Power sector effects of alternative options for electrifying heavy-duty vehicles

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Short summary

In the passenger car segment, battery-electric vehicles have emerged as the most promising option to decarbonize transportation. For heavy-duty vehicles, the technology space still appears to be more open. Aside from stationary-charged battery-electric trucks, electric road systems (ERS) for dynamic power transfer to electric vehicles are also discussed, as well as trucks that use hydrogen fuel cells or e-fuels. Here we investigate the power sector implications of these different options. We apply an open-source power sector capacity expansion model to future scenarios of Germany with high renewable energy shares, drawing on detailed route-based truck mobility data. Results show that power sector costs are highest in the case of e-fuels, and lowest for battery-electric and ERS trucks. The latter technologies can generally provide more temporal flexibility to the power sector than battery-electric and ERS trucks. Yet, these flexibility benefits do not outweigh their disadvantages in terms of energy efficiency. In equilibrium, the different flexibility characteristics lead to higher capacity expansion and use of solar PV for battery-electric and ERS trucks, and to a higher use of wind power for hydrogen and e-fuel trucks. If battery-electric and ERS trucks are charged in a non-optimized manner, power sector costs increase, but still remain below those of hydrogen and e-fuel trucks.

Keywords: Battery-electric vehicles, Catenary, Electrification and decarbonization of transport, Heavy-duty vehicles, Hydrogen, Power sector modeling.

1 Introduction

Making energy consumption climate neutral in all end-use sectors is of paramount importance for mitigating climate change de Coninck et al. (2018). A key strategy for achieving this is to substitute fossil fuels by renewable electricity, facilitated by direct or indirect electrification of end uses in mobility, heating, and industrial applications Shukla et al. (2022). In the transportation sector, battery-electric vehicles (BEV) have emerged as the most promising option for the passenger car segment. Already today, BEV can lead to sizeable greenhouse gas emission reductions compared to internal combustion engines Hoekstra (2019), which will further increase when the electricity mix becomes cleaner. In many countries, markets for electric passenger cars have been soaring in the past years, and are expected to continue to grow strongly in the near future IEA (2022). For heavy-duty vehicles (HDV), however, the technology space still appears to be more open. While the feasibility of pure battery-electric HDV has been assessed to be increasing Nykvist & Olsson (2021), they compete with other options. This includes electric road systems (ERS), which allow for dynamic power transfer to electric vehicles on the road (Boltze et al., 2020; Speth & Funke, 2021); trucks with hydrogen fuel cells; or conventional HDV with internal combustion engines that use liquid e-fuels which are produced with renewable electricity Hannula & Reiner (2019); Lajevardi et al. (2022); Plötz (2022); Li et al. (2022).

These options of direct or indirect electrification of HDV have different properties concerning, on the one hand, energy efficiency, and, on the other hand, temporal flexibility of electricity use. For example, direct electrification via BEV is more energy efficient compared to indirect electrification via electrolysis-based hydrogen or e-fuels Ueckerdt et al. (2021); Lajevardi et al. (2022). Yet, the temporal flexibility of BEV may be constrained by charging availability and limited battery capacities, as vehicle batteries are costly and heavy. In contrast, indirect electrification via hydrogen or e-fuels may entail large-scale and low-cost storage options Taljegard et al. (2017); Stöckl et al. (2021), but the overall energy efficiency of these supply chains is lower compared to BEV. Temporal power sector flexibility becomes increasingly important with growing shares of renewables, as the potential for firm renewable generation such as hydropower, bioenergy, or geothermal power is limited in many countries. In contrast, wind and solar power potentials are often abundant, but they have variable generation profiles that depend on weather conditions and daily and seasonal cycles (López-Prol & Schill, 2021). Integrating growing shares of such variable renewables thus requires an increasing use of flexibility options in the power sector (Kondziella & Bruckner, 2016).

Against this background, we investigate the power sector implications of different options for (in-)directly electrifying HDV, particularly focusing on the trade-off between energy efficiency and temporal flexibility. To do so, we apply an open-source capacity expansion model Zerrahn & Schill (2017); Gaete-Morales, Kittel, et al. (2021) to 2030 scenarios of the Central European power sector with high renewable energy shares. We focus on the domestic traffic of HDV in Germany with a gross vehicle weight above 26 tonnes, drawing on a detailed data set of truck trips on inner-German origin-destination pairs. We include stationary-charged BEV trucks as well as hybrid battery-catenary trucks as a particular example of an electric road system technology (ERS-BEV), fuel-cell hydrogen electric trucks (FCEV), and such with internal diesel combustion engines powered by e-fuels (ICEV PtL). For hydrogen, we further differentiate two domestic supply chains, either decentralized electrolysis at filling stations, which is temporally inflexible, or centralized electrolysis and transport via gaseous hydrogen, which also comes with low-cost storage opportunities and is thus more flexible. We compare the power sector costs of these options, as well as their repercussions on the optimal power plant fleet, under different assumptions on the temporal flexibility of the electric load of electric HDV usage.

