38th International Electric Vehicle Symposium and Exhibition (EVS38) Göteborg, Sweden, June 15-18, 2025

Flexibility from public electric vehicle charging to reduce redispatch demand in Germany

Sabine Pelka[1], Fabian Liesenhoff[1], Daniel Speth[1], Annegret Stephan[1]
[1]*Fraunhofer Institute for Systems and Innovation Research, Breslauer Straße 48, 76139 Karlsruhe, Germany*

Executive Summary

Electric vehicles (EVs) have the potential to provide flexibility by adapting charging processes to the conditions of the energy system. This study assesses the flexibility potential of EVs charging at public charging points and its use for reducing grid congestion, i.e., redispatch demand, and its associated carbon emissions in Germany with a focus on the South-West control zone. The analysis combines data of public charging stations from 2022 and 2023 with respective redispatch activities and makes projections for the future until 2045. We identify a shifting potential of 9.8 GWh (2022) and 18.9 GWh (2023) and emission reduction potentials of 8.4 kt CO_2 (0,6% of total redispatch CO_2 emissions) and 15.8 kt CO_2 (1.4% of total redispatch CO_2 emissions), respectively. This potential will increase substantially until 2045, with a decreasing effect due to the gradual conversion of the power plant portfolio used for redispatch towards more carbon-friendly solutions.

Keywords: Electric vehicles, Consumer behaviour, Charging business models, Smart charging, Smart grid integration and grid management

1 Introduction

The increase in renewable power production and in electricity demand, in particular due to the electrification of the transport and heat sectors, pose challenges for future electricity systems and require increasing flexibility: The flexibility needs in Europe are expected to double until 2030 compared to 2021 [1]. In particular short-term flexibility (i.e., on a daily basis) is expected to increase to more than 900 TWh/year in the European Union in 2050 [2]. While uncontrolled simultaneous charging of many electric vehicles (EVs) can lead to high peak loads and grid overloads, smart charging, i.e., adapting charging processes, can provide flexibility to the power system. There are several power system applications and benefits of smart EV charging along the entire electricity value chain, ranging from supporting generation capacity and transmission and distribution planning to supporting the end consumer, e.g., by increasing the self-consumption of a photovoltaic power plant [3]. A recent study focusing on Europe estimates system cost savings of more than 10% if smart and bidirectional charging is implemented [4]. While many of the extant studies have investigated the entire power system [3] or put a dedicated focus on home and/or work charging [4] analyses of flexibility from public charging locations is scarce.

One measure, mainly used in regions with a high proportion of renewable power production, to avoid temporary bottlenecks and to ensure grid stability is redispatch. Redispatch is the request of the transmission system operators (TSOs) to power plants to shift their originally planned electricity production to keep the number of the next day's short-term, grid-stabilizing interventions at a minimum [5]. Redispatch results in ramp downs of specific power plants and ramp ups of others, i.e. shifting the electricity production from one location to another, so that supply and demand match without temporarily overloading the local network. Yet, redispatch results in less economically and environmentally friendly solutions because it causes cost and carbon emissions: (1) Power plants that are requested by the TSO to provide power and curtailment measures must be financially compensated. (2) Typically, power production by renewable power plants is replaced by traditional fossil fuel-based power production. In Germany, for example, the total cost for redispatch amounted to 1.7 billion euros (more than 60% of the total cost for grid congestion management) [6]. Nearly 10 TWh from renewable energy production had to be curtailed in 2024 [7]. Energy storage in general and the battery capacity of EVs in particular could help to reduce the curtailment of renewable power production or its replacement with fossil fuel-based power production.

Recent work has started to investigate the flexibility potential of aggregated EV fleets for redispatch in different geographies in the European electricity system. For example, earlier work [8] finds that already using 2 million EVs for redispatch in Germany can reduce the need for conventional redispatch significantly and yield in average monetary benefit of individual EVs of around 56 euros, which decreases with increasing amounts of EVs. Another study [9] find for Austria that redispatch cost and associated carbon emissions could be reduced by 3.3% and 20% respectively if 200,000 EVs (i.e., 4% of the total passenger car fleet in Austria) were used for redispatch—in contrast to market-based charging strategies, which would increase costs and carbon emissions substantially. Again, for Austria, extant work [10] finds that flexible charging of commercial fleets (light- and heavy-duty fleets and busses) can reduce redispatch costs by up to 35%. In general, extant work finds that cost and emission savings increase with an increasing number or share of EVs considered [8–10]. To the best of the authors' knowledge, extant work has yet not focused on the potential of public charging, which might be easier to implement e.g., due to more centralized, and hence coordinated, operating approaches. Moreover, improved grid integration and load management can be achieved more effectively due to the centralized nature of public charging infrastructure, which enables better real-time coordination with the grid. In addition, operating at scale allows for significant cost advantages through standardized systems and aggregated control.

In this paper, we address this gap and assess the flexibility potential of EVs charging at public charging points and its use for reducing grid congestion, i.e., redispatch demand, and associated carbon emissions. We focus on one control zone operated by one transmission grid operator in Germany and on the postponement of charging processes. Hence, we do not consider bidirectional charging, i.e., the provision of positive redispatch. We base our analysis on real-world data and combine the German charging data for public charging stations in the year 2022 and 2023 with the respective German redispatch activities. The savings are projected into the future for the key years 2025, 2030, 2040 and 2045. Our analysis yields in two main contributions: We identify the flexibility potential at public charging stations during periods of redispatch demand. Based on these findings, we derive implications for decisionmakers in industry, policy, and academia.

2 Case and method

2.1 The case of one control zone in Germany

We focus on Germany for three main reasons. First, Germany has ambitious targets for renewable power production increasing the need for grid extension and/or flexibility resources and redispatch. While Germany wants to reach net zero by 2045, it aims for a share of 80% of renewable power production by 2030 [11]. In 2024, 59% (about 255 TWh) of the produced power was provided by renewable sources, nearly half of it stemming from wind power plants [12]. Germany is increasing struggling with the incorporation of regionally clustered renewable power production, increasing the demand for redispatch from around 4 TWh in 2014 to more than 22 TWh in 2024 [13]. Costs that occur for redispatch, i.e., the financial compensation for both electricity not produced and electricity produced at a different location are ultimately transferred to the end consumer via grid surcharges [14–16]. In 2022, redispatch caused an increase of approximately one million tons CO_2, resulting from the curtailment of renewable (mostly wind) power production, which was replaced mostly by coal power production [16].

