role for the distribution grid.

Benefit of load shifting. In a single grid line, such grid relief only occurs during the highest feed-out (in load-dominated distribution grids) or during the highest feed-in (in generation-dominated grids). In all other hours, load shifting does not result in any cost savings in the distribution grid, as no grid costs are incurred apart from line losses, and their relative amount hardly varies over time. However, this strong temporal concentration of grid costs becomes blurred the more grid lines and their connecting elements are considered together. In a larger grid area, the higher the (absolute) residual load, the more likely it is that individual grid elements will be overloaded. There are therefore more hours in which load shifting reduces the probability of grid overload.

Difference: market and network. Illustration 2 uses schematic cost functions to illustrate the main difference between providing flexibility for the electricity market and for the distribution grid. Load shifting for the electricity market is almost always worthwhile because the marginal costs of generation increase relatively continuously. In contrast, the almost flat marginal cost function of the distribution grid over a large area means that load shifting often provides no added value. Load shifting for the distribution grid in hours without grid congestion is even counterproductive, as it prevents the use of flexibility for the electricity market. It should therefore only be carried out if bottlenecks are really to be feared.

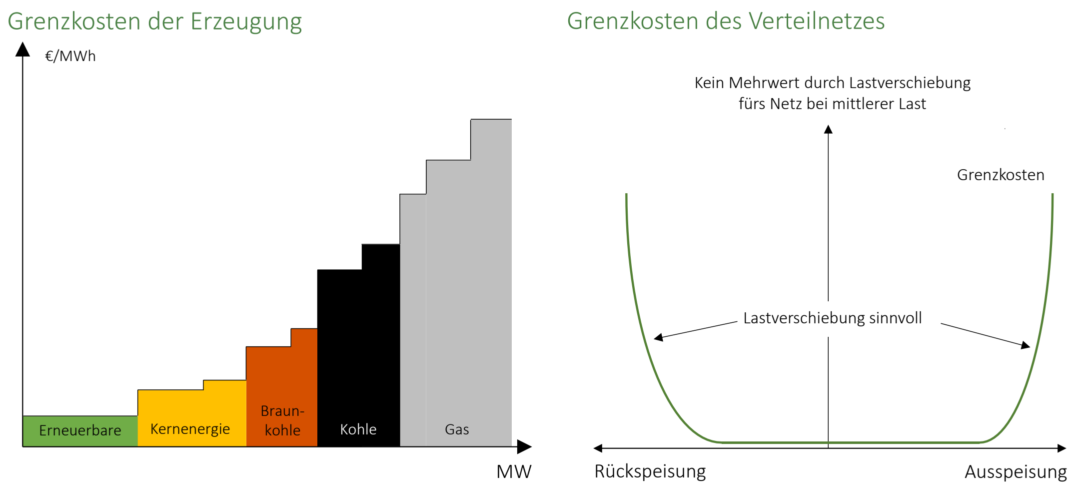

Illustration 2The marginal costs of generation (left) increase more continuously than the marginal costs in the distribution grid (right). Load shifting is therefore almost always worthwhile in the electricity market, but only rarely in the distribution grid.

Challenges in the distribution grid. In contrast to generation, where the wholesale price is a robust indicator of marginal economic costs, there is no comparable price signal in the distribution grid that objectively and comprehensibly reflects the benefits of flexibility for the distribution grid. The function of marginal costs can vary depending on the assumptions made. In addition, the costs are determined with a high degree of uncertainty because the current grid situation at low-voltage level is generally unknown to the distribution grid operators. Real-time load measurements are still the exception today; local grid transformers generally only have a trailing indicator, which is only used to record the annual peak load.

3 Decentralized flexibility in energy system studies

Big Five. Decentralized flexibility plays a subordinate role in Germany's five major energy system studies. These studies, often referred to as the "Big Five", show possible development paths for the German energy system between 2030 and 2050 (Table 1). In addition to the electricity sector, they also cover the consumption sectors, including industrial consumption, the heating sector and the transport sector. Due to the very broad scope, the analyses are partly carried out by linking several individual models for the relevant sectors; overall, the accuracy of detailed questions is naturally rather low.

Methodology. Heat pumps, electric cars and home storage systems are not the focus of any of the five studies. This is also due to the fact that only two of the five studies are based on an hourly-resolved electricity market model (BMWK long-term scenarios and Agora Energiewende). The other studies work with investment models with a lower temporal resolution, in which the mapping of load flexibility is methodologically challenging. In most studies, heat pumps and electric cars at least partially follow the price signals of the electricity market (BMWK, Agora Energiewende, BDI); in the Dena study, they are load-led. The load on the distribution grids is only modeled in the BMWK long-term scenarios.

Table 1. Modeling approaches of the five major energy system models for Germany ("Big Five")

	Electricity market model	Electricity market modeled	Distribution grid modeled
BDI *Climate Pathways 2.0*	BCG	(✓)	✗
BMWK *Long-term scenarios*	FN ISI	✓	✓
Ariadne *Climate neutrality 2045*	PIK	(✓)	✗
Agora Energiewende *Climate-neutral Germany 2045*	Prognos	✓	✗
Dena *Towards climate neutrality*	EMI	(✓)	✗

Results. All five studies anticipate a strong increase in heat pumps and electric cars. Without suitable flexibilization incentives, this would have a significant impact on the overall system. For example, the BDI study estimates that the peak load in the electricity system would increase by almost 60% in 2030 compared to flexible operation. An analysis based on the Agora study states that the market-based curtailment of renewable energies would increase from

32 TWh to 86 TWh (+169%) in 2035 and expensive gas and hydrogen power plants would generate 20 TWh more electricity (Prognos, Öko-Institut and Wuppertal-Institut, 2021). The long-term scenarios also examine the operation of flexible consumers to support the distribution grid. Although this reduces distribution grid costs, it leads to an increase in overall costs because flexibility is then no longer available for the electricity market. The studies are unanimous in their assessment that the flexibility potential of electric cars and heat pumps is orders of magnitude higher than the flexibility potential of conventional consumers.

Agora study. The study published at the end of 2023, which was carried out by the Research Center for Energy Economics on behalf of Agora Energiewende, is closest to our study in terms of content and methodology (Agora Energiewende, 2023). However, one key difference is that the Agora study examines the impact of household consumers on the distribution grids in 2029 and 2035. In terms of methodology, the Agora study is based on a complex distribution grid model, while our study estimates distribution grid bottlenecks based on the residual grid load at the low-voltage level.

4 Modeling

In this chapter, we quantitatively estimate the current economic added value of the flexible operation of heat pumps, electric cars and home storage systems.

4.1 Methodology

Basic approach. We quantify the economic added value of flexible operation in the status quo. We differentiate between the savings for households and the economic benefit that arises from the flexible operation of an additional system ("marginal consideration"). For the calculation, we use an hourly simulation over one year. We assume a typical household with conventional consumption patterns and an average system configuration. Load shifting is only carried out using existing technical storage systems, i.e. without any loss of comfort or additional investment. We determine the added value of each flexible system individually; there is no interaction between the various consumers.

4.1.1 Operating modes, costs, and electricity tariffs

Operating modes. We compare the operation of flexible systems under three operating modes. In *load-controlled operation*, which corresponds to the status quo of the vast majority of households, wholesale prices and the utilization of the distribution grid have no influence on consumption behavior. The operation of the systems is therefore based solely on the user profile. The electric car, for example, charges as soon as it is connected to the charging station until it is fully charged. In *market operation,* the existing flexibility potential is used to benefit from price fluctuations on the wholesale market. The state of the distribution grid, on the other hand, is not considered. In market *and grid-serving operation,* the utilization of the distribution grid *is* taken into account in addition to the wholesale prices. Where possible, flexible consumers are operated when electricity prices are low *and* the grid is free.

Electricity tariffs. The operation of the heat pump, electric car and home storage system is determined by a mathematical optimization problem. To do this, the household minimizes its electricity costs under one of three alternative electricity tariffs. In all cases, the electricity tariff is made up of generation costs, grid charges and taxes, levies and surcharges. We do not take margins for sales and basic costs into account.

- *Load-controlled operation* results from a *fixed price tariff.* Here, the energy price (ct/kWh) is constant throughout the year and reflects the average generation costs, grid fees, taxes, levies and charges.
- We model the *market operation* using the *semi-flex tariff*. This passes on the hourly day-ahead prices to consumers, while the other cost components remain the same throughout the year (with the exception of VAT).

- *Operation in line with the market and grid* results from the *full flex tariff*. In this tariff, in addition to the generation costs, the grid charges are also time-variable in the form of three tariff levels. Illustration 3 visualizes this tariff for two days as an example.