While there is a broad literature on the potential power sector impacts of battery-electric passenger cars Richardson (2013); Muratori & Mai (2020); Mangipinto et al. (2022), according research for electric HDV is sparse Schill & Gerbaulet (2015); Gnann et al. (2018); Sadeghian et al. (2022); Pickering et al. (2022).

We contribute to the literature by providing, to the best of our knowledge, the first analysis that co-optimizes the charging and discharging operations (including V2G) of different types of electrified HDV with capacity and dispatch decisions in the power sector. We do so for a wide range of HDV technologies, including dynamic power supply via electric road systems. We use a power sector model that fully captures the hourly variability of load and renewable generation over all hours of a full year, and apply it to a future scenario with high shares of variable renewables. The model code and all input data, including detailed hourly HDV mission profiles for domestic transport in Germany, are provided open source for transparency and reproducibility.

2 METHODOLOGY

The power sector model DIETER

We use the open-source power sector model *Dispatch and Investment Evaluation Tool with Endogenous Renewables* (DIETER). It is a linear program that minimizes power sector costs by optimizing capacity and dispatch decisions for a full year in an hourly resolution Zerrahn & Schill (2017); Gaete-Morales, Kittel, et al. (2021). Its objective function includes fixed an variable costs of all electricity generation and storage technologies, electrolysis and PtL plants, as well as hydrogen or e-fuel transportation. It does not include the costs of charging or catenary infrastructure, hydrogen filling stations, or PtL filling stations. Accordingly, the power sector cost figures provided above do not include the costs of HDV electrification infrastructure. We further do not consider the option of hydrogen imports, as these are likely to be unavailable at scale by 2030. In general, the global scaling up of green hydrogen supply remains uncertain Odenweller et al. (2022).

Endogenous model variables include power sector costs, optimal generation and electricity storage capacities (Germany) and their hourly use (all countries), hourly decisions for HDV charging and discharging, as well as the capacity and operational decisions of electrolysis and PtL generation and storage infrastructure. In addition, we interpret the marginals of the hourly energy balance as wholesale prices (compare (Brown et al., 2018)).

Exogenous model inputs include fixed and variable costs of all electricity generation and storage technologies, efficiency parameters, as well as time-series variable renewable energy availability profiles and electric load. In the case of inflexible HDV charging (BEV Inflex, ERS-BEV Inflex), we assume that the vehicles always start charging as soon as an opportunity arises, and that vehicles batteries are fully charged by the time the next trip starts, if possible. The charging power is set to facilitate exactly this for each charging period, i.e., charging power is generally lower, the longer a vehicle is connected to the grid. This resembles the “balanced” charging profile defined in Gaete-Morales, Kramer, et al. (2021). For Germany, we further assume upper limits for investments in fossil generation capacities as given by the federal Grid Development Plan 2030.

The geographic scope of the model version used here includes Germany and its neighboring countries plus Italy. In order to reduce numerical complexity and improve tractability, we allow for endogenous generation capacity investment only in Germany, and fix the power plant portfolio for the other countries to values derived from ENTSO-E’s Ten Year Network Development Plans ENTSOE (2018). The model is required to satisfy at least 80 percent of the load in Germany with domestic renewable electricity generation. This includes the additional load related to directly or indirectly electrifying HDV. This reflects the current German government’s target for 2030 that has also been set out in the Renewable Energy Sources Act.

Mobility data of heavy-duty vehicles

We generate synthetic truck usage patterns that are intended to approximate the German fleet of HDV larger than 26 tons. The main data source for the usage patterns is the traffic model PTV Validate, from which we extract a database of daily truck trips in domestic German road freight transport.

For these profiles, the time series of charging availability (in the depot, during idle and driver’s resting times) and of the electricity demand of pure BEV-HDV (500 km battery range) and ERS-HDV (150 km battery range) are calculated. The resulting electricity demands and charging availabilities are used as inputs for the DIETER model.

3 Results and discussion

Lowest power sector costs and electricity prices for BEV with V2G

Compared to the reference case without electrified HDV, yearly power sector costs increase in all scenarios with electrified HDV (Figure 1, upper panel). That is, the cost of the additional electricity demand induced by HDVs always outweighs their potential flexibility benefits. Cost effects, however, vary strongly between different options. Flexible BEV with V2G incur the lowest additional power sector costs (1.8 bn Euros/year, or around 5,600 Euros/year per vehicle), followed by BEV without V2G (2.3 bn Euros/year, or around 7,200 Euros/year per vehicle). If BEV charging is not optimized, system costs are markedly higher (3.8 bn Euros/year, or 11,900 Euros/year per vehicle). Results are qualitatively similar for ERS-BEV, but on a slightly higher cost level. The differences between the three ERS-BEV cases are much less pronounced than for pure BEV, as their temporal flexibility potential is much smaller. The battery capacity of an ERS-BEV fleet is only around a quarter of that of an alternative pure BEV fleet (655 kWh usable capacity per pure BEV and 181 kWh per ERS-BEV truck). In contrast, power sector cost are substantially higher for FCEV (12.6 or 12.7 bn Euros/year, for decentralized or centralized hydrogen provision, i.e. around 39,700 Euros/year per vehicle) and even more so for PtL (16.8 bn Euros/year, or 52,700 Euros/year per vehicle). This is a direct consequence of high conversion losses of hydrogen and PtL supply chains and vehicles drive trains. Because of these losses, the two hydrogen supply chains increase the electricity demand more than twice as much as the battery-electric options. The electricity demand of PtL-HDV is nearly four times as high as in the case of BEV. Notably, the cost differences between BEV and ERS-BEV are much smaller than the differences between these direct-electric options and indirect electrification via hydrogen or PtL.

