Transformation of the German energy and transport sector a national analysis

Pre-Print

Authors: Oliver Arnhold, Marlon Fleck, Kathrin Goldammer, Fabian Grüger, Oliver Hoch, Birgit Schachler

Abstract:

The transition of the transport sector is still at its beginning. Several possible vehicle concepts are currently part of the discussion about what mobility will look like in the future, for instance battery electric vehicles (BEV), fuel cell electric vehicles (FCEV), or synthetic fuels. Systemic research at the Reiner Lemoine Institut (RLI) shows that all of these technologies have specific advantages and disadvantages. We have modelled and compared several future scenarios for the German transport sector with an energy supply setting consisting of 100 % renewable energy. Our scenarios consider BEV and FCEV individual mobility and several flexibility options, such as vehicle-to-grid (V2G) and time-flexible charging.
Our analyses show that the need for additional energy for mobility can be significantly reduced if flexibility of the BEVs is increased. Furthermore, required storage capacities can be significantly reduced if V2G is available. V2G also induces a technology shift from off-shore wind to less expensive Photovoltaics.

Full Text:

1 Introduction

A lot is going on in the political debate about the future of mobility. Politicians from all countries are pushing forward with regard to climate protection and have set themselves the ambitious 1.5-degree goal in Paris. For the first time in history, the German climate protection plan 2050 – an ambitious project promoted by Federal Environment Minister Barbara Hendricks finally implemented in November 2016 – includes transport sector carbon emission goals for Germany [1]. The target: 42-40 % carbon emission reductions until 2030 compared to 1990. Although it is true that other sectors have higher goals to achieve (e.g. around 60 % reduction for the electricity sector), the 40 % reduction is an extremely ambitious target for the German transport sector. Statistics [2] show that it has continuously failed to reduce its carbon emissions during the last few years while other energy sectors achieved reductions. Figure 1 shows recent greenhouse gas emissions by sectors.

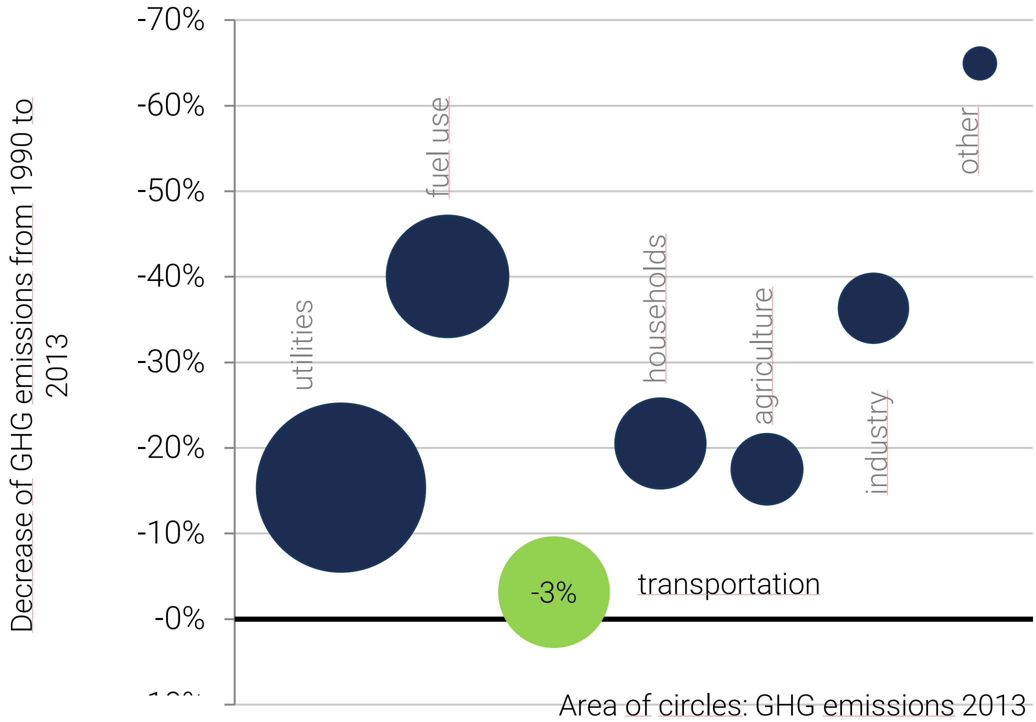

Figure 1: Reduction of GHG emissions by sector. Diagram by author, based on [2]

This is relevant, because the transport sector accounts for nearly 30 %of the national primary energy consumption and more than 90 % of it are based on fossil fuels [1]. This is where electric mobility comes in. The vision is: emission-free individual transport (possibly also freight transport) directly or indirectly fueled by electricity generated from renewable sources.

E-mobility is promoted by the German Federal Government through the so-called "Environmental Bonus" for the purchase of electric vehicles, plug-in hybrid, and fuel cell vehicles. The numbers show, that it is not exactly adopted enthusiastically by German car owners: Since the Bonus' introduction in July 2016, it was retrieved only 15,348 times [3]. During the same period, more than 2.5 Mio new passenger cars with traditional engines were registered in Germany [4].