Second, Germany has ambitious targets for the deployment of EVs: It aims to reach 15 million EVs by 2030 [17, 18]. While EV deployment decreased in 2024, an increase can be seen at the beginning of 2025 [19]. While these EVs can stress the grid in case of fast and cumulative charging, they can also serve as a source for redispatch and other flexibility services.

Third, Germany has ambitious targets for public charging infrastructure and supports its deployment—in line with activities also ongoing on European level such as the Alternative Fuels Infrastructure Regulation (AFIR), which entered into force in 2024 [20]. Until 2030, Germany wants to have one million public charging points and since 2017, the German government has been supporting the deployment of charging infrastructure [21]. With tenders for the "Deutschlandnetz", a policy measure to support the deployment of public charging infrastructure at currently underexplored locations, for example, the German government has supported 9.000 additional fast charging points at 1.100 locations since 2021 [22]. Currently, there are about 125,000 normal charging points and 36,000 fast charging points in operation (February 2025) with a total capacity of 6.11 GW in case of simultaneous charging [23]. In 2019, Germany established the National Centre for Charging Infrastructure, which coordinates the activities on charging infrastructure in Germany and across levels (federal, state, municipality) [24]. The National Centre for Charging Infrastructure also helped in developing the Charging Infrastructure Masterplan II, containing measures to support the deployment of charging infrastructure suitable for current and future demand and being user-friendly [25].

Unlike in many other (European) countries, the German electricity transmission grid has been divided into four zones since 2012, which are managed by different TSOs [26]. Redispatch is coordinated within one control zone and across zones. In 2024, 31% of the redispatch energy occurred within one zone and 69% across zones [27]. In this paper, we focus on the flexibility potential and emission reduction in one control zone. We chose the control zone in the south-west of Germany, which is the geographically smallest and most compact control zone of the four zones. Moreover, this zone exhibits relatively high requests for positive redispatch power capacity [28], which they might want to reduce. We discuss the generalizability of our findings to other zones and countries.

2.2 Charging data

Our analyses are based on the collection of the actual charging behavior of battery EVs at publicly funded charging points in Germany; the data was provided by the National Centre for Charging Infrastructure (NLL)[1]. Our database consists of around 11.5 million charging processes from the years 2022 and 2023, of which around 8 million charging processes occurred at public normal charging points ($\leq$ 22 kW) and 3.4 million charging processes at fast charging points (>22 kW). We focus on normal charging points because we consider the flexibility potential at fast charging points rather small. The data was scaled to the selected control zone using a scaling factor of 1.27 based on the existing availability of charging points in 2023[2]. For each charging process, the data consists of an identifier for the charging station and charging point, the nominal capacity of the charging point, the beginning and the end of the plug-in duration, the plug-in duration and the amount of energy charged during the plug-in time. Table 1 gives an overview of the public charging processes in Germany in 2022 and 2023 by summarizing the amount of energy delivered, the number of charging processes, charging stations and charging points for normal charging included in the data set over the half-years.

[1] https://nationale-leitstelle.de/

[2] In 2023, Germany had 93,000 charging points with capacities <= 22kW, whereof 16,200 were located in the area of the considered control zone.

Table 1: Overview of public charging processes (≤ 22 kW) in Germany in 2022 and 2023. Source: Based on data from the National Centre for Charging Infrastructure (NLL)

	01/2022-06/2022	**07/2022-12/2022**	**01/2023-06/2023**	**07/2023-12/2023**
Energy [kWh]	26,613,768	31,122,384	33,945,608	36,408,309
Charging processes	1,840,708	2,020,986	2,070,613	2,085,430
Charging stations	6,579	6,596	6,653	6,634
Charging points	12,515	12,563	12,717	12,640

Figure 1 shows the energy demand of public normal charging points in the years 2022 and 2023. Seasonal fluctuations are shown: charging demand is higher in winter than in summer. This could be explained by the higher energy consumption of EVs at lower temperatures in winter, especially due to heating demand. The analysis also shows higher charging demand during the day, when EV owners use public charging stations.

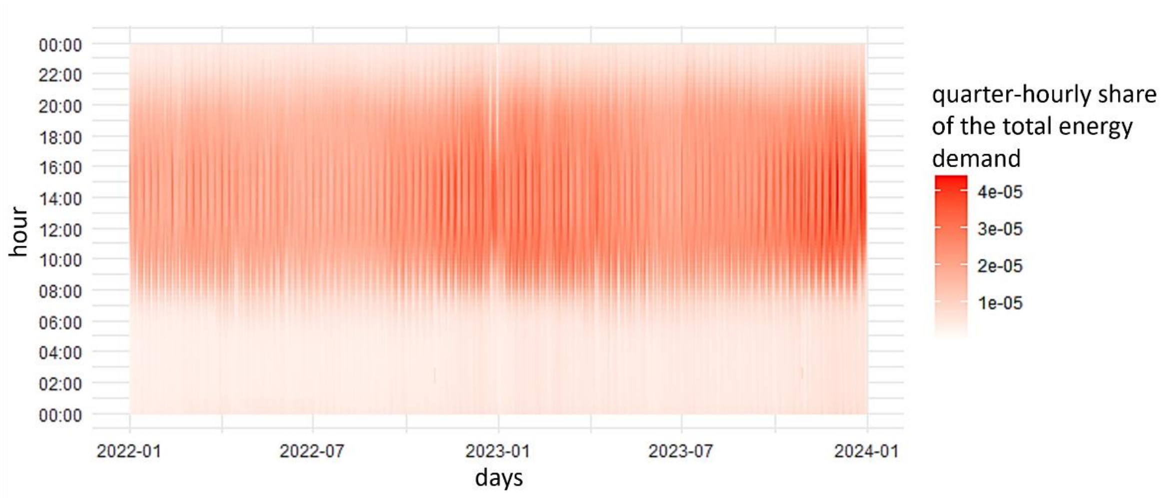

Figure 1: Annual energy demand at normal public charging points in 2022 and 2023. Source: Own illustration, based on data from the National Centre for Charging Infrastructure (NLL)

To estimate future charging demand, we assume that charging infrastructure will develop similarly to the vehicle stock, i,e. the ratio of vehicles to charging points remains constant. To estimate the future vehicle stock, the development of the long-term scenarios prepared on behalf of the German Federal Ministry of Economics and Climate Protection (BMWK) is assumed. An average between a highly electrified scenario (O45-Strom) and a scenario that also includes hydrogen (O45-H2) is chosen. Figure 2 shows the assumed development of the vehicle stock and charging points over time.