Complementary to power sector costs, we also evaluate average yearly wholesale electricity prices

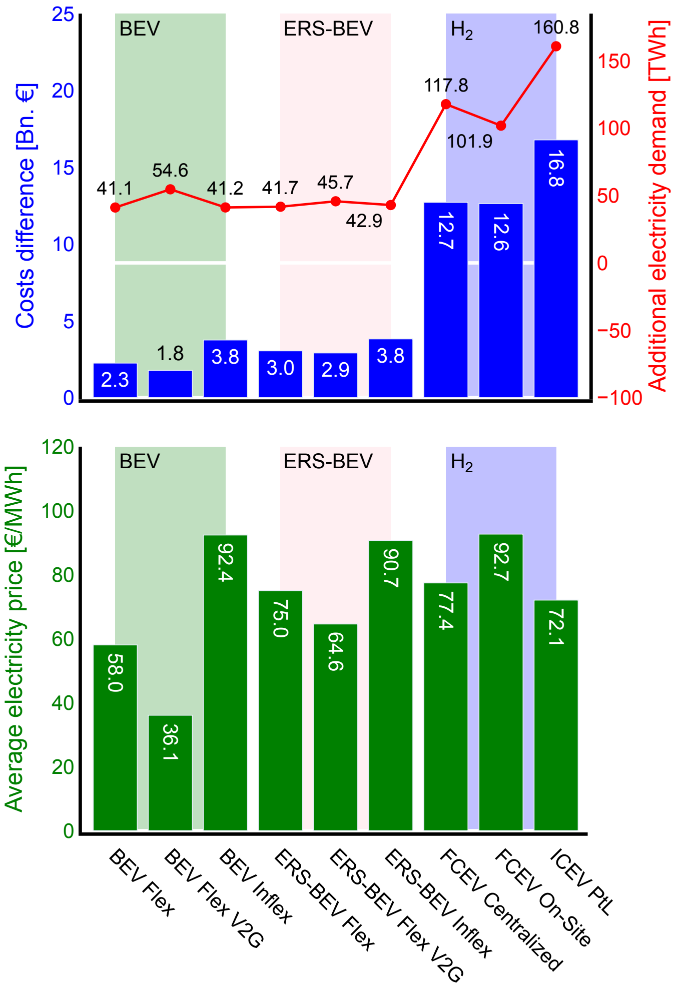

Figure 1: Changes in yearly power sector costs and electricity demand induced by different HDV options (upper panel), and average wholesale market prices of charging electricity (lower panel).

for HDV electricity (Figure 1, lower panel). This allows to largely separate the differences in overall electricity consumption of the various HDV options from their ability to make use of low-cost electricity. Average prices are calculated by multiplying hourly wholesale prices of electricity consumed by the different HDV options or fed back to the grid with respective hourly quantities, summing up over the whole year, and dividing by the overall electricity consumption of the fleet. That is, the numbers also account for revenues of electricity sold via V2G.[1] BEV with V2G face the lowest average electricity prices, as these also benefit from revenues of feeding back to the grid, followed by BEV without V2G. Average electricity prices paid by ERS-BEV are somewhat higher, as their smaller batteries limit the ability for temporally optimizing their charging and V2G decisions. In contrast, pure BEV can leverage their larger battery capacity to make better use of hours with low electricity prices.

In contrast, average electricity prices faced by inflexibly charged BEV are high, and even slightly above those of inflexible ERS-BEV. Note that inflexibly charged BEV generally benefit less from cheap electricity prices around midday related to abundant PV feed-in than inflexible ERS-BEV, while they are driving. With flexible charging, BEV can compensate for this charging availability disadvantage at midday by making better use of low prices in other periods, e.g., in windy nights, leveraging their larger batteries. In the case of inflexible charging, however, this is no longer possible, and the higher day-time grid availability of ERS-BEV gives them a slight competitive edge over BEV in terms of average charging prices. Prices for electricity used in hydrogen and

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[1] Here we assume that HDV operators receive the respective hourly wholesale price whenever they feed electricity back to the grid.

PtL supply chains are in the same range as those of ERS-BEV options. Centralized hydrogen and PtL supply can make use of lower prices than decentralized supply, because their low-cost storage options allow for higher temporal flexibility. Electricity prices of centralized hydrogen supply chains and PtL are also cheaper than those faced by inflexibly operated BEV or ERS-BEV. In terms of overall costs, these temporal flexibility benefits are, however, by far outweighed by the higher overall energy consumption of the FCEV and PtL options (Figure 1, upper panel).