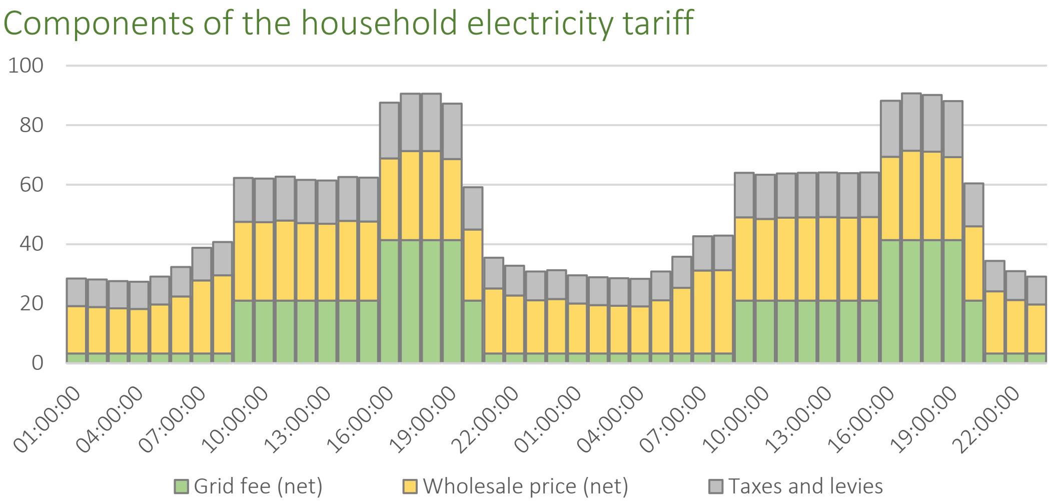

Illustration 3. Visualization of the full flex fare for two exemplary days in September 2021.

Wholesale prices. We use day-ahead prices from 2021 as wholesale prices. In the crisis years 2022 and 2023, electricity prices and price fluctuations were significantly higher, so that an even greater savings potential could be expected, although we do not consider this situation to be representative for the future. If decentralized flexibilities can also react to short-term intraday and balancing energy prices, a significant additional added value can also be assumed. In this respect, our estimates are conservative in several respects.

Grid costs. The costs of the transmission grid are assumed to be time-invariant and amount to 2 ct/kWh in the model. The distribution grid costs are calculated according to the method described in Chapter 2 presented in chapter 2: they increase with the increasing probability of overloading individual grid elements. The hourly difference between withdrawn and fed-in electricity ("residual load") at the low-voltage level of the distribution grid operator Stromnetz Berlin serves as the data basis. We assume that at less than 70% of the annual peak load, no grid elements are overloaded and therefore only line losses are incurred. The grid costs then correspond to the grid losses of 0.5 ct/kWh and the costs of the transmission grid. Furthermore, we assume that at more than 70% of the annual peak load, the distribution grid costs increase linearly with the residual load because the probability increases that individual grid elements will reach their design limit (Illustration 4left). Assuming that the average grid costs correspond to the current grid charges for households of 8.2 ct/kWh, the total grid costs rise to just over 60 ct/kWh in individual hours. In about 70% of the hours, however, the grid costs are only 2.5 ct/kWh (Illustration 4right).

Estimation of grid costs

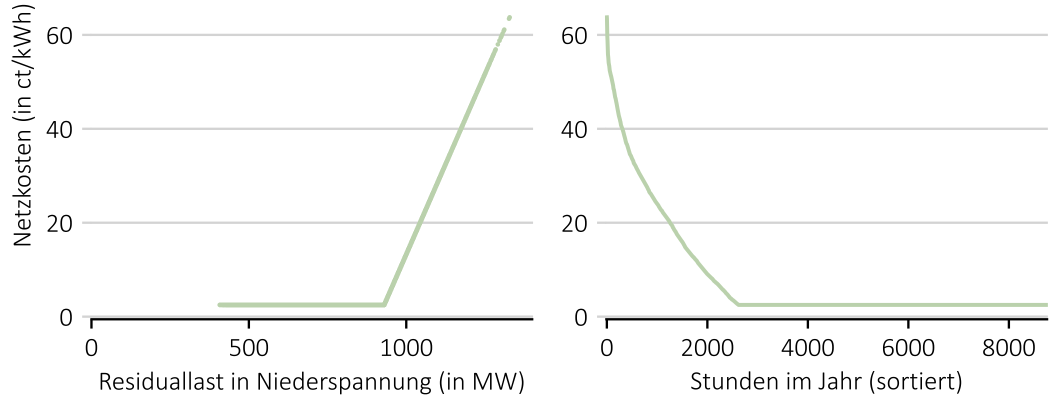

Illustration 4. Estimation of grid costs based on the residual load in the Berlin low-voltage grid in 2021

Static time-variable grid charges. From this time series of grid costs, we create a static time-variable grid charge with three tariff levels (Illustration 5). For this purpose, we minimize the quadratic hourly deviation between grid costs and grid charges under the following constraints:

- There are only three different tariff levels throughout the year.
- The occurrence of fare levels during the course of the day may vary between months, but not within a month. For example, the high fare window may apply from 16:00 to 21:00 in January and from 17:00 to 21:00 in February.
- All working days have the same rate structure, weekend days may have a different one.

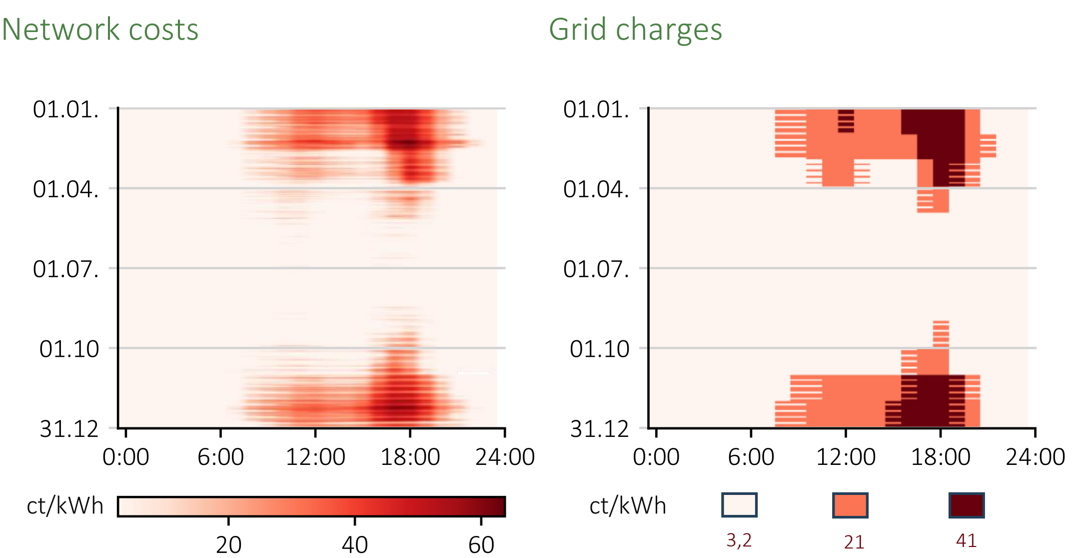

Illustration 5. Grid costs a suitable optimized static time-variable grid charge with three tariff levels

Taxes, levies and surcharges. The taxes, levies and surcharges include electricity tax (2.05 ct/kWh) and VAT (19%), concession levy (1.66 ct/kWh), the surcharges for uniform and atypical grid usage in accordance with Section 19(2) of the Electricity Grid Charges Ordinance (0.417 ct/kWh), offshore grid connection (0.591 ct/kWh) and CHP plants (0.357 ct/kWh). As VAT is also charged ad valorem on generation and grid costs, it is variable over time in the half and full flex tariffs. All other taxes, levies and surcharges are time-invariant in all electricity tariffs.

Comparability. An inflexible consumer pays the same in all three electricity tariffs over the year. This is achieved by weighting the average electricity and grid costs with the inflexible consumption profile. The fixed price of each consumer therefore corresponds to the costs incurred at the time of supply and not to the costs of a continuous consumer (unweighted prices). This means that flexible and inflexible operation management are directly comparable.

Difference in tariffs. Illustration 6 shows the three electricity tariffs for a heat pump. While the integral is the same for all three electricity tariffs, the average absolute deviation between the full-flex tariff and the fixed price is 17.0 ct/kWh, which is about twice as high as the deviation between the half-flex tariff and the fixed price (8.1 ct/kWh). The full-flex tariff therefore creates about twice as much incentive to flexibilize as the half-flex tariff.

Comparison of the three tariffs

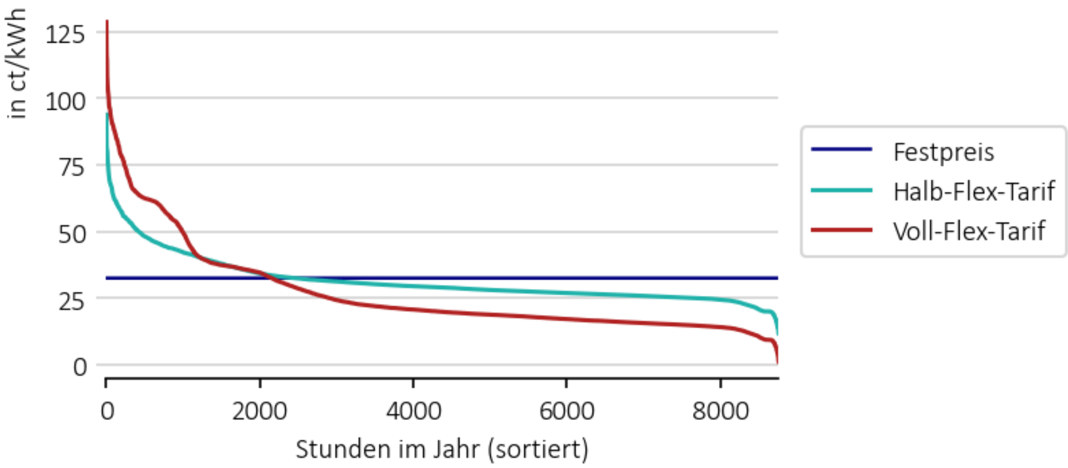

Illustration 6. Comparison of the three electricity tariffs for operating a heat pump. The average costs of inflexible operation are the same for all tariffs, but the distribution over time differs greatly.