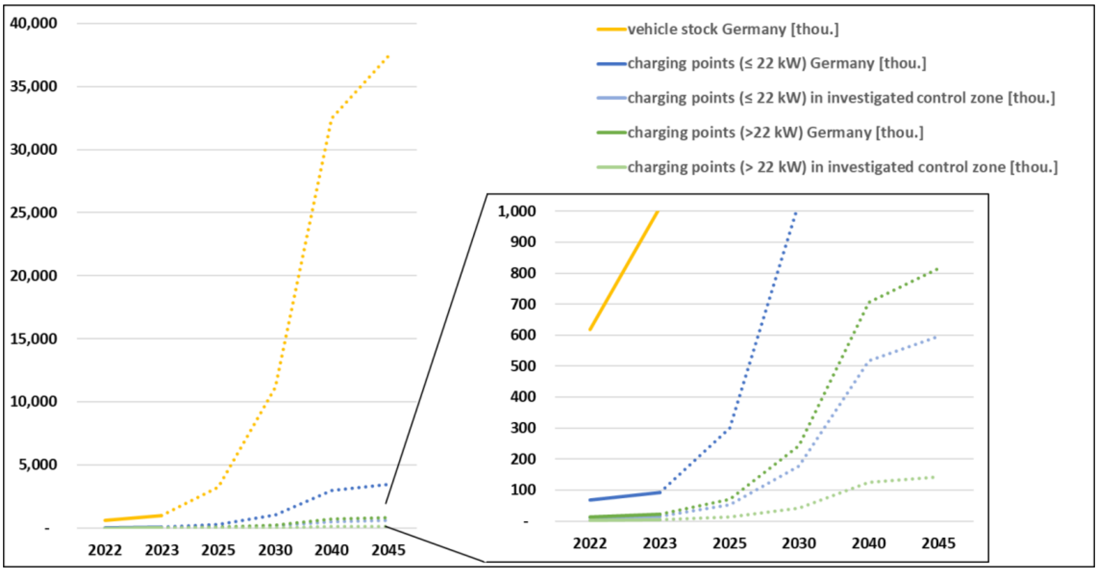

Figure 2: Assumed development of vehicle stock and charging points in Germany

Furthermore, we assume that the charging and plug-in behavior and the utilization of individual charging stations do not change over time. Shifts in charging behavior can only occur within the plug-in time.

2.3 Redispatch Data

The data on the redispatch activities in Germany is publicly available and provided by the German TSOs [27]. Figure 3 shows that from 2022 to 2023, both the annual redispatch volume (from 4,701 GWh in 2022 to 3,869 GWh in 2023) and the number of redispatch processes (from 2741 to 2605) and thus also the median redispatch duration (from 6,75 h to 5,5 h) declined in the considered control zone.

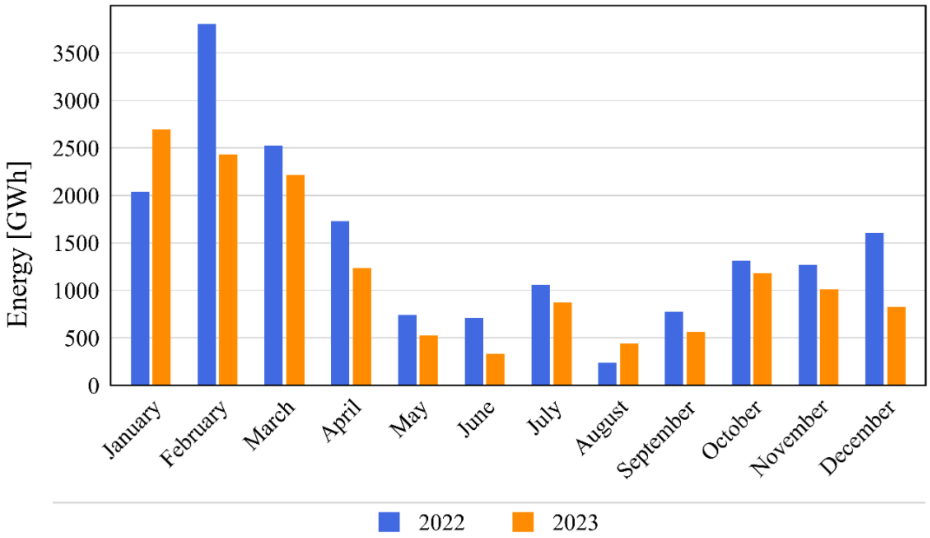

Figure 3: Monthly redispatch volume in the considered control zone in 2022 and 202. Source: Own illustration based on data provided by the German TSOs [27].

A comparison between the charging and redispatch data shows that the redispatch volume and duration significantly exceed those of the charging processes in the years considered: In South-West Germany, the energy volume provided by redispatch activities is about 77 (2022) and 32 times larger (2023) than the total charging volume. Additionally, the average duration of a redispatch activity is 2-3 times longer than a typical charging process. Also, the redispatch volumes show strong seasonal differences. The requested volumes are significantly lower in summer than in winter. This may be due to high feed-in of photovoltaic power between April and September in southern Germany, and increased electricity production from wind during winter months. As the majority of wind power capacity is installed in northern Germany, this results in corresponding capacity utilization in the transmission grid, which also requires redispatch in the south. The high volume of redispatch demand, the increasing numbers of EVs in the future and a similar seasonality of redispatch and public charging render EV flexibility a promising option for replacing redispatch power plants.