Capacity and dispatch effects

The upper panel of Figure 2 shows optimal generation capacities in the reference (on the left) and the changes induced by HDV (on the right) in Germany, where minimum renewable energy share of 80% applies. In the reference, variable solar PV and onshore wind power dominate the capacity mix. These are complemented by smaller firm capacities of natural gas and bioenergy. The capacity additions related to the electrification of HDVs are predominantly a mix of solar PV and onshore wind power. Flexible BEV and ERS-BEV lead to the highest PV shares in the capacity additions, especially if combined with V2G. BEV with V2G essentially serve as short-duration grid storage, which favors the expansion of solar PV. HDV options that are temporally less flexible or that, overall, require more electricity favor higher onshore wind power capacities. If, alternatively, more PV was built, this would lead to increasing amounts of unused renewable surplus energy. Offshore wind power is not added here because of relatively unfavourable costs. FCEV and PtL options have the highest capacity needs because of substantial conversion losses. Decentralized electrolysis further requires a substantial addition of long-duration electricity storage capacity (9.4 GW) to compensate for the temporal inflexibility of the additional electricity demand (10.3 TWh). Aside from natural gas and oil, no fossil fuel generation capacities are used, partly due to a CO_2 price of 100 Euros/ton which discourages such investments. However, in the more inflexible scenarios (BEV Inflex, ERS-BEV Inflex and FCEV Distributed), investments into natural gas and oil generation capacity are at the assumed maxima.

The changes in yearly electricity generation are shown in the lower panel of Figure 2. On the left-hand side the overall electricity generation of the reference scenario is displayed. Whereas the right-hand side figure shows electricity additions or reductions according to the HDV options and generating technologies.[2] Here, the share of wind power in additional electricity generation is higher than in additional capacity because of its higher full-load hours as compared to solar PV.

Flexible BEV and ERS-BEV options show large solar PV generation, the lowest gas and oil generation and an inferior electricity import that led them to reach a higher renewable share (above 81%) than the reference case (80%). Centralized FCEV and PtL increased the gas power output of the most efficient plants, the combined-cycle ones, even without investing in more capacity leading to an increase in the capacity factor and maintaining the same low renewable share as the reference scenario (80%). As the coal power investment was disincentivized due to the high carbon price and having reached the maximum investment in gas and oil power, FCEV distributed option was forced to increase the share of renewables to 82.6% to fulfil the highest energy consumption. It also replaced in part power import by long-term storage, P2G2P, to overcome the inflexibility that distributed hydrogen entailed to the power sector.

Direct carbon emissions

Among all scenarios, CO_2 emissions increase the most if the HDV fleet uses e-fuels or hydrogen (Figure 3). This is a consequence of additional electricity generation from natural gas in these scenarios. Among the two hydrogen cases, on-site electrolysis at filling stations leads to lower emissions impacts compared to centralized electrolysis, as its temporal flexibility limitations require additional long-duration electricity storage, which in turn is charged to a substantial extent by renewable surplus energy. Emission effects are smaller for BEV and ERS-BEV, and even negative for flexibly charged BEV, especially if combined with V2G. The latter is driven by an additional expansion of solar PV facilitated by V2G, as shown above. For neighboring countries, relative emission effects are smaller, as by assumption they have lower renewable energy shares and, in turn, higher emissions, as well as no electrified truck fleets.

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[2] This chart also shows the output power associated with storage options. These figures do not represent generation as long as it corresponds to energy throughput.