4.1.2 Private and economic added value

Procedure. We examine both the reduction in the electricity bill of individual households ("private-sector added value") and the savings in the electricity system ("macroeconomic added value") through the flexible operation of household consumers. To this end, we evaluate the consumption profiles of the three systems on the basis of the corresponding electricity tariffs and the costs actually incurred in the electricity system.

generation costs. Assuming that the wholesale electricity prices reflect the costs of electricity generation, the share of the electricity bill for the generation costs also corresponds to the costs incurred in the electricity system. Both are determined as the product of electricity consumption and the day-ahead wholesale price. In the case of the PV-home storage combination, revenue is generated in addition to the generation costs if the household feeds electricity into the public grid. In the case of the fixed price, we assume that the household receives a constant feed-in tariff corresponding to the average electricity price. In the other tariffs, we assume that the grid feed-in is remunerated at the current electricity exchange price.

Grid costs. In contrast to the generation costs, the grid costs differ between the private and the economic perspective. The decisive factor for the household's electricity bill is the grid charges, i.e. the 3-stage tariff described in the section. However, this is only an approximation of the marginal costs of grid usage, which we use to evaluate the consumption profile to determine the system costs. In addition, the two perspectives differ for the grid feed-in of PV electricity. The household is not reimbursed any grid fees for this. However, the grid feed-in reduces the residual load in the distribution grid under consideration, which is always undercovered. We therefore assume that feeding electricity into the grid reduces the grid load and therefore creates an economic benefit corresponding to avoided grid costs.

Taxes, levies and levies. Taxes, levies and surcharges are irrelevant from an economic perspective, as this is only a redistribution. When determining the individual electricity bill, we take into account that when operating the home storage system, no levies are incurred for the grid purchase of electricity that is fed back into the grid at a later date (§21 Energy Financing Act).

4.1.3 System configuration

Overview. Table 1 shows the main system parameters. In the following paragraphs, we discuss the configuration of the three systems and the possibilities and limitations of load shifting in detail.

Table 2Central parameters of the system configuration

Consumers	Parameters
Heat pump	Air-to-water heat pump output: 3.7 kW el. Heating rod output: 8 kW el. Volume hot water tank: 15 kWh th. Heat requirement: 17,500 kWh th. (15,000 space heating, 2,000 kWh hot water) Storage losses: 1% per hour, 5% per cycle
Electric car (VW ID3 Pure)	Battery capacity: 45 kWh Charging power: 11 kW Charging losses: 10% Mileage: 10442 km per year Electricity consumption: 2180 kWh per year (of which around 2/3 charged at home)
PV home sto-rage	PV system output: 6 kWp PV system generation: 5,564 kWh Energetic capacity home storage: 6 kWh Home storage charging capacity: 3 kW Power consumption: 4214 kWh Storage losses: 12% per cycle

Heat pump. For the heat pump, we consider a household with an annual heating requirement of 17,500 kWh (thermal). The heating system comprises a heat pump and a heating element to cover the peak load. The coefficient of performance (COP) of the heat pump depends on the outside temperature and is therefore generally higher during the day than at night and higher in summer than in winter. The hourly time series for heat demand and coefficient of performance come from the "when2heat" data set (Ruhnau & Muessel, 2023). Overall, the heating system achieves an annual coefficient of performance of 3, a typical value for a heating system with radiators.

Flexibility potential. The flexibility potential results from the heat storage system. This has a storage capacity of 15 kWh, heat losses of 1% per hour and charging losses of 5%. However, the thermal inertia of the building is not considered. With the fixed price tariff, the heat pump is operated more during the hours with higher outside temperatures, as it then requires less electricity to provide heat due to the higher coefficient of performance. With flex tariffs, the electricity tariff is also taken into account. This means that it can reduce costs to postpone heat generation, even if this increases electricity consumption due to additional storage losses.

Electric car. To model the electric car, we use a mobility profile of a female commuter with a VW ID 3 Pure from Gaete-Morales et al. (2021). The annual consumption is 2181 kWh, the battery capacity 45 kWh and the charging power 11 kW. The household can charge two thirds of the vehicle's electricity requirements using the wallbox at home, while the rest is drawn from public fast-charging stations. Energy losses of 10% occur during charging. The modeled household can freely choose the charging period as long as the car is at home and sufficiently charged before departure. This is a considerable potential for flexibility, as the car only charges at home for just under 20 minutes a day on average at full charging capacity. With flex tariffs, the household shifts charging to the hours with the lowest tariffs, provided this is compatible with the planned journeys. We have not taken bidirectional charging, i.e. feeding electricity back into the grid, into account.

Home storage. To evaluate the home storage system, we model a household with a rooftop PV system and a home storage system. The PV system is south-facing and generates 5564 kWh of electricity per year with an installed capacity of 6 kWp. The household's electricity consumption follows the synthetic load profile of a family of four (Pflugradt et al., 2022) and amounts to a total of 4214 kWh per year. The home storage system has an energy capacity of 6 kWh and a maximum charging capacity of 3 kW.

Flexibility potential. Flexibility can be provided by the home storage system. However, the mode of operation of the home storage system and thus the provision of flexibility differs greatly between the tariffs. With the fixed price, the home storage system is used exclusively to consume as much PV electricity as possible on site ("self-consumption optimization"). This is worthwhile as no grid charges, levies, taxes and surcharges are incurred for the self-generated electricity. PV generation in excess of self-consumption is therefore temporarily stored in the home storage system for later self-consumption. Excess PV electricity is only fed into the public grid when the storage system is full. In the case of flex tariffs, the household also takes into account the time-variable purchase and sales prices. The storage system is used to reduce grid consumption in hours with high procurement costs and to increase grid feed-in in hours with high wholesale prices. Where technically and economically feasible, the storage facility can also be used for arbitrage on the spot market.

4.2 Results

Potential. Making heat pumps, electric cars and home storage systems more flexible can result in significant cost savings in the electricity system: almost 70% of the costs caused by charging electric cars can be saved. The figure for the heat pump is 24%. With appropriate tariffs, the household's electricity bill is reduced by almost 60% for the electric car and around 20% for the heat pump.

Delayed flexibilization. In other words, delayed flexibilization of household consumers causes considerable costs in the electricity system and leads to unnecessarily high electricity bills for households. An electric car that is always charged immediately when it is connected to the charging station is more than three times as expensive as a smartly charged car. In this case, the intelligently operated solar battery creates 6.6 times more benefit for the energy system than a battery with classic self-consumption optimization.

System benefits. The savings with the full-flex tariff are always higher than with the half-flex tariff for all three systems examined. However, even the half-flex tariff reduces grid costs, although it only passes on electricity market signals to the household. In economic terms, dynamic electricity tariffs therefore have a positive external effect on the distribution grid in the current system.

Structure. The following sections show the results for the three system types and in a cross-system comparison.

4.2.1 Heat pump

Operation management. With the fixed price, the heat pump is preferably operated when heat is required. The heat pump only runs more frequently in the afternoon in order to benefit from the higher outside temperatures. It then fills the heat storage tank and is therefore needed less in the evening and at night (Illustration 7). The time-variable tariffs cause a greater shift in the operation of the heat pump. Electricity consumption is reduced, particularly in the evening and morning hours, and increases at night and in the afternoon.

Heat pump operating modes

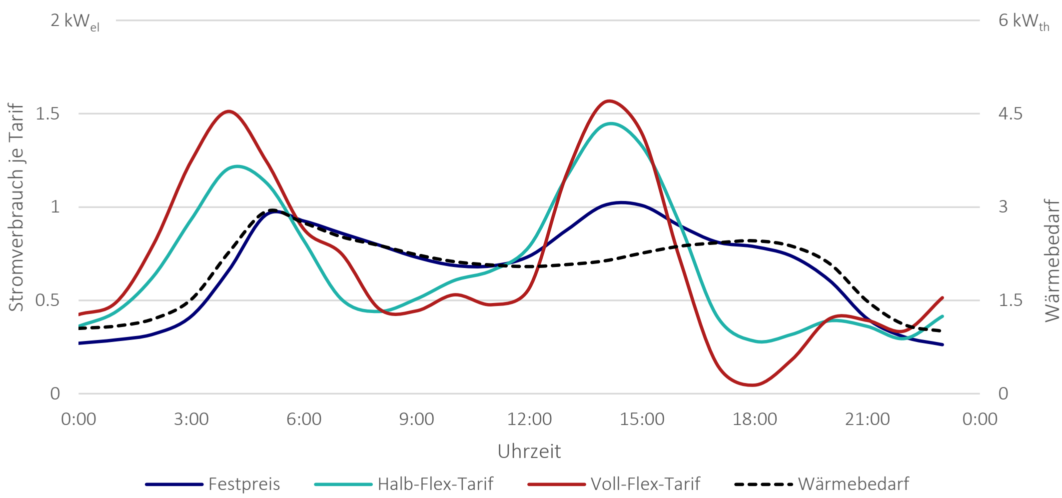

Illustration 7Comparison of the three operating modes of the heat pump and the heat demand profile

Electricity bill. With the full flex tariff, the household can save electricity costs for the heat pump amounting to 398 euros (Illustration 8). This is a reduction in the electricity bill of 19% compared to inflexible operation. The semi-flex tariff, on the other hand, only offers a rather small savings potential of 64 euros (3%).