Figure 4 shows the shares of the different energy carriers on the requested redispatch volumes in the considered control zone in 2022 and 2023. Coal-fired power plants provided 86 % (2022) and 83 % (2023) of the requested redispatch volume of 4.7 TWh and 3.9 TWh, respectively. Hydropower accounted for 12 % (2022) and 15 % (2023), while the remining requested redispatch was covered by oil, gas and purchased exchange electricity.

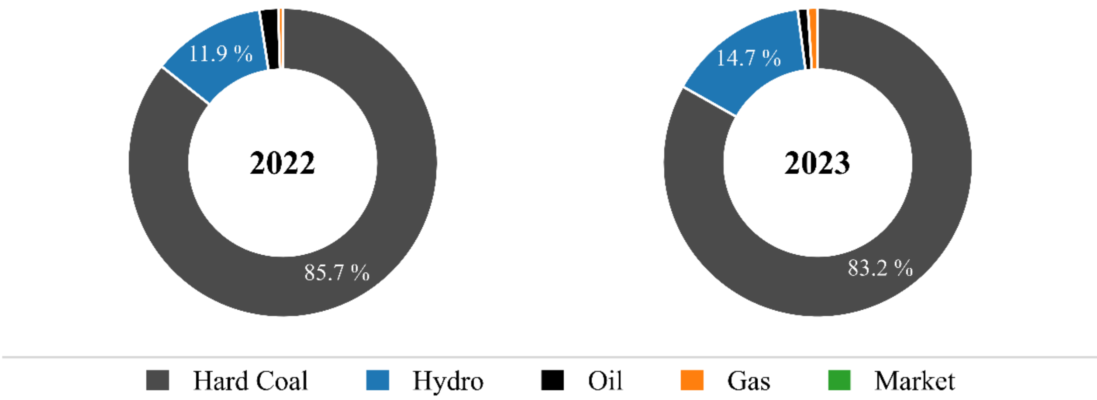

Figure 4: Shares of different energy carriers on the requested redispatch volumes in the considered control zone in 2022 and 2023. Source: Own illustration based on data provided by German TSOs [27].

For the calculation of the emission savings, we assume that the redispatch is provided by those power plants with the highest emission avoidance potential. Yet, in practice, other factors such as the operationalization of the power plants can also play a role in the selection of power plants. Table 2 shows the carbon emission factors by the different power plant types [29].

Table 2: Emission factors considered for the different types of power plants

Types of power plant	**Emission factor [tons CO_2/MWh]**
Gas	0.20
Oil	0.28
Hard coal	0.33

We base our assumptions regarding the future development of redispatch based on the network development plans (NEP) prepared by the TSOs. Depending on the scenario, the most recent NEP 2037/2045 (2023) assumes redispatch volumes between 1.5 and 3.4 TWh for the year 2037 for Germany [30]. We scale these data based on the historical proportions to the considered control zone and hence, assume a constant ratio between the redispatch volumes in the considered area and the redispatch volumes in Germany. In addition, we assume changes in the portfolio of power plants providing redispatch. The strong dependence on fossil fuel-fired power plants, especially coal-fired power plants, will be replaced by the gradual transformation of the energy system towards less carbon intense power plants, which also reduces the achievable avoidance of carbon emissions in the future. In Germany, the phase-out of coal power plants has been agreed in 2020 [31], which will gradually reduce the remaining lignite and hard coal capacities (15.1 GW and 17.5 GW respectively in 2023) by 2038 at the latest. However, the NEP assumes that hard coal-fired power generation will be phased out completely as early as 2035, and even for lignite, only one scenario of the NEP 2035 (2021) assumes residual capacities of 7.8 GW in that year. According to the current NEP, the already small installed capacity of oil-fired power plants is also to be completely dismantled by 2037. Gas-fired power plants are an exception to this development. Their existing capacity of currently 36 GW (2023) is to be largely retained across all scenarios assumed in the NEP. In addition, with the agreement on the power plant strategy as part of the last German government's growth pact for the economy, tenders have been invited for the modernization and new construction of gas-fired power plants. In addition to 500 MW of pure hydrogen power plants and 7 GW of hydrogen-ready power plants, 5 GW of pure gas-fired power plants are planned, which should contribute to security of supply, particularly during dark and windless periods. If installed in southern Germany, they should also contribute to grid stability and a reduction in redispatch cost [32]. In contrast to the NEP, the long-term scenarios also consider the dismantling of gas-fired power plants and the ramp-up of hydrogen power plants, so that by 2040, natural gas will have been completely replaced by hydrogen and fossil fuels will no longer play a role.

2.4 Restrictions for charging shifts to replace redispatch power plants

Figure 5 shows the installed capacity of the charging station and the actual power charged for all charging processes. We can observe that in most cases the average charging power is less than the installed capacity of the station. This means that the charging process can be accelerated by increasing the charging power up to the capacity limit of the station. As many vehicles are not able to slowly charge with more than 11 kW, charging events with less than 11 kW on average are assumed to have a maximum of 11 kW, even if the installed capacity is higher. The lower the amount of energy charged in relation to the duration of the charging process, the higher the scope regarding the time it can be shifted. However, the recharged energy also limits the amount of energy that can be shifted.