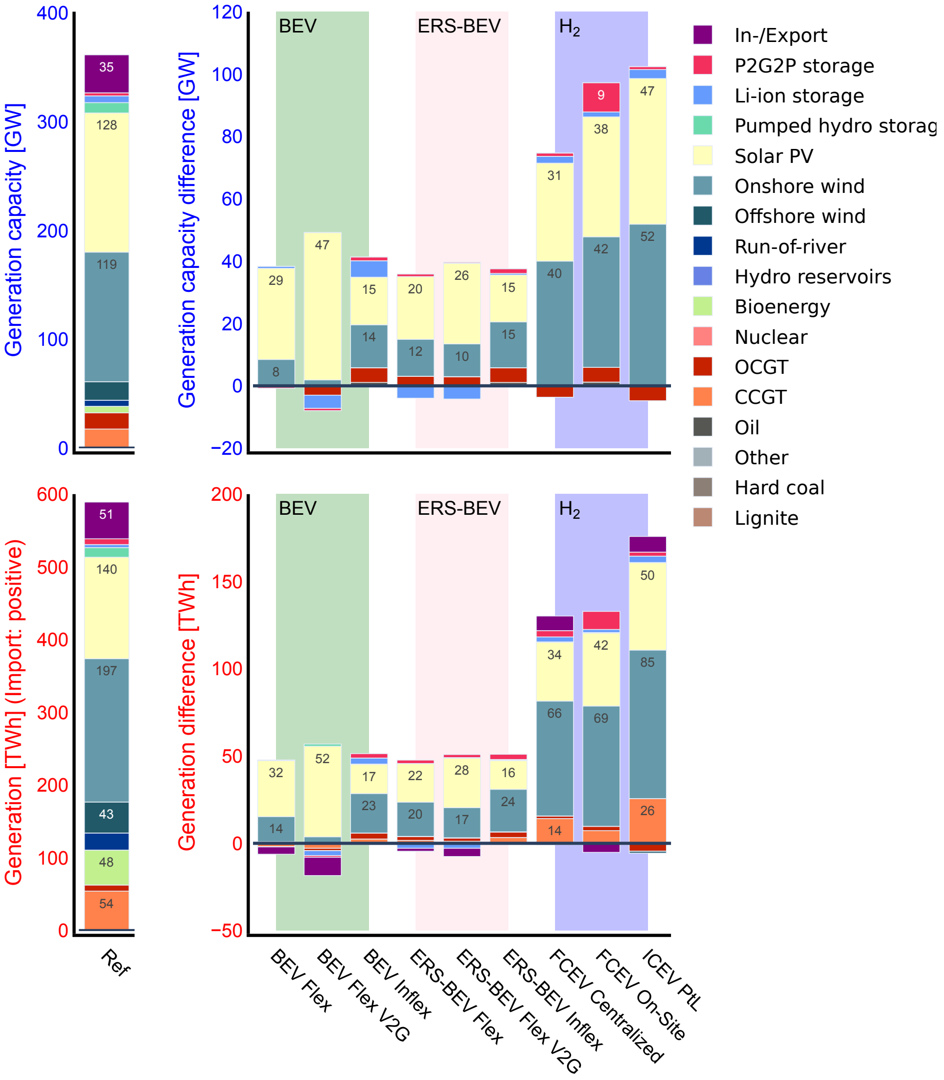

Figure 2: Effects of different HDV scenarios on optimal generation capacity (upper panel) and on yearly generation (lower panel) in Germany

Time series reveal differences in flexibility characteristics

Figure 4 illustrates that flexible BEV HDV are able to charge their batteries in hours of low residual load, and especially to make use of renewable surplus energy to a substantial extent. They also make use of the V2G option to some extent to feed back renewable surplus energy to the grid, whenever the battery capacity is not needed for driving. In the exemplary illustration, this is visible particularly in summer (right panel). Note that the time series shown begins on a Saturday.[3] BEV with V2G store a substantial amount of renewable (i.e., solar PV) surplus energy on Saturday afternoon, and feed it back to the grid in the night between Saturday and Sunday (top right time series shown in Figure 4). This is possible because HDV are not used on Sunday, so the battery capacity is idle. Note that this is different in the following days, as HDV are used between Monday and Friday, and much less battery capacity is available for V2G. If BEV charging is not optimized, but follows an inflexible, pre-determined pattern, charging profiles are less peaky and much more balanced (second panels from top). This especially means that BEV are not able to make much use of cheap renewable surplus electricity in this case, but also carry out a lot of charging in hours with positive residual load.

ERS-BEV generally follow similar patterns as non-catenary BEV. Yet, their smaller batteries make ERS-BEV temporally less flexible, so they can make less use of renewable surplus events and also

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[3] For simplification, we assume that both Saturday and Sunday are truck-free.

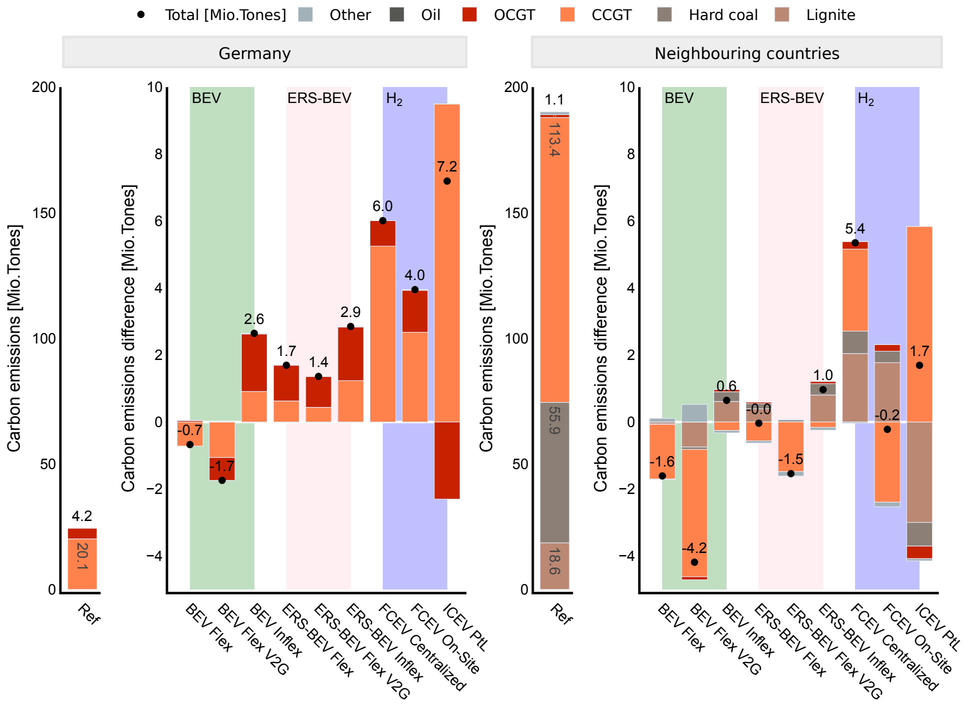

Figure 3: Direct CO_2 emissions from electricity generation. The left panel shows annual emissions from Germany, while in the right panel are the emissions from Germany's neighbouring countries. Each panel contains, on the left, the overall emissions of a reference scenario with no trucks. On the right is the emissions difference of the scenarios with direct or indirect power demand.