However, as the German Federal Government is currently releasing funding for a boost of infrastructure for charging and hydrogen fueling, and with sector targets for carbon emissions remaining strict, it is very likely that e-mobility integration is only a matter of time.

Generally, decarbonization of the transport sector can be achieved with different technologies that differ in fuel type and therefore have great influence on refueling behavior of customers. In this work, we mainly focus on e-mobility and its influence on the German energy system considering different charging powers and flexibility

2 Method

The national analysis examines the effects of an increased share of BEVs and FCEVs in individual traffic with special regard to the expansion requirements for renewable energy sources and storage technologies for a power supply fully based on renewable energy. A combined analysis of the electricity and transport sectors of Germany with the scope of one year and a time increment of one hour is conducted. The expansion and usage of generation and storage facilities are optimized for different scenarios varying the charging power and flexibility of BEVs, as well as the market penetration of BEVs and FCEVs (see Table 1) to the lowest overall economic costs. For this, we use the linear invest and dispatch optimization of the open energy modeling framework oemof [5].

oemof, short for the Open Energy Modeling Framework, is a tool created by RLI in collaboration with the Center for Sustainable Energy Systems (ZNES – University and University of Applied Sciences Flensburg) and Magdeburg University. It is an open-source software composed of flexible modules and can thus be compiled according to different specific needs. This makes it very useful for inter-sector studies. We use an open tool, because we are convinced that all researchers benefit from using open research tools, that research results become more trustworthy by making them transparent and that therefore, the process of the energy transition is promoted and sped-up. For this analysis, we have chosen oemeof, because its structure allows different modeling approaches to coexist within one software framework. So far, we have mainly used the SOLPH Library which makes it possible to describe energy systems with linear problems as well as with mixed-integer linear problems (MILP). Many examples that demonstrate how SOLPH works already exist in oemof. For this analysis, we have developed a particular application based on oemof that can be used to model mobility options based on renewable energy. oemof is implemented in Python and builds upon different libraries. As our approach has generally been collaborative from the very beginning and relies on flexible modules, the concept offers maximum freedom for users concerning which functions they wish to employ.

Figure 2 shows the basic model components of the oemof application used in the analysis presented here. The calculation includes photovoltaic, wind, run of river, geothermal, and biomass power plants, battery and pumped storage, as well as power-to-gas technologies. Feed-in time series for wind and photovoltaics are generated using the oemof feedinlib [6] and weather data from 2011 from the coastdat2 dataset [7]. The expansion of renewable energy power plants as well as pumped storages is limited by their technical potential.

Restrictions of the electricity grid are not taken into account. It is further assumed, that the current electricity demand without sector coupling does not change. The load of the BEVs and FCEVs must be projected. BEV load profiles are calculated based on assumptions for annual average kilometers traveled, charging options, travelling purpose, and related driving time, speed, and distance, etc. from the MiD 2008 report [8]. The modeling of the vehicles is shown in Figure 2. We assume that all grid-connected vehicles form one combined storage. Returning vehicles add to the storage capacity and state of charge, while departing vehicles reduce the storage capacity and state of charge. While the flexibility with which a vehicle can be charged during the time it is connected to the grid is a scenario variable, it is a requirement that departing vehicles need to be fully charged. Depending on the travelling purpose, the state of charge of the returning vehicle is estimated and added to the state of charge of the combined storage. Charging of the combined storage is restricted by the number of vehicles connected to the grid at that time and the charging power that is as well a scenario variable (see scenario table).In some scenarios, the possibility of so called vehicle-to-grid (V2G) options is examined. In that case, feed-in into the grid from the combined BEV storage with a power equal to the combined charging power is allowed. Refueling behavior of FCEVs is estimated based on data from an existing motorway refueling station for conventional vehicles [9].