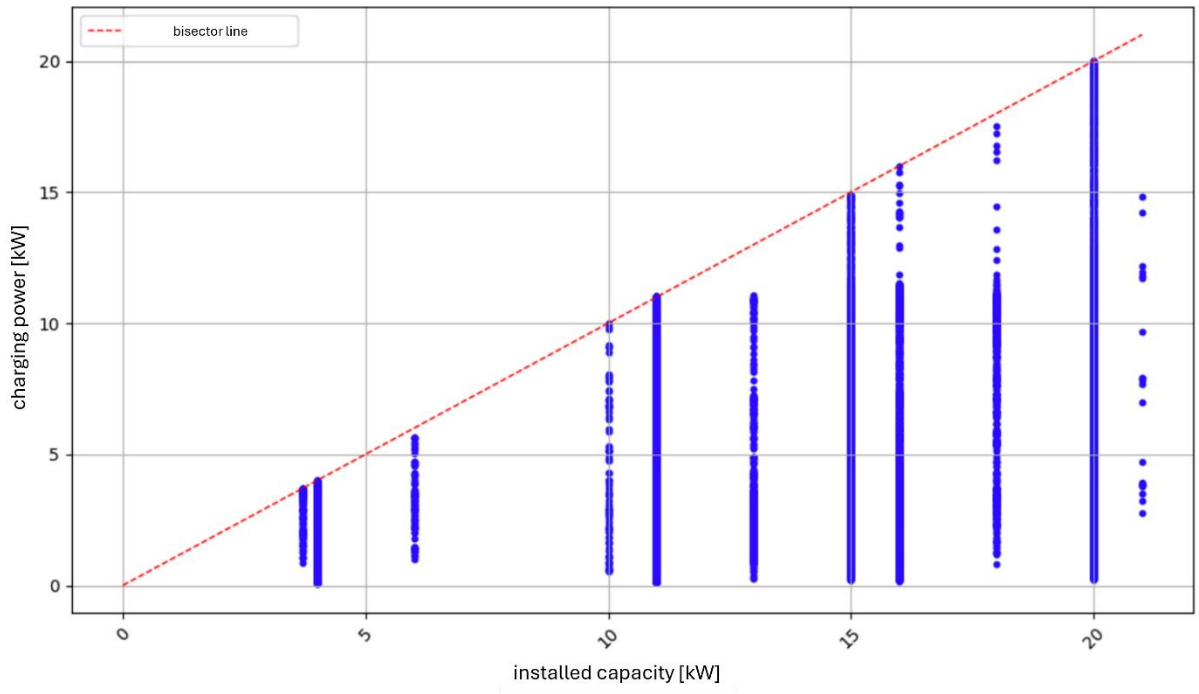

Figure 5: Installed capacity and charging power per charging process at public charging stations in Germany

We apply two boundary conditions to the shifting of EV charging loads to reduce redispatch and to determine the amount of energy that can be shifted. Condition 1: The charging process occurs at the same time as the redispatch process. Condition 2: The amount of energy shifted can be covered during the same plug-in time. This assumes that the provision of flexibility affects neither the mobility nor the assumed comfort of the EV user. Figure 6 illustrates the two conditions applied.

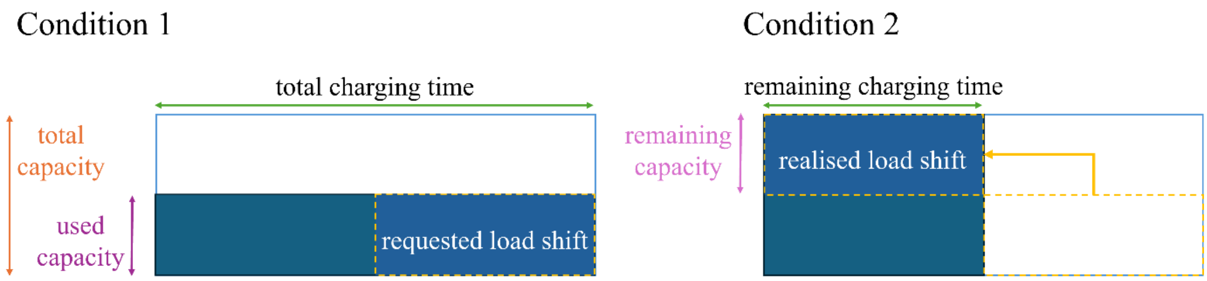

Figure 6: Schematic illustration of the two conditions applied for shifting charging loads

3 Results

Figure 7 shows the emission reduction potential for the years 2022 and 2023 and the future development of the years 2030, 2040 and 2045, based on three different scenarios – (1) technology mix of 2023, (2) 100% natural gas, and (3) a mixture of 50% natural gas and 50% hydrogen – for the future power plant fleet.

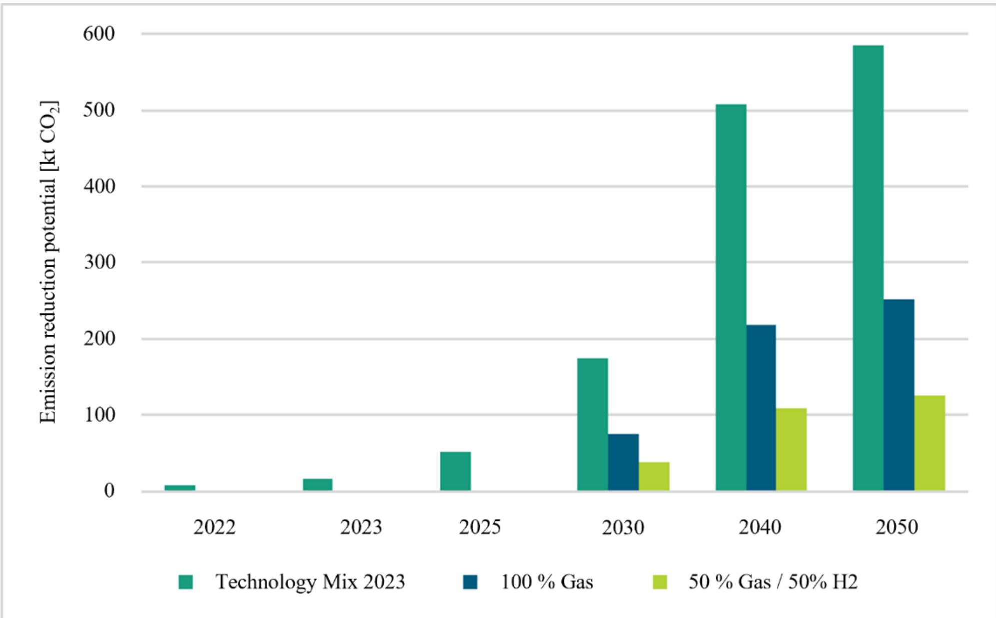

Figure 7: Emission reduction potential using electric vehicles for redispatch, considering three scenarios for the power plant mix

3.1 Emission reduction potential in 2022 and 2023

Our assessments for the years 2022 and 2023 show that shifting energy volumes could have saved 8.4 kt CO_2 and 15.8 kt CO_2 of emissions from reduced redispatch, respectively. In 2022, this corresponds to 0.6% of total redispatch emissions and increases to 1.4% in 2023. These carbon emission savings are associated with energy volumes of 9.8 GWh and 18.9 GWh that can be shifted. Hence, 2.5 kWh (2022) and 3.8 kWh (2023) of energy can be shifted on average per charging process, relating to savings of approximately 142 g CO_2 (2022) and 188 g CO_2 (2023) per charged kWh.