have to draw electricity from the grid during hours with positive residual load to some extent. For the same reason, their potential for feeding electricity back to the grid is also much smaller than in the case of pure BEV. Note that ERS-BEV partly also charge their batteries during driving.

Hydrogen and PtL supply chains show very different patterns of electricity use compared to BEV or ERS-BEV. FCEV with centralized hydrogen supply chains (i.e., centralized electrolyzers with large-scale hydrogen storage capacities) generally have a flat consumption profile in many hours, as their high fixed costs make it optimal to use them with relatively high full load hours. This also limits their ability to make use of renewable surplus energy (lower electricity consumption on first summer day shown in the graph compared to BEV V2G). Yet, they can use the temporal flexibility provided by centralized, large-scale hydrogen storage to reduce electricity consumption in hours of high positive residual load, i.e., high prices. In contrast, on-site electrolysis follows the actual hydrogen demand much more closely. This is because decentralized electrolyzers sited at filling stations by assumption only come with very limited hydrogen storage. Accordingly, they can avoid electricity consumption in hours of high residual load only to a minor extent, and much less than centralized electrolyzers. The PtL supply chain has a relatively similar pattern as the one for centralized hydrogen. The peak load is however higher because of higher overall energy consumption which also goes along with the highers PEM electrolysis capacity (24.4 GW).[4]

4 CONCLUSIONS

We analyze the power sector effects of alternatives options for electrifying heavy-duty vehicles in Germany, focussing on power sector costs costs, investment decisions, dispatch and direct carbon emission in the power sector. Temporal flexibility and energy efficiency are important drivers of results.

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[4] PEM electrolyzer capacity. FCEV centralized: 13.5 GW, FCEV distributed: 19.1 GW, ICEV PtL: 24.4 GW.