System costs. The private-sector savings from making the heat pump more flexible are offset by a similarly high system benefit. We estimate that the half-flex tariff currently reduces the costs in the electricity system caused by operating the heat pump by EUR 212 (15%). In addition, the load on the grid is also reduced. This is due to the fact that the hours with high electricity prices are often also hours in which grid utilization is high. If flexible systems draw less electricity during these hours, the maximum grid load also decreases accordingly. In the full flex tariff, distribution grid price signals are also passed on to consumers, which increases the savings in the electricity system to a total of EUR 346 (24%). Flexible system operation reduces electricity prices and the probability of distribution grid overload decreases. Households without corresponding systems therefore also benefit from flexibilization.

Annual electricity costs for heat pump

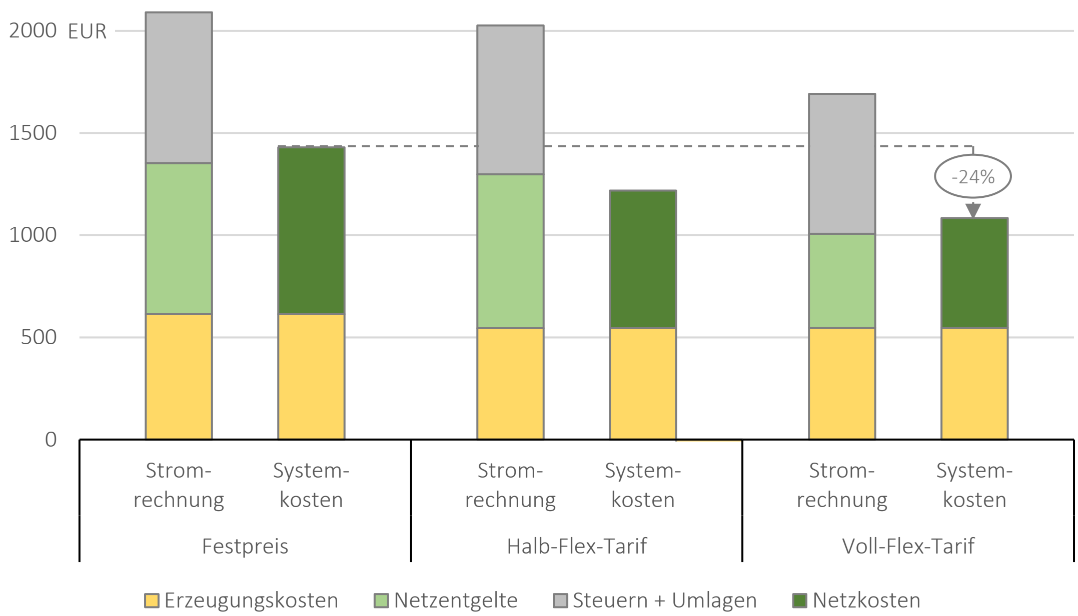

Illustration 8. Annual electricity bill for operating a heat pump with different electricity tariffs and the resulting costs in the electricity system.

4.2.2 Electric vehicle

Electricity bill. The relative savings potential through flexible charging behavior of the electric vehicle even exceeds the potential of the heat pump (Illustration 9). The half-flex tariff can already reduce the electricity bill by 158 euros (29%), the full-flex tariff by as much as 316 euros (57%). The savings potential would be higher if bidirectional charging were taken into account or if a larger proportion of electricity consumption were to be charged at home.

System costs. The dynamization of energy costs in the semi-flex tariff already achieves a large part of the possible cost reduction from a system perspective. Overall, the system costs fall by 67% compared to inflexible operation. A large part of these savings is based on lower generation costs, which fall by 124 euros; however, a considerable additional benefit also arises from the reduction in grid costs (by 53 euros). This side effect is considerable because these grid cost savings are already achieved without time-variable grid charges. The considerable discrepancy between grid charges and the underlying grid costs arises because the static time-variable grid charges only approximate the actual grid costs. The car therefore often charges during hours in which the tariff exceeds the actual grid costs. The economic added value of additional time-variable grid charges ("full flex tariff") is no longer high in the example under consideration. The costs caused in the electricity system then fall by a total of 70% compared to inflexible operation.

Annual electricity costs for electric car

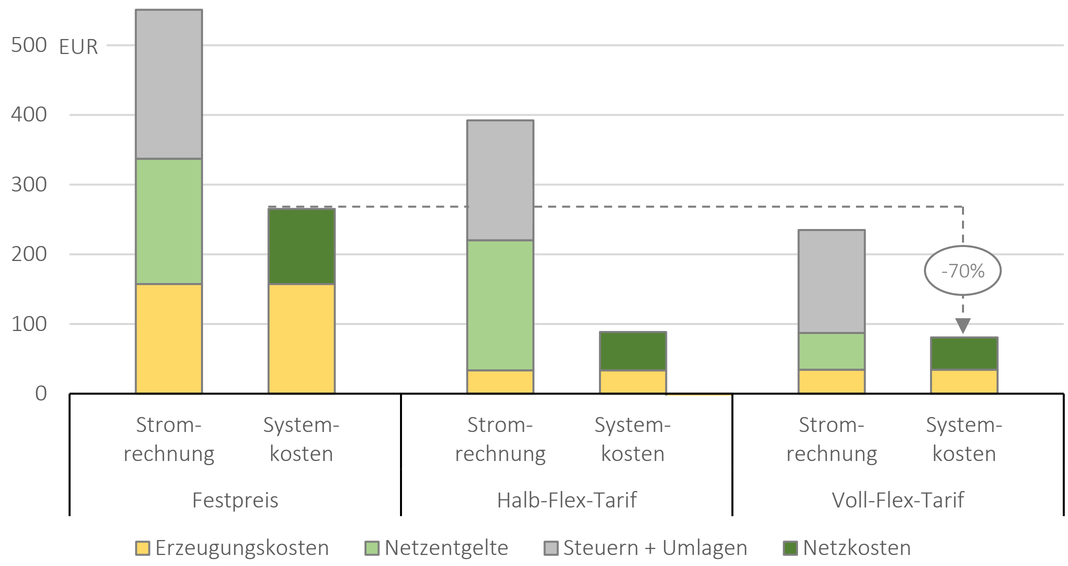

Illustration 9. The annual electricity bill for the use of a VW ID3 Pure with different electricity tariffs and the costs caused by charging in the electricity system.

4.2.3 Home storage

Electricity costs. The household we examined with a PV system has annual electricity costs of EUR 870 without a home storage system, which are offset by feed-in revenues of EUR 302. The net electricity bill therefore amounts to a total of 568 euros.

Self-consumption optimization. The home storage system allows the household to increase its own consumption of the electricity generated by the PV system and reduce grid consumption and feed-in accordingly. As a result, it pays less grid charges, taxes, levies and surcharges, which reduces the electricity bill by a total of 343 euros (Illustration 10). This is offset by savings of only 26 euros in the electricity system. The difference between private and economic cost savings is redistribution. This means that only just under 8% of the savings for individual households are genuine savings, with more than 92% coming from the pockets of other households.

System-friendly flexibilization. If the household uses the semi-flex tariff, there are major benefits for the electricity system. The additional cost savings in the electricity system amount to 116 euros; the electricity bill is reduced by a further 99 euros. If dynamic grid charges are also passed on to the household (full flex tariff), the household adapts its consumption and feed-in behavior even more and can thus reduce its electricity bill by a further EUR 96. However, the additional benefit from a systemic perspective is only 48 euros. This example shows the relevance of system-friendly incentives for the operation of home storage systems.

Savings through home storage (compared to no storage)

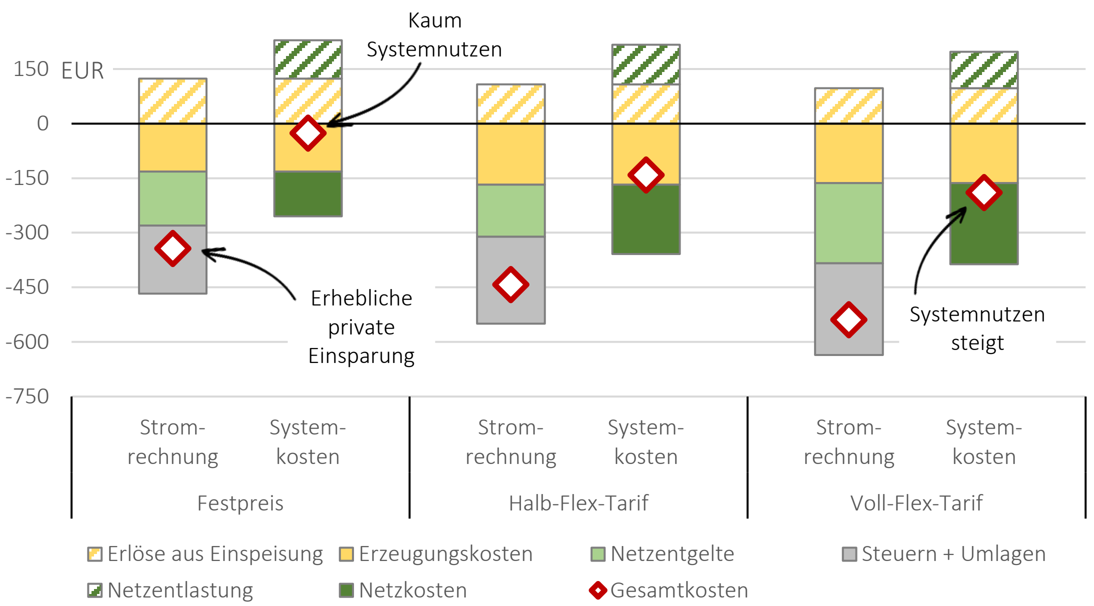

Illustration 10. Savings from the home storage system with an existing PV system for the household and in the electricity system (compared to no home storage system).