As explained in section 2.4, only the amount of energy that is charged in parallel to occurring redispatch operations (condition 1) and that can still be charged during the same charging process (condition 2) can be used as flexibility. The analysis of the effect of condition 1 shows that a large proportion of the charging processes (77-83% depending on the seasonal quarter) occur during a redispatch process. Due to the higher redispatch volume in the winter than in the summer, charging and redispatch processes in particular occur simultaneously in the first and fourth quarters. It can also be seen that a large proportion of the energy (69-73% depending on the seasonal quarter) is charged during a redispatch process. The analysis for condition 2 examines the extent to which the amount of energy that is charged at the same time as the redispatch process can be added at other points in the same charging process, considering the remaining charging capacity and time. The remaining charging time is the strongest constraint on the amount of energy that can be shifted. In most cases, the charging capacity can be increased to make up for the amount of energy that has been shifted. However, two-thirds of the charging processes take place entirely during a redispatch process. In this case, postponing the charging process would not be possible, since the avoided power plant utilization at that point in time would have to be made up at a different point in time. 25%-33% of the simultaneous charging volume can be used as flexibility, depending on the seasonal quarter of 2022 and 2023. While currently EV drivers are incentivized to plug out their EVs after a specific time, e,g., by charging a premium for charging durations longer than four hours, more flexibility could be provided if cars were plugged-in for longer periods.

3.2 Future emission reduction potential

The future potential of redispatch emission reduction is affected by three partially opposing developments. First, the potential for load shifting will increase due to the growing number of EVs. The current long-term scenarios from the BMWK assume 11.2 million EVs in 2030 and 37.4 million in 2045. Second, the necessity of redispatch measures will decrease due to the expansion of renewable power production in southern Germany and increased capacities in the transmission grid. Third, the composition of the power plant portfolio and the associated CO_2 intensity will change. To be able to quantify the possible savings, a complete conversion to fossil gas (100% gas) and a provision by gas and hydrogen to the same extent (50% gas and 50% green hydrogen) are assumed. We compare these two scenarios with a scenario that extrapolates the current power plant portfolio.

Our results show that in 2030, 175 kt CO_2 could be saved, assuming the 2023 power plant portfolio, which is reduced to 75 kt CO_2 (100% gas power plants) and even further to 37,5 kt CO_2 (50% gas and 50% green hydrogen). From 2045, the potential for carbon emission reduction in more than 500 kt CO_2, assuming a 2023-power plant mix, and more than 200 kt CO_2 or 100 t CO_2 considering the gas-only and the gas-and-hydrogen scenarios, respectively.

4 Discussion

Our results show that flexible charging at public charging points can reduce redispatch requirements and carbon emissions. Controlling charging processes in a way that specifically targets the reduction of redispatch requirements can help to reduce power demand at critical parts of the grid and hence, reduce the necessity for more fossil fuel-based power for redispatch. In the short and medium term in particular, flexible charging at public charging stations for redispatch offers a starting point for avoiding high emissions from fossil fuel-fired power plants, especially those fueled by coal (e,g., nearly 16 kt of CO_2 would have been possible in 2023). In the longer term, the importance of emission reduction in redispatch will increase less due to the expansion of renewable energy, increased capacities in the transmission grid and the generally lower-emission power plant fleet. While the overall effect is relatively small (0.6%-1.4% of the overall redispatch emissions in the years 2022 and 2023, respectively), the effect is increasing over time.

This potential can be further increased with several measures such as incentivizing longer plug-in durations, shifting between charging periods, and considering bidirectional charging. Longer plug-in durations would increase the time that can be used to shift loads and hence, the potential. Yet, changing plug-in behavior into the desired direction would require respective incentives, or at least the elimination of fees for long-term charging. EV drivers would ideally share their departure time with the operators. Moreover, shifting loads not only within but also between charging periods offers more options to provide flexibility, not only regarding timing but also considering different locations. On top, bidirectional charging would also allow for the feed in of power from the EVs into the grid or other loads and provide an additional buffer capacity as well as positive redispatch. In addition, dynamic electricity tariffs, which electricity suppliers have to offer in Germany since the beginning of 2025 [33], create a direct financial incentive to charge the EV during periods of high availability of renewable energies. While, hence, EV charging would help to increase the feed-in of high amount of renewable power, the interplay between charging according to dynamic tariffs and redispatch requires more investigation. In addition to investigating the measures mentioned, further research should also aim to better understand the interplay of the effects of different optimization strategies, such as charging strategies that aim to reduce redispatch with others, which aim to increase the self-consumption of locally produced photovoltaic power. Moreover, including private charging stations into redispatch would probably have a substantial effect that could yield in much higher emission savings such as those identified in extant work [9]. Private charging of fleets or commercial cars at companies or depots (normal charging), in particular, could also increase the potential substantially. These cases seem to be very promising because of relatively well-known and plannable plug-in and charging times. However, the operation of private charging points would be more difficult due to many individual actors and interests as well as charge point operators involved. Including fast charging could also increase the potential – yet to a relatively small extent due to the relatively short plug-in duration limiting the potential for load shifting.