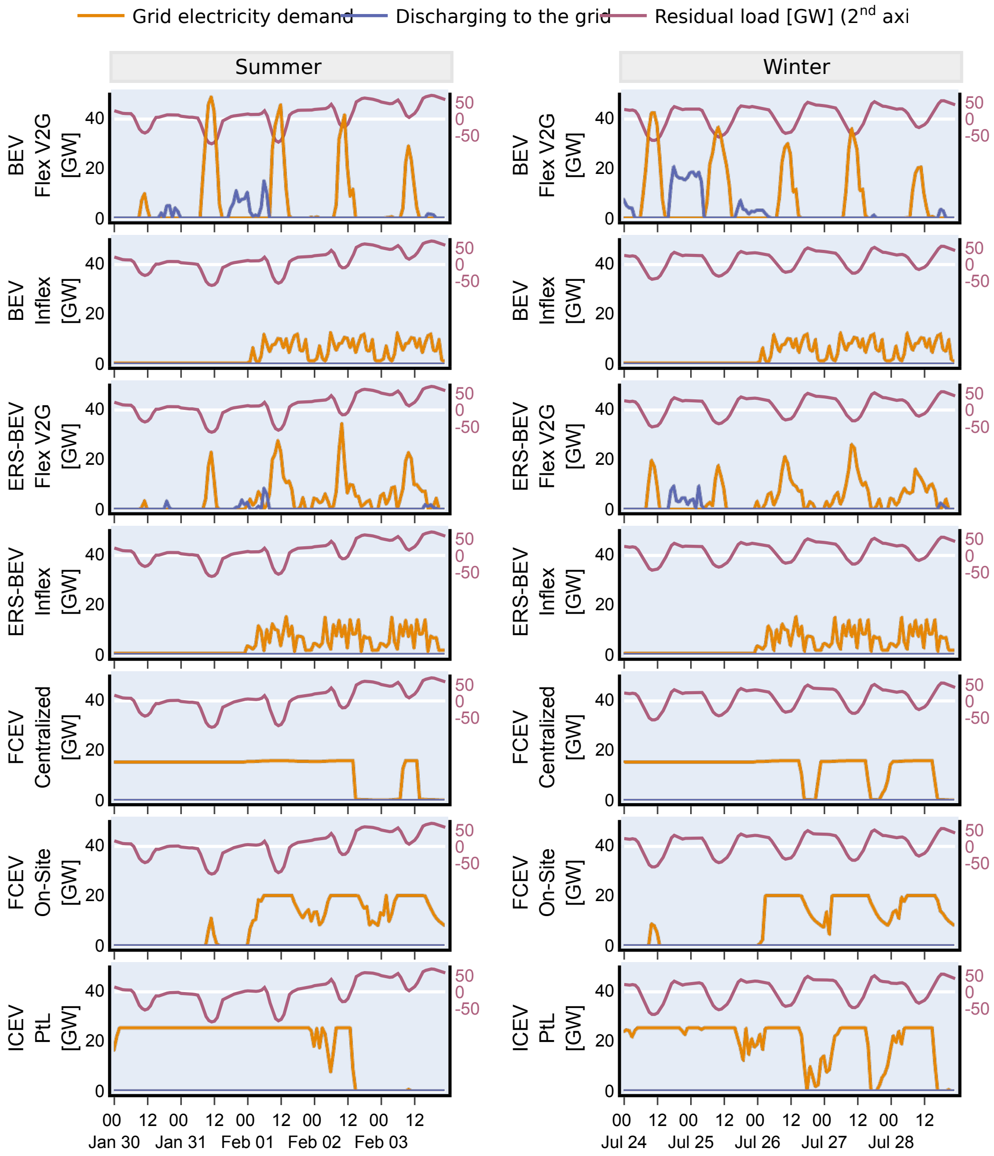

Figure 4: Five days sample for winter and summer of electricity flow time series. It contains residual load, electricity consumed to fulfil the demand for mobility (loading) and electricity returned to the grid in case of Vehicle to Grid (V2G) in GW. The samples start on Saturday.

Flexibly operated BEV and ERS-BEV, especially if combined with vehicle-to-grid, lead to the lowest power sector costs because of their energy efficiency benefits. In contrast, FCEV and PtL are temporally more flexible, but this does not outweigh their energy efficiency drawbacks.

From a pure power sector perspective, direct electrification of the truck fleet would be clearly preferable. Moreover, temporally flexible charging, including V2G, is desirable, as this leads to the lowest electricity sector costs and carbon emissions, and the highest use of renewable electricity. In contrast, inflexible charging should be discouraged as it performs poorly compared to flexible and bi-directional charging.

Future research may investigate overall system cost effects, also considering cost differences of charging and ERS infrastructures, as well as purchase cost differences of the trucks, which was beyond the scope of this study.

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REFERENCES

Boltze, M., Linke, R., Schöpp, F., Wilke, J., Öztürk, O., & Wauri, D. (2020, 05). Insights into the operation of overhead line hybrid trucks on the elisa test track. In *Ersc2020 - 4th electric road systems conference* (p. 1-6).

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

de Coninck, H., Revi, A., Babiker, M., Bertoldi, P., Buckeridge, M., Cartwright, A., . . . Sugiyama, T. (2018). Strengthening and Implementing the Global Response. In V. Masson-Delmotte et al. (Eds.), *Global Warming of 1.5° C. An IPCC Special Report on the Impacts of Global Warming of 1.5° C Above Pre-Industrial Levels and Related Global Greenhouse Gas Emission Pathways, in the Context of Strengthening the Global Response to the Threat of Climate Change, Sustainable Development, and Efforts to Eradicate Poverty* (pp. 313–444). Cambridge University Press. doi: 10.1017/9781009157940.006

ENTSOE. (2018). *TYNDP 2018. Project Sheets.* `https://tyndp.entsoe.eu/tyndp2018/projects/projects`.

Gaete-Morales, C., Kittel, M., Roth, A., & Schill, W.-P. (2021). DIETERpy: a Python framework for the Dispatch and Investment Evaluation Tool with Endogenous Renewables. *SoftwareX*, *15*, 100784. doi: 10.1016/j.softx.2021.100784

Gaete-Morales, C., Kramer, H., Schill, W.-P., & Zerrahn, A. (2021). An open tool for creating battery-electric vehicle time series from empirical data, emobpy. *Scientific Data*, *8*(1), 152. doi: 10.1038/s41597-021-00932-9

Gnann, T., Klingler, A.-L., & Kühnbach, M. (2018). The load shift potential of plug-in electric vehicles with different amounts of charging infrastructure. *Journal of Power Sources*, *390*, 20-29. doi: 10.1016/j.jpowsour.2018.04.029

Hannula, I., & Reiner, D. M. (2019). Near-term potential of biofuels, electrofuels, and battery electric vehicles in decarbonizing road transport. *Joule*, *3*(10), 2390–2402. doi: 10.1016/j.joule.2019.08.013

Hoekstra, A. (2019). The underestimated potential of battery electric vehicles to reduce emissions. *Joule*, *3*(6), 1412–1414. doi: 10.1016/j.joule.2019.06.002

IEA. (2022). *Global EV outlook 2022.* `https://www.iea.org/reports/global-ev-outlook-2022`. (Paris)

Kondziella, H., & Bruckner, T. (2016). Flexibility requirements of renewable energy based electricity systems - a review of research results and methodologies. *Renewable and Sustainable Energy Reviews*, *53*, 10–22. doi: https://doi.org/10.1016/j.rser.2015.07.199