4.2.4 Flexibility potentials in comparison

System costs. In the case of heat pumps and electric cars, the relative cost reduction potential compared to inflexible consumption is a good indicator of the added value of flexibility. From a system perspective, electric cars can be operated up to 70% more cheaply through flexibilization; for heat pumps, the figure is up to 24% (Illustration 11). The private-sector savings are somewhat lower (Illustration 12). From this perspective, electric cars are therefore almost three times as flexible as heat pumps. However, because a heat pump generally consumes significantly more electricity than an electric car, the absolute cost savings are higher for the latter. While the heat pump we looked at can save system costs of up to EUR 346 in market and grid-friendly operation, the figure for an electric car is EUR 185. This is partly due to the fact that the car in question draws around a third of the electricity it consumes from public charging points and therefore only partially exploits the available flexibility potential. Home storage systems, on the other hand, are not directly comparable with the other two types of system, as they also generate energy, and their savings potential therefore depends largely on the dimensions of the PV system compared to household consumption and the size of the battery.

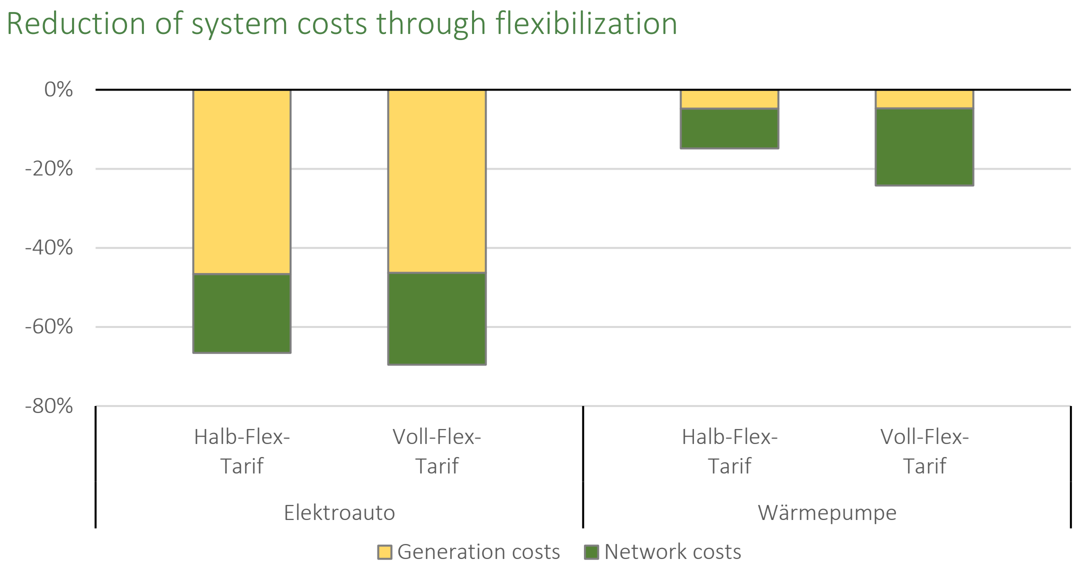

Illustration 11. Reduction in costs caused by heat pumps and electric cars in the electricity system (compared to inflexible operation).

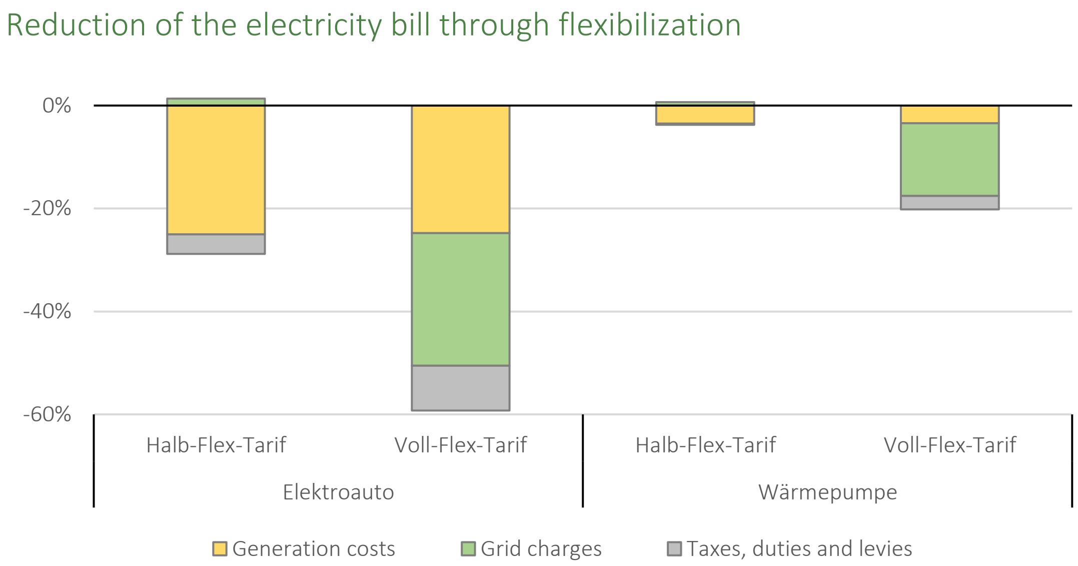

Illustration 12. Reduction in electricity costs for operating the heat pump and electric car (compared to inflexible operation).

5 Regulation and market design

Support instruments. This study shows that the inflexible operation of heat pumps, electric cars and home storage systems leads to high and avoidable costs in the electricity system. In comparison, system-friendly operation causes significantly lower costs. We therefore recommend economic incentives to make these three household-related consumers more flexible. On the one hand, these incentives should reflect the resulting system benefits as accurately as possible and, on the other hand, consider legal and technical framework conditions as well as transaction costs.

Recommendation. In this chapter, we discuss and evaluate instruments that create incentives for balancing electricity price fluctuations and avoiding distribution grid bottlenecks. A suitable instrument for incentivizing flexibility in the electricity market is the passing on of wholesale prices to consumers. However, the introduction of distribution grid signals is more challenging due to the lack of natural price signals in the distribution grid. In principle, dynamic time-variable grid charges seem promising to us. In the long term, however, these must be supplemented by additional instruments to avoid new load peaks caused by excessive load shifting.

5.1 Flat-rate investment promotion

Flexibility promotion. A blanket (investment) subsidy for flexibility resources without accompanying incentives for system-friendly operation is generally not sensible, as our and many other analyses of home storage systems show: A home storage system in itself does little for the energy system, solar it is not subject to incentives for system-serving operation. This is remarkable in light of the corresponding subsidy programs: in Germany, for example, home storage systems are subsidized by the KfW (German institution that hands out governmental subsidies) through reduced loans and repayment subsidies. The current EU electricity market reform also mentions flexibility targets and corresponding funding regimes without making this dependent on system-beneficial incentives. In our view, investment promotion with a view to providing flexibility for the electricity system only makes sense if there are corresponding incentives for plant operation.

5.2 Instruments for the electricity market

Semi-flex tariff. Suitable incentives to compensate for fluctuations in electricity prices arise when wholesale prices are passed on to households as time-variable retail tariffs. Because wholesale prices generally reflect the marginal costs of electricity generation well, the resulting incentives are beneficial to the system. Corresponding "dynamic" tariffs have been established in many European countries for many years. In Germany, they have only been available for a few years and are not yet widespread.

Utilities. Passing on wholesale prices to households differs from the previous business model of traditional energy supply companies. Firstly, forecasting the consumption of their customers is becoming more challenging due to the incentives to make consumption more flexible. Even the consumption of a large customer portfolio no longer depends primarily on the time of year, time of day and weather, but is also influenced by the wholesale price. The standard load profiles that have predominantly been used to date will then no longer be applicable. Instead, supply companies must anticipate the load shift of the customers supplied and translate this into a bid function (price-dependent buy order) on the day-ahead market. On the other hand, long-term load forecasts and hedging are no longer necessary. Electricity suppliers currently procure electricity for their customers on a long-term basis to hedge against price fluctuations. This is no longer necessary in the classic semi-flex tariff, as the price fluctuations are borne by the household and no longer by the energy supply company. Energy supply companies now only need load forecasts on the previous day and not several years in advance as was previously the case. The elimination of risk premiums also means that dynamic tariffs are on average cheaper for customers than fixed-price tariffs.

Price fluctuations. The simple semi-flex tariff offers consumers no protection against sharp price fluctuations on the wholesale market, such as the European energy price crisis in 2021/22 triggered by the Russian war of aggression or the energy crisis in Texas in February 2021 caused by a cold spell. As the full volatility of wholesale prices is passed on to consumers, electricity bills can rise exorbitantly in such exceptional situations, which can cause social consequences and energy poverty as well as, as in the example of Texas, lead to the insolvency of providers of dynamic electricity tariffs.