We consider our general findings being transferrable also to those control zones in Germany and beyond that exhibit similar redispatch mechanisms and power plant portfolios. Yet, the extent of the effect ultimately depends on the redispatch requirements of the respective control zones as well as the number of EVs and public charging stations considered. The control zone under consideration is characterized by a high demand for additional power plant output in the event of redispatch, whereas only small amounts of generation need to be curtailed. In addition, it has a relatively small geographic area, indicating that the number of public charging points as well as of electric vehicles, limiting the flexibility potential, might not exceed those of the other control zones. Yet, given the interplay of many different effects, the exact potential for other control zones and countries would have to be determined by further research.

Our study does not come without limitations. We highlight three limitations because they might affect the results. First, our findings assume perfect foresight for charging processes. While there might be patterns, exact loads and timings are unknown, and buffer capacities would need to be considered reducing the total flexibility potential. Second, we do not consider capacity limitations on the vehicle side. While we cap maximum charging capacities at 11 kW in case vehicles charge at smaller capacities, we ignore that some vehicle might not be able to even charge at 11 kW, which would also further reduce the potential and the emission savings. Finally, we assume that all publicly charged EVs participate in the provision of flexibility for redispatch. However, not all EV drivers might be willing to participate, also reducing the potential. Considering more technical and social restrictions might, hence, reduce the overall potential. Yet, there are also options to counteract these effects at least partly in practice such as sharing departure times with charge point operators, increasing charging capacities at the vehicle side and implementing measures such as information campaigns to increase the willingness of EV drivers to contribute to system stability by allowing the provision of flexibility. Incentive mechanisms for vehicle owners are not part of our analysis but should be given closer consideration in future.

Acknowledgments

This publication was written in the framework of the KAMO High Performance Center Profilregion, which is funded as a national High Performance Center by the Fraunhofer-Gesellschaft. AS and DS acknowledge funding from the German Federal Ministry of Education and Research (Ariadne project FKZ 03SFK5D0-2).

References

[1] EEA/ACER, “Flexibility solutions to support a decarbonised and secure EU electricity system,” European Environment Agency, Luxembourg, 2023.

[2] D. Koolen, M. de Felice, and S. Busch, “Flexibility requirements and the role of storage in future European power systems: A 2030 and 2050 modelling assessment with METIS,” European Commission, Luxembourg, EUR JRC130519, 2023.

[3] M. B. Anwar *et al.*, “Assessing the value of electric vehicle managed charging: a review of methodologies and results,” *Energy Environ. Sci.*, vol. 15, no. 2, pp. 466–498, 2022, doi: 10.1039/D1EE02206G.

[4] M. Kühnbach *et al.*, “Potential of a full EV-power-system-integration in Europe and how to realise it,”

Study on behalf of Transport & Environment, Fraunhofer Institute for Solar Energy Systems ISE, Fraunhofer Institute for Systems and Innovation Research ISI, Freiburg, Karlsruhe, 2024.
[5] *What are Dispatch and Redispatch?* [Online]. Available: https://www.next-kraftwerke.com/knowledge/dispatch (accessed: Apr. 24 2025).
[6] Statista, *Kosten für Netzengpassmanagementmaßnahmen im deutschen Stromnetz nach Art in den Jahren von 2019 bis 2024 (in Milliarden Euro) [Graph].* [Online]. Available: https://de.statista.com/statistik/daten/studie/618806/umfrage/kosten-fuer-die-sicherstellung-der-versorgungssicherheit-des-deutschen-stromnetzes/ (accessed: Apr. 24 2025).
[7] Statista, *Entwicklung der Ausfallarbeit durch Redispatch von erneuerbaren und konventionellen Kraftwerken in Deutschland von 2019 bis 2024 (in Gigawattstunden) [Graph].* [Online]. Available: https://de.statista.com/statistik/daten/studie/617949/umfrage/einspeisemanagement-in-deutschland/ (accessed: Apr. 24 2025).
[8] P. Staudt, M. Schmidt, J. Gärttner, and C. Weinhardt, "A decentralized approach towards resolving transmission grid congestion in Germany using vehicle-to-grid technology," *Applied Energy*, vol. 230, pp. 1435–1446, 2018, doi: 10.1016/j.apenergy.2018.09.045.
[9] C. Loschan, D. Schwabeneder, G. Lettner, and H. Auer, "Flexibility potential of aggregated electric vehicle fleets to reduce transmission congestions and redispatch needs: A case study in Austria," *International Journal of Electrical Power & Energy Systems*, vol. 146, p. 108802, 2023, doi: 10.1016/j.ijepes.2022.108802.
[10] A. Golab, C. Loschan, S. Zwickl-Bernhard, and H. Auer, "The value of flexibility of commercial electric vehicle fleets in the redispatch of congested transmission grids," *Energy*, vol. 316, p. 134385, 2025, doi: 10.1016/j.energy.2025.134385.
[11] Deutsche Bundesregierung, *Wo steht Deutschland bei der Energiewende | Bundesregierung.* [Online]. Available: https://www.bundesregierung.de/breg-de/aktuelles/faq-energiewende-2067498 (accessed: Apr. 24 2025).
[12] Bundesnetzagentur, *Bundesnetzagentur veröffentlicht Daten zum Strommarkt 2024.* [Online]. Available: https://www.bundesnetzagentur.de/SharedDocs/Pressemitteilungen/DE/2025/20250103_smard.html (accessed: Apr. 24 2025).
[13] Statista, *Entwicklung des Gesamtvolumens der Redispatchmaßnahmen im deutschen Übertragungsnetz in den Jahren 2014 bis 2024 (in Gigawattstunden) [Graph].* [Online]. Available: https://de.statista.com/statistik/daten/studie/916903/umfrage/volumen-redispatchmassnahmen-im-deutschen-uebertragungsnetz/ (accessed: Apr. 24 2025).
[14] *Verordnung über die Entgelte für den Zugang zu Elektrizitätsversorgungsnetzen (Stromnetzentgeltverordnung - StromNEV)*, 2005. Accessed: Apr. 25 2025. [Online]. Available: https://www.gesetze-im-internet.de/stromnev/BJNR222500005.html
[15] TenneT, *Redispatch: Systemsicherung im Übertragungsnetz.* [Online]. Available: https://www.tennet.eu/de/blog/redispatch-systemsicherung-im-uebertragungsnetz (accessed: Apr. 25 2025).
[16] M. Wettingfeld, P. Martin, and F. Collmer, "Redispatch im deutschen Stromsystem - Hintergründe, Kostenverteilung, Emissionen: Kurzstudie für die EWS Elektrizitätswerke Schönau eG," Sep. 2023. (accessed: Apr. 24 2025.)
[17] D. Bundestag, "Antwort der Bundesregierung auf die Kleine Anfrage der Abgeordneten Leif-Erik Holm, Dr. Malte Kaufmann, Enrico Komning, weiterer Abgeordneter und der Fraktion der AfD – Drucksache 20/10591 – Wirksamkeit der Zuschüsse zur Neuanschaffung von Elektrofahrzeugen," *Deutscher Bundestag Drucksache*.
[18] Sozialdemokratische Partei Deutschlands (SPD), BÜNDNIS 90/DIE GRÜNEN, and Freie Demokratische Partei (FDP), Eds., "Mehr Fortschritt wagen – Bündnis für Freiheit, Gerechtigkeit und Nachhaltigkeit: Koalitionsvertrag 2021-2025 zwischen der Sozialdemokratischen Partei Deutschlands (SPD), BÜNDNIS 90/DIE GRÜNEN und den Freien Demokraten (FDP)," Berlin, Dec. 2021. (accessed: Apr. 25 2025).
[19] Statista, *Anzahl der Neuzulassungen von Elektroautos in Deutschland von 2003 bis März 2025 [Graph].* [Online]. Available: https://de.statista.com/statistik/daten/studie/244000/umfrage/neuzulassungen-von-elektroautos-in-deutschland/ (accessed: Apr. 24 2025).
[20] European Commission, *Alternative Fuels Infrastructure.* [Online]. Available: https://transport.ec.europa.eu/transport-themes/clean-transport/alternative-fuels-sustainable-mobility-europe/alternative-fuels-infrastructure_en (accessed: Apr. 24 2025).
[21] Deutsche Bundesregierung, *Mehr Ladepunkte für E-Autos.* [Online]. Available: https://www.bundesregierung.de/breg-de/aktuelles/ladepunkte-in-deutschland-1884666 (accessed: Apr. 24 2025).
[22] Nationale Leitstelle Ladeinfrastruktur, *The Deutschlandnetz.* [Online]. Available: https://nationale-