Lajevardi, S. M., Axsen, J., & Crawford, C. (2022). Simulating competition among heavy-duty zero-emissions vehicles under different infrastructure conditions. *Transportation Research Part D: Transport and Environment*, *106*, 103254. doi: 10.1016/j.trd.2022.103254

Li, S., Djilali, N., Rosen, M. A., Crawford, C., & Sui, P.-C. (2022). Transition of heavy-duty trucks from diesel to hydrogen fuel cells: Opportunities, challenges, and recommendations. *International Journal of Energy Research*, *46*(9), 11718–11729. Retrieved from `https://onlinelibrary.wiley.com/doi/abs/10.1002/er.8066` (_eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1002/er.8066) doi: https://doi.org/10.1002/er.8066

López-Prol, J., & Schill, W.-P. (2021). The economics of variable renewable energy and electricity storage. *Annual Review of Resource Economics*, *13*(1), 443–467. doi: 10.1146/annurev-resource-101620-081246

Mangipinto, A., Lombardi, F., Sanvito, F. D., Pavičević, M., Quoilin, S., & Colombo, E. (2022). Impact of mass-scale deployment of electric vehicles and benefits of smart charging across all european countries. *Applied Energy*, *312*, 118676. Retrieved 2022-10-06, from `https://www.sciencedirect.com/science/article/pii/S0306261922001416` doi: 10.1016/j.apenergy.2022.118676

Muratori, M., & Mai, T. (2020, December). The shape of electrified transportation. *Environmental Research Letters*, *16*(1), 011003. Retrieved 2022-10-06, from `https://doi.org/10.1088/1748-9326/abcb38` doi: 10.1088/1748-9326/abcb38

Nykvist, B., & Olsson, O. (2021). The feasibility of heavy battery electric trucks. *Joule*, *5*(4), 901–913. doi: 10.1016/j.joule.2021.03.007

Odenweller, A., Ueckerdt, F., Nemet, G. F., Jensterle, M., & Luderer, G. (2022). Probabilistic feasibility space of scaling up green hydrogen supply. *Nature Energy*, *7*(9), 854–865. doi: 10.1038/s41560-022-01097-4

Pickering, B., Lombardi, F., & Pfenninger, S. (2022). Diversity of options to eliminate fossil fuels and reach carbon neutrality across the entire european energy system. *Joule*, *6*(6), 1253–1276. doi: 10.1016/j.joule.2022.05.009

Plötz, P. (2022). Hydrogen technology is unlikely to play a major role in sustainable road transport. *Nature Electronics*, *5*(1), 8–10. doi: 10.1038/s41928-021-00706-6

Richardson, D. B. (2013). Electric vehicles and the electric grid: A review of modeling approaches, impacts, and renewable energy integration. *Renewable and Sustainable Energy Reviews*, *19*, 247-254. Retrieved from `https://www.sciencedirect.com/science/article/pii/S1364032112006557` doi: https://doi.org/10.1016/j.rser.2012.11.042

Sadeghian, O., Oshnoei, A., Mohammadi-ivatloo, B., Vahidinasab, V., & Anvari-Moghaddam, A. (2022). A comprehensive review on electric vehicles smart charging: Solutions, strategies, technologies, and challenges. *Journal of Energy Storage*, *54*, 105241. Retrieved from `https://www.sciencedirect.com/science/article/pii/S2352152X22012403` doi: https://doi.org/10.1016/j.est.2022.105241

Schill, W.-P., & Gerbaulet, C. (2015). Power system impacts of electric vehicles in germany: Charging with coal or renewables? *Applied Energy*, *156*, 185–196. doi: 10.1016/j.apenergy.2015.07.012

Shukla, P., et al. (Eds.). (2022). *Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge, UK and New York, NY, USA: Cambridge University Press. doi: 10.1017/9781009157926

Speth, D., & Funke, S. A. (2021). Comparing options to electrify heavy-duty vehicles: Findings of german pilot projects. *World Electric Vehicle Journal*, *12*(2), 67. doi: 10.3390/wevj12020067

Stöckl, F., Schill, W.-P., & Zerrahn, A. (2021). Optimal supply chains and power sector benefits of green hydrogen. *Scientific Reports*, *11*(1), 14191. doi: 10.1038/s41598-021-92511-6

Taljegard, M., Göransson, L., Odenberger, M., & Johnsson, F. (2017). Spacial and dynamic energy demand of the E39 highway – Implications on electrification options. *Applied Energy*, *195*, 681-692. doi: 10.1016/j.apenergy.2017.02.025

Ueckerdt, F., Bauer, C., Dirnaichner, A., Everall, J., Sacchi, R., & Luderer, G. (2021). Potential and risks of hydrogen-based e-fuels in climate change mitigation. *Nature Climate Change*, *11*(5), 384–393. doi: 10.1038/s41558-021-01032-7

Zerrahn, A., & Schill, W.-P. (2017). Long-run power storage requirements for high shares of renewables: review and a new model. *Renewable and Sustainable Energy Reviews*, *79*, 1518–1534. Retrieved from `https://www.sciencedirect.com/science/article/pii/S1364032116308619` doi: https://doi.org/10.1016/j.rser.2016.11.098