Hedging. With this in mind, we recently proposed a tariff model that incentivizes load flexibility and energy savings while offering price security for consumers: the dynamic tariff with price hedging (Neon, 2023). The tariff specifies an annual volume (kWh), an hourly consumption profile and a price (ct/kWh) over the contract term of one or more years. If households consume as much electricity as agreed, they pay exactly the contractually agreed price - regardless of price movements on the spot market. In other words, they are fully insured against price peaks for these quantities. However, if actual consumption deviates from the agreed volume, the hourly excess or shortfall is billed or reimbursed at spot prices. This means that the incentive for savings and load shifting is always determined by the spot price, regardless of the previously hedged profile. This allows households to use their flexibility and energy-saving potential to reduce their electricity bills. Instead of suffering from price peaks, they could even benefit financially from them.

Outlook. Supply companies can already pass on day-ahead electricity prices to households. This is currently a free decision for distribution companies. From January 1, 2025, all suppliers will be obliged to offer customers with smart metering systems a time-variable electricity tariff (EnWG Section 41a). However, this also includes the option of time-of-day-dependent tariffs, the benefit of which for the electricity system is limited compared to passing on the exchange electricity price. However, the lack of metering infrastructure has so far made these tariffs attractive to very few consumers. Apart from the nationwide introduction of smart meters, no major political efforts are therefore required to disseminate such tariffs. In the medium term, it is also conceivable that intraday and balancing energy prices could be passed on to households by energy suppliers or aggregators, which would leverage further flexibility potential. It would probably be technically and logistically easy to implement the quarter-hourly prices of the intraday opening auction at 3 pm instead of the hourly prices of the day-ahead auction at 12 pm.

5.3 Instruments for the distribution grid

Variety of instruments. The introduction of distribution grid signals is challenging due to the lack of natural price signals, the high heterogeneity, and the lack of real-time information in the distribution grid. Table 3 shows the variety of regulatory instruments that can provide an incentive for the grid-friendly operation of flexible consumers.

Criteria. In the following, we present three key differentiation criteria for the instruments and evaluate the advantages and disadvantages of the design options:

- The *voluntary nature of the activation*. In the case of price signals, flexibility is provided voluntarily, but not in the case of intervention by the grid operator.
- The *length of the lead time* with which the intervention or price signal is announced. The lead time varies from up to a year, a few days or hours to the retroactive determination of high price windows.
- The *fineness of the resolution of the signals*, i.e. the number of level steps of an instrument, which can be configured from finely graduated to binary (only on or off).

Table 3. Instruments to prevent bottlenecks in the distribution grid

	Instrument	Description
Rights of intervention	Dimming of selected systems	Unannounced dimming of certain system types to predefined output (e.g. modules 1 and 2 of the current BNetzA stipulation on EnWG §14a)
	Shutdown of selected systems	Complete shutdown of certain types of systems. Shutdown can take place when necessary (in the event of measured bottlenecks) or during fixed, predetermined shutdown periods (e.g. old version of EnWG §14a)
	Dimming household consumption	Dimming of the total household connected load. Time windows can be set for the long or short term (e.g. current proposal by the Dutch regulatory authority)
Price instruments	Static time-variable grid usage fees	Time-variable grid charges (energy prices) that are set well in advance (e.g. Module 3 of the BNetzA definition of EnWG §14a)
	Dynamic time-variable grid usage fees	Time-variable grid charges (energy prices) that are only set shortly before delivery, e.g. the day before (e.g. some Swiss DSOs)
	Critical Peak pricing	Very high grid charges (energy prices) in a few hours a year. The tariff level is determined with a long lead time, the time at which high price levels occur only at short notice. Voluntary participation combined with a discount on grid fee labor prices in all other hours (e.g. in the USA and France)
	Grid fee surcharge for maximum grid load	Sharply increased grid charges (energy prices) in the quarter hours with the highest grid load in the year. The quarter hours are determined retrospectively on the basis of the measured grid load. (e.g. Triads in the UK)
	Situational, short performance prices	Grid charge power price for peak consumption in a defined period of a few hours. Power price is only greater than zero in periods in which grid congestion can be expected (e.g. transmission and distribution grid charges in Greece)

5.3.1 Voluntary nature of the activation

Voluntariness. Grid-friendly operation of flexible consumption systems can be achieved through direct control by the grid operator or as a voluntary response to a price signal. With the right to intervene, grid operators decide which systems are switched off and when, or draw electricity at a reduced output. The right of access can either be mandatory or voluntary. Households that grant a right of access usually receive financial compensation, such as a reduced grid fee. The alternative is price signals, such as time-variable working prices for grid usage fees. These are high when the grid is heavily loaded and low when there are no bottlenecks. Load shifting can then benefit from lower grid charges. In contrast to the right of intervention, however, the decision on the use of flexibility remains with the households or their aggregators. The essential difference in definition between intervention rights and price signals is therefore the voluntary nature of operations.

Willingness to pay. Many intervention rights treat all systems of a household equally in the activation, especially if the household connection as such is dimmed. In other implementation variants, a distinction is made between system types, so that only heat pumps and electric cars are dimmed, for example. Even in this case, however, it is not possible to differentiate between the individual preferences of the various households. For example, the grid operator would restrict the charging of a car shortly before a long journey in the same way as for a car that is expected to be used very little. Similarly, all heat pumps in a street would be shut down equally, regardless of the temperatures in the respective hot water tank and house. This would not be the case with the price signal. Households, or their aggregators, can decide for themselves how important an uninterrupted supply is to them. This differentiation of consumption according to the current, individual willingness to pay is economically efficient, whereas the equal treatment of all consumers at all times is not. [1]

Network / market trade-off. Furthermore, in the case of intervention rights, there is no trade-off between the different flexibility signals: the grid signal corresponds to a price signal with an infinitely high price and therefore always outweighs the market signal. A price signal that serves the grid, on the other hand, is compatible with the wholesale price signal and allows a sensible trade-off between the two flexibility targets. One advantage of intervention rights is that they create a high degree of certainty about the actual shift in consumption, while price signals leave a certain degree of uncertainty about the amount of load shifted. However, the advantage is small because distribution system operators have always carried out grid planning and operation using stochastic methods under considerable uncertainty due to a lack of data availability. Table 4 summarizes the comparison of intervention rights and price signals.

---

[1] Theoretically, price-based and quantity-based instruments can lead to the same results and be equally efficient, e.g. the classic instruments for reducing CO2 emissions: Emissions trading (quantity fixed) and CO2 tax (price fixed). The intervention rights for grid operators correspond to a certain extent to an emissions trading system without the possibility of trading and are therefore inefficient.

Table 4. Comparison of intervention rights and price signals for grid-supportive consumer control

	Right of intervention	Price signal
Prioritization between consumers	No prioritization	Differentiation of consumers according to willingness to pay
Interaction of signals	No balancing: Network signal always superimposed on market signal	Interaction between price signals from the electricity market and the distribution grid
Safety via load shifting	High security	Less security
Economic efficiency	Inefficient (cf. tax vs. cap-and-trade system without trading)	Efficient use of potential

Assessment. We advise against a regular limitation of electricity consumption by grid operators. In addition to the reasons mentioned above, it would make electrification less attractive from a consumer perspective if electrically powered systems could not be used reliably, unlike their fuel-powered counterparts. Instead, we recommend the use of price signals to provide grid-friendly incentives for flexible consumers.

5.3.2 Lead time

Design options. Both price and intervention rights can be designed with a long or short lead time. In the case of price signals, it is even possible to determine them retrospectively (Table 5).

Table 5. Lead time of intervention rights and price signals

	Right of intervention	Price signal
Long-term (e.g. previous year)	Load dimming or switch-off in fixed blocking times	Static time-variable grid charges
Short-term (e.g. previous day)	Unannounced load dimming or switch-off	Dynamic time-variable grid charges; Critical Peak pricing
Retroactive		Grid fee surcharge for maximum grid load; Situational, short performance prices

Trade-off. There is a trade-off in the length of the lead time. Weather-related grid bottlenecks, for example due to high load at particularly low temperatures or exceptionally high PV feed-in, can only be predicted at short notice. Long-term forecasts of grid load can only reflect seasonal and daily patterns and are therefore imprecise in individual cases, particularly with regard to the timing of (rare) grid congestion situations. For this reason, the early determination of shifts in consumption always leads to undesirable use of flexibility in times without congestion. On the other hand, a longer lead time enables the flexible consumption systems to react more strongly when the shift in consumption needs to be prepared. A heat pump, for example, can only reduce its consumption temporarily if the heat storage tank or the living spaces are sufficiently warm. If the heat pump output is reduced at short notice and cannot be anticipated, the potential for flexibility cannot be fully exploited or there would be a loss of comfort due to lower room temperatures. Long lead times also allow manual processes (such as the publication of price sheets as PDF files), while short lead times require a high degree of automation.

Retroactive determination. The time of the annual peak load can only be determined after the end of the year. For this reason, some price-based instruments only determine the level of the grid charge retrospectively, such as the grid charge surcharge for the peak load, as applied in the United Kingdom. This creates a strong incentive for households and their aggregators to keep electricity consumption low during hours with potentially high grid loads. The forecast of hours with annual peak load is therefore decentralized to a certain extent. However, this causes considerable price risks and effort to identify the corresponding hours. Furthermore, it is unlikely that other players will be able to anticipate the distribution grid load better than the distribution grid operator.