leitstelle.de/en/deutschlandnetz/ (accessed: Apr. 24 2025).
[23] Bundesnetzagentur, *E-Mobilität: Öffentliche Ladeinfrastruktur.* [Online]. Available: https://www.bundesnetzagentur.de/DE/Fachthemen/ElektrizitaetundGas/E-Mobilitaet/start.html (accessed: Apr. 24 2025).
[24] Nationale Leitstelle Ladeinfrastruktur, *Nationale Leitstelle Ladeinfrastruktur.* [Online]. Available: https://nationale-leitstelle.de/en/ (accessed: Apr. 24 2025).
[25] Bundesministerium für Digitales und Verkehr (BMDV), Ed., "Masterplan Ladeinfrastruktur II der Bundesregierung," Oct. 2022. Accessed: Apr. 24 2025.
[26] Bundesnetzagentur, *Regelzone.* [Online]. Available: https://www.smard.de/page/home/wiki-article/446/205156 (accessed: Apr. 24 2025).
[27] netztransparenz.de, *Redispatch.* [Online]. Available: https://www.netztransparenz.de/en/Ancillary-Services/System-operations/Redispatch (accessed: Apr. 24 2025).
[28] Bundesnetzagentur, *Netzengpassmanagement.* [Online]. Available: https://www.bundesnetzagentur.de/DE/Fachthemen/ElektrizitaetundGas/Versorgungssicherheit/Netzengpassmanagement/start.html (accessed: Apr. 24 2025).
[29] "Informationsblatt CO2-Faktoren: Bundesförderung für Energie- und Ressourceneffizienz in der Wirtschaft - Zuschuss," Feb. 2025. (accessed: Apr. 25 2025).
[30] Übertragungsnetzbetreiber, Ed., "Netzentwicklungsplan Strom 2037/2045, Version 2023: Zweiter Entwurf der Übertragungsnetzbetreiber," 2023. (accessed: Apr. 24 2025).
[31] Deutsche Bundesregierung, *Von der Kohle zur Zukunft.* [Online]. Available: https://www.bundesregierung.de/breg-de/bundesregierung/gesetzesvorhaben/kohleausstieg-1664496 (accessed: Apr. 24 2025).
[32] Bundesministerium für Wirtschaft und Klimaschutz (BMWK), *Auf dem Weg zur klimaneutralen Stromerzeugung: Grünes Licht für Kraftwerkssicherheitsgesetz*, 2024. (accessed: Apr. 24 2025). [Online]. Available: https://www.bmwk.de/Redaktion/DE/Pressemitteilungen/2024/07/20240705-klimaneutrale-stromerzeugung-kraftwerkssicherheitsgesetz.html
[33] Bundesministerium für Wirtschaft und Klimaschutz (BMWK), *Smart Meter-Gesetz final beschlossen: Flächendeckender Einsatz intelligenter Stromzähler kommt: Bis 2032 sollen Smart Meter weitgehend Standard sein und althergebrachte Stromzähler ersetzen*, 2023. (accessed: Apr. 24 2025). [Online]. Available: https://www.bmwk.de/Redaktion/DE/Pressemitteilungen/2023/05/20230512-smart-meter-gesetz-final-beschlossen.html

Presenter Biography

Dr. Annegret Stephan is a senior researcher at the Fraunhofer Institute for Systems and Innovation Research ISI in Karlsruhe (Germany). Her research centers on technological innovation for a clean energy system, specifically on the coupling of the energy and transport sectors. After studying business engineering at Karlsruhe Institute of Technology (KIT), she conducted her doctoral thesis with a focus on energy technology innovations, specifically batteries, in the Group for Sustainability and Technology (SusTec) at ETH Zurich (2013-2016) and continued working in this group as postdoctoral and senior researcher (2017-2021) before joining the Competence Center Energy Technologies and Energy Systems of Fraunhofer ISI in 2022.