Recommendation. How long the lead time should be depends heavily on the respective grid area. The extent to which overload events can be precisely calendared plays a decisive role here. A distinction can be made between three typical grids:

- Load-dominated distribution grids, for example in large cities.
- Generation-dominated distribution grids, especially in regions with high solar output at low voltage.
- Flexibility-dominated distribution grids where (in the future) load shifting is so large that it shapes the grid load.

In principle, longer lead times appear to be sufficient in primarily load-dominated distribution grids as long as the volume of reacting consumption is still manageable. Here, the grid load can be described with sufficient accuracy by time, day of the week and season. This is also shown by our simulation of a static time-variable three-stage grid charge for the Berlin distribution grid. In generation-dominated distribution grids, on the other hand, shorter lead times are necessary, as the grid load can hardly be determined by calendar. This applies in particular to wind energy; even with solar energy, generation peaks can only be predicted at short notice, but these follow clearer seasonal and diurnal patterns. In distribution grids with a high penetration of flexible consumers, the grid load is primarily caused by load shifting. Here, all types of time-variable grid charges will reach their limits and will probably have to be combined with additional instruments, which we will discuss in section 5.5 in more detail.

Feasibility. In Germany, a short lead time of one day or less hardly seems feasible in the next two to three years. This would also make little sense both for intervention rights and for price-based instruments as long as there is no corresponding communication infrastructure and the utilization of the distribution grids is based on estimates due to a lack of real-time information, which in turn is primarily based on calendar variables such as the time of year and time of day. However, the medium-term goal should be to significantly reduce the lead time. However, a lead time of one week is not a significant advantage from a grid perspective compared to a determination at the beginning of the year, as weather forecasts and therefore grid utilization are only sufficiently accurate with a lead time of around 24 hours. Most of the flexibility potential is also still available in this time frame, as the load shifting of heat pumps and electric cars would hardly take place over more than a few days. In the medium term, a decision should therefore be made the day before at the earliest on the basis of good weather forecasts and a precise picture of the grid load, regardless of whether the right to intervene or a price signal is used.

Static signals. On the way to such short lead times, we recommend the prompt and large-scale introduction of distribution grid signals with a long lead time. These pave the way for dynamic signals by enabling grid operators to gain initial experience with the billing of time-variable charges and triggering innovations among consumers and system manufacturers. Such static instruments should be designed as precisely as possible. In other words, not as a high-price window every day between 8:00 and 20:00, but, depending on the grid area, e.g. on weekdays between December and February between 17:00 and 19:30. The time slots described in section 4.1.1 could be used by network operators as a basis for determining the price levels.

5.3.3 Fineness of resolution

Design options. A third key criterion for evaluating the instruments is the fineness of the resolution of the signals, i.e. the number of levels in a time-variable grid charge or the levels of dimming. The possible spectrum ranges from a binary control (e.g. simple cut-off times or two-stage grid charges) to a finely graduated control (different cut-off times with different dimming levels or many price levels).

Evaluation. The dimension of fineness of resolution seems to us to be underexposed in the German debate. We see two reasons that speak strongly in favor of the finest possible resolution of the instrument. Firstly, a fine resolution can limit the use of flexibility better and more precisely to what is necessary. In principle, the load should only be reduced or increased to such an extent that the distribution grid is unlikely to be overloaded. Any load shifting beyond this is inefficient and should be avoided wherever possible. Therefore, information about the grid status should be passed on as precisely as possible. For example, static time-variable grid charges should be lower at the beginning and end of winter, when the probability of particularly low temperatures is also slightly lower than in the middle of winter. Secondly, the advantage of fine-grained control is that it makes a strong concentration of consumption as a result of catch-up or preferential effects less likely. In the case of blackout periods, for example, there is a risk of new distribution grid bottlenecks directly before or after the blackout periods, as well as sharp jumps in grid charges. A finer resolution of the instrument would equalize the timing of the resumption of consumption.

Digitization. One reason for a low resolution may be that people are better at remembering less complex tariffs. In a digitized system, however, a finer resolution is preferable to a coarser resolution because IT systems, unlike humans, can easily remember a higher number of tariff or dimming levels.

5.4 Emergency intervention rights

Emergency. We believe it is sensible and urgently necessary for grid operators to be able to dim or shut down individual systems such as storage systems, electric cars and heat pumps in exceptional emergency situations. This makes sense in emergency situations in which entire distribution grids would otherwise have to be shut down, for example to stop a dangerous drop in frequency. Such situations should only occur once every few years to decades. With such control options, as with smart meters, the IT security of decentralized systems is key to ensuring the resilience of the energy system.

Assessment. Switching off individual loads is clearly preferable to taking entire regions off the grid. For example, in Texas in February 2021, it would have been better to switch off electric heating systems than to take entire cities off the grid. So far, grid operators in Germany have hardly been able to target certain types of systems. We therefore recommend introducing such a regulation as soon as possible. However, such an emergency measure is not a sensible instrument for regular use and should be severely restricted in its application.

5.5 New grid load due to flexibility?

Fears. In the debate about household-related flexibility, the concern is often raised that the use of flexibility could cause new grid overloads. The fear is that too many consumers will shift their load at the same time, for example if all electric cars charge at the same time, causing a new load peak ("overshoot"). This concern exists on the one hand with distribution grid instruments (blocking time windows, time-variable grid charges, etc.), but also with pure electricity market flexibility: With today's dynamic electricity tariff (semi-flex tariff), it is initially plausible that, for example, many electric cars will shift their entire electricity consumption to the one hour with the lowest day-ahead prices in the case of digitally optimized charging, as many cars have a charging time of less than one hour per day in everyday operation.

New load peaks. Whether flexible consumers cause new load peaks in the distribution grid initially depends on the amount of shifted consumption. While the maximum grid load may initially fall if only a few consumers are shifted, it will rise again at some point as consumption shifts if no appropriate countermeasures are taken. With very high flexibility use, it is even possible that this will cause new, even higher, load peaks (Illustration 13).

Influence of the use of flexibility on the distribution grid

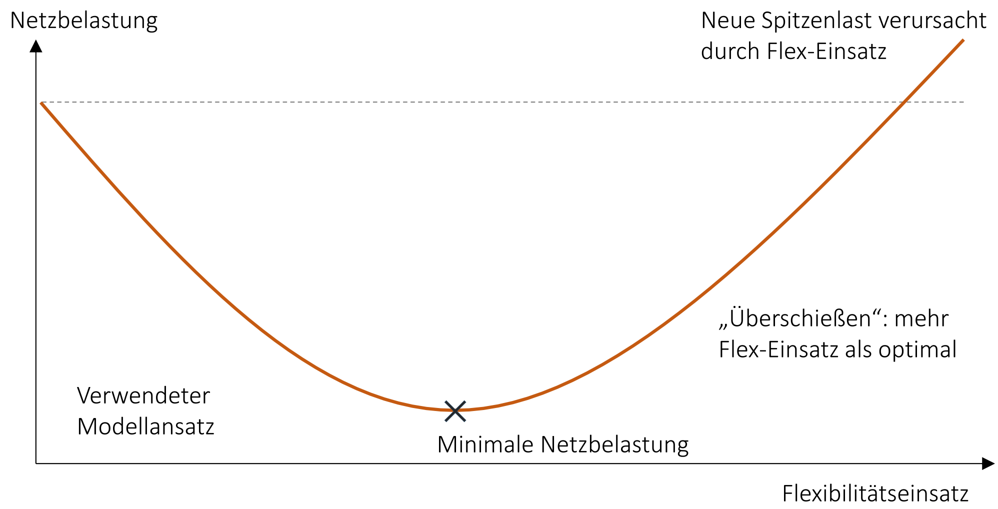

Illustration 13. Grid load as a function of shifted consumption

Classification of our model results. The concentration of consumption due to the use of flexibility is not accounted for in the model approach we used, as only one system is modeled at a time and a new peak load can only arise if many systems react synchronously. However, a strong concentration of consumption is currently unlikely in Berlin's distribution grid. This is mainly due to the still small number of flexibly operated systems. In addition, a look at real data shows that hours with a high grid load also tend to have high wholesale prices, meaning that market-oriented flexibility should relieve the grid (Illustration 14). This is also reflected in our simulation results, where a significant reduction in grid costs can already be achieved with the semi-flex tariff.

Wholesale prices and distribution grid load

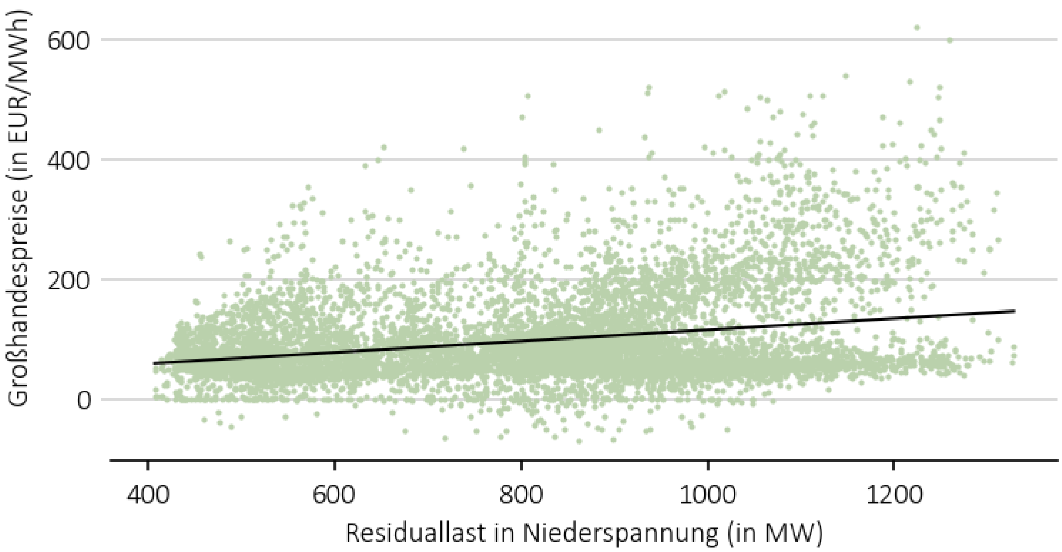

Illustration 14. The wholesale prices correlate with the distribution grid load. Each point in the figure corresponds to one hour in 2021, the residual load comes from the low-voltage level of the Berlin distribution grid.

Practical relevance. For a new load peak to occur due to a strong concentration of the shifted load, a large number of optimized systems and highly synchronized behavior are required. The extent to which flexibility incentives concentrate flexible consumption in practice depends on the heterogeneity of the system configurations, the correlation between the daily rhythms of consumers and their preferences with regard to load shifting, as well as the diversity of optimization approaches. The more heterogeneous these factors are, the more "smeared" the concentration of consumption over longer periods of time. The degree of synchronization of flexible systems is difficult to estimate without experience from real operation. However, even today, distribution grid planning is strongly determined by empirically determined simultaneity factors. Existing studies are often based on typified mathematical modeling that does not consider a scattering of parameters.

Ex-ante signal. The fundamental cause of consumption concentration is the fact that signals are determined before the consumption decision (ex-ante) and are not changed afterwards. This means that there is no feedback from the actual load shift to the signal. This applies to grid fees set in advance, day-ahead electricity prices, blocking time windows and consumption dimming by grid operators. These instruments therefore differ from equilibrium prices, which react to changes in demand.

Outlook. The challenge of concentrating consumption will become more relevant as the number of flexibly operated systems increases. However, in view of the slow progress in the flexibilization of consumption, we do not consider it necessary to implement precautionary measures now. On the other hand, static time-variable grid charges or simple blocking time windows will not be able to prevent distribution grid overload in the long term due to the lack of feedback. It is therefore helpful to think about supplementary instruments at an early stage.

Equilibrium prices. The economically and theoretically optimal solution would be to implement grid charges and electricity prices as equilibrium prices, i.e. to introduce nodal prices at distribution grid level. Local load concentration would then always lead to rising prices and overshooting would be ruled out. However, this is not a viable option, even in the medium term, due to the high complexity and transaction costs. In practice, grid operators would have to anticipate the distribution grid load caused by load shifting when using intervention rights and adjust the corresponding interventions. Ex-ante price signals, such as time-variable grid charges, would have to be supplemented with additional instruments. This could be done, for example, by a retroactively determined grid charge surcharge in the hours with the highest distribution grid load. As described in section 5.3.2 however, this causes high price risks.

Situational performance prices. We therefore consider situational, short-term demand charges to be more promising. Like today's demand charges for RLM customers, these are prices based on the quarter-hourly individual peak load. Unlike these, however, they are only applied in periods in which a new peak load is to be expected and have a calculation period of a few hours. They would then be applied to the period with the lowest grid charge labor prices (and the lowest expected wholesale prices), for example during the winter at night from 22:00 to 4:00 or in the summer months at midday from 11:00 to 15:00. Such power prices make peak loads unattractive and lead to consumption being distributed more evenly over the time window: instead of charging in the quarter of an hour with the lowest exchange prices, electric cars would then draw electricity evenly over the entire period. Because power prices depend on individual consumption and not on the distribution grid peak load, it does not require a grid load forecast from households or aggregators. There are also no price risks as with the retroactive grid surcharge.

6 Summary and recommendations

Procedure. The number of heat pumps, electric cars and home storage systems in Germany will increase significantly in the coming years, which is likely to create a need for new generation and distribution grid investments. Against this background, this study shows what costs can be saved in the electricity system by making these new consumption technologies more flexible in a way that benefits the system, without any loss of comfort. We also discuss approaches to regulation and market design that create incentives for such flexibilization.

Results. For a typical household, the quantification shows that system-friendly operation reduces the costs that a heat pump causes in the electricity system by around a quarter compared to load-driven operation. The costs of an electric vehicle are even reduced by 70%. These calculations do not even account for further revenue potential, such as the use of intraday electricity prices or bidirectional charging. Delaying the flexibilization of household consumers therefore comes at a considerable cost. The importance of meaningful economic incentives is also illustrated by the example of optimizing self-consumption of home storage systems. Although the classic self-consumption optimization that dominates today reduces the electricity bill of the respective households, it achieves almost no benefit for the electricity system. Above all, it results in a redistribution of the costs of the electricity system at the expense of other consumers.

Grid-friendly dynamic tariffs. In the energy policy debate, it is sometimes argued that today's dynamic electricity tariffs lead to a burden on the distribution grids. Our analyses show the opposite: load shifting from hours with high wholesale prices to hours with low prices, i.e. the market-driven use of flexibility, nowadays also tends to *relieve* the distribution grid. This means that dynamic tariffs are currently beneficial to the grid and reduce the costs of all other grid customers.

Recommendations. Dynamic electricity tariffs that pass on wholesale prices to households make the flexibility of household consumers usable for the electricity market. Such tariffs are already available today, so there is no immediate need for regulatory action. The introduction of grid-serving signals is much more challenging due to the lack of natural price signals in the distribution grid. In the short term, the introduction of static, time-variable distribution grid charges, i.e. grid charges whose amount is fixed on a calendar basis seems sensible and feasible to us. Based on our analyses, it is currently unlikely that such charges will create new grid bottlenecks, but they are certainly conceivable in the longer term. Such static, time-variable network charges should therefore be developed further in the medium term: they should be determined with a short lead time in order to be able to take weather situations such as cold spells and wind fronts into account. We also recommend a finer gradation of the tariff levels to avoid a concentration of consumption catch-up. Situational power prices could be a further element of the future grid fee system to smooth out new consumption peaks of flexible systems.

7 Bibliography

ACER (2023). Demand response and other distributed energy resources: what barriers are holding them back? 2023 Market Monitoring Report. https://www.acer.europa.eu/sites/default/files/documents/Publications/ACER_MMR_2023_Barriers_to_demand_response.pdf.

Agora Energiewende und Forschungsstelle für Energiewirtschaft e. V. (2023): Haushaltsnahe Flexibilitäten nutzen. Wie Elektrofahrzeuge, Wärmepumpen und Co. die Stromkosten für alle senken können. https://www.agora-energiewende.de/publikationen/haushaltsnahe-flexibilitaeten-nutzen.

Agora Energiewende, Prognos, Consentec (2022): Klimaneutrales Stromsystem 2035. Wie der deutsche Stromsektor bis zum Jahr 2035 klimaneutral werden kann. https://www.agora-energiewende.de/publikationen/klimaneutrales-stromsystem-2035.

Deutsche Energie-Agentur GmbH (Hrsg.) (dena, 2021). „dena-Leitstudie Aufbruch Klimaneutralität". https://www.dena.de/dena-leitstudie-aufbruch-klimaneutralitaet/.

Europäische Kommission (2023). Electricity Market Reform for consumers and annex. https://energy.ec.europa.eu/publications/electricity-market-reform-consumers-and-annex_en?prefLang=de

Gaete-Morales, C., Kramer, H., Schill, WP. et al. (2021). An open tool for creating battery-electric vehicle time series from empirical data, emobpy. Sci Data 8, 152. https://doi.org/10.1038/s41597-021-00932-9.

Kopernikus-Projekt Ariadne (2021): Ariadne-Report: Deutschland auf dem Weg zur Klimaneutralität 2045 - Szenarien und Pfade im Modellvergleich. https://doi.org/10.48485/pik.2021.006.

Nobis, C. & Kuhnimhof, T. (2018). Mobilität in Deutschland – MiD: Ergebnisbericht. https://elib.dlr.de/125879.

Neon (2023). Stromtarife für Preissicherheit und Flexibilität. Ausgestaltung eines dynamischen Tarifs mit Preisabsicherung. Kurzstudie Im Auftrag von LichtBlick SE. https://neon.energy/Neon-Dynamischer-Tarif.pdf.

Pflugradt. N., Stenzel, P., Kotzur, L., Stolten, D. (2022). LoadProfileGenerator: An Agent-Based Behavior Simulation for Generating Residential Load Profiles. Journal of Open Source Software, 7(71), 3574, https://doi.org/10.21105/joss.03574.

Prognos, Öko-Institut, Wuppertal-Institut (2021): Klimaneutrales Deutschland 2045. Wie Deutschland seine Klimaziele schon vor 2050 erreichen kann. Langfassung im Auftrag von Stiftung Klimaneutralität, Agora Energiewende und Agora Verkehrswende. https://www.agora-energiewende.de/publikationen/klimaneutrales-deutschland-2045-1.

Ruhnau, O., Muessel, J. (2023). When2Heat Heating Profiles. Open Power System Data. https://doi.org/10.25832/when2heat/2023-07-27.