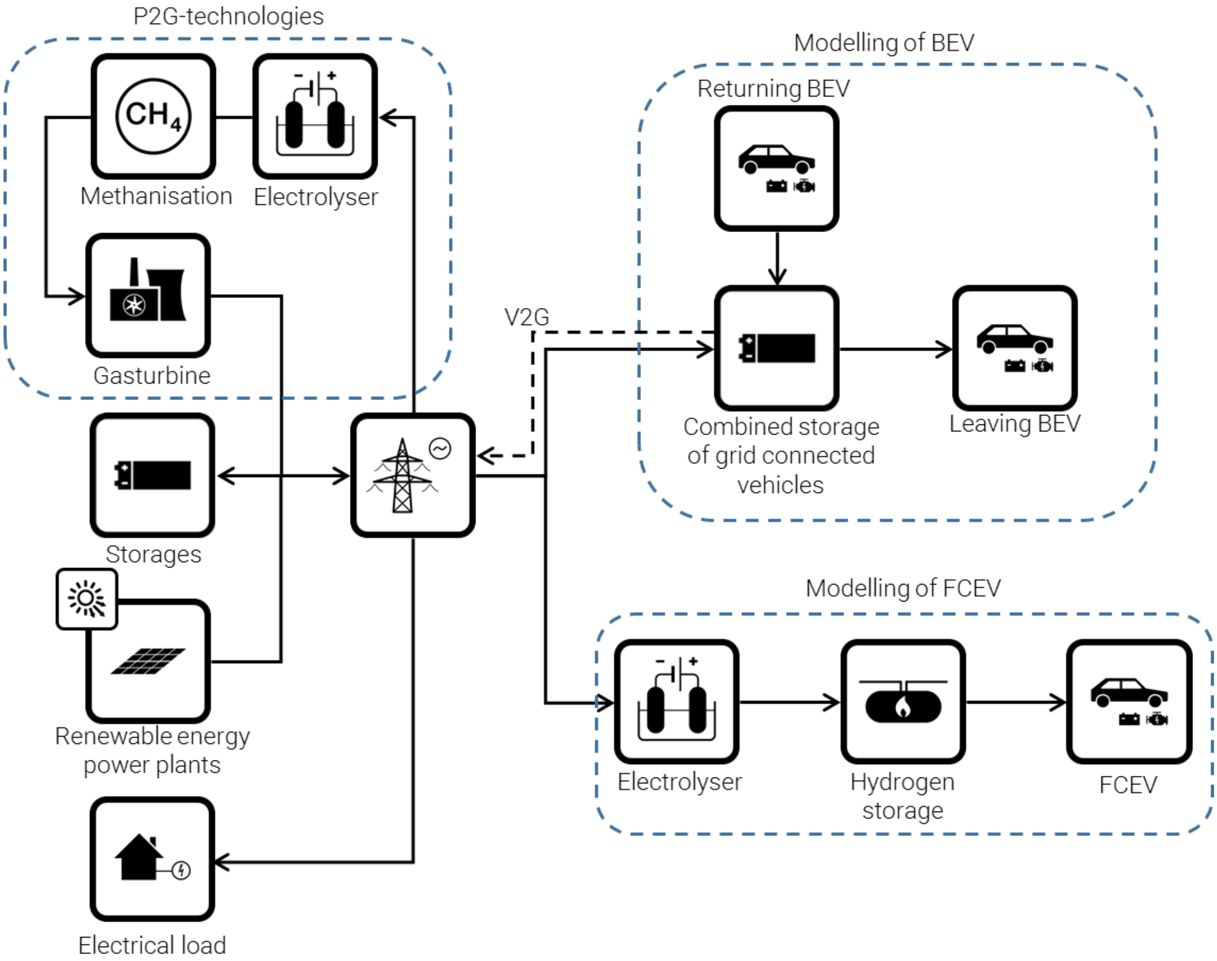

Figure 2: National Analysis Model

For the scenario definition, different aspects of current developments in the transport sector are taken into account: the trend towards higher charging powers, the possibility of flexible charging and vehicle-to-grid, as well as a higher market penetration of FCEVs. As for the charging power, two set-ups were chosen: a "Low Power" set-up considering current average charging powers (3.7 kW at home and work and 50 kW at public places, such as refueling stations) and a "High Power" set-up examining potential charging power (22 kW at home and work and 350 kW at public places).

Regarding the temporal flexibility of the charging process, a fixed ("No Flex") and a completely flexible ("Full Flex") charging of the vehicles is considered. Furthermore, a semi-flexible charging process ("Mid Flex"), allowing to not charge the vehicle during the first four hours, as long as the vehicle is fully charged at the end of the charging period, is examined. In the case of fully flexible charging, any delay of charging is allowed, as long as the vehicle is fully charged when departing. Scenarios comprising V2G also allow full flexibility in charging ("V2G").

An overview of all scenarios is given in Table 1:

Scenario name	Charging power (home + workplace)	Charging power (public)	BEV charging flexibility	Share of FCEVs
Low Power No flex	3.7 kW	50 kW	0 h	0 %
Low Power Mid Flex	3.7 kW	50 kW	4 h	0 %
Low Power V2G	3.7 kW	50 kW	Full + V2G	0 %
High Power No Flex	22 kW	350 kW	0 h	0 %
High Power Mid Flex	22 kW	350 kW	4 h	0 %
High Power High Flex	22 kW	350 kW	Full	0 %
High Power V2G	22 kW	350 kW	Full + V2G	0 %
Low Power No Flex + FCEV	3.7 kW	50 kW	0 h	50 %
Low Power V2G + FCEV	3.7 kW	50 kW	Full + V2G	50 %

Table 2: Overview of scenarios analyzed

3 Results

A complete penetration of the transport sector with BEVs results in an additional energy demand of about 90 TWh. When comparing the influence of charging flexibility, we observe that higher flexibility leads to a reduction of required storage capacities, especially if V2G is available (see Figure 3). V2G also induces a technology shift from offshore wind to less expensive Photovoltaics. This can be explained by BEV load adjusting to times of high renewable energy production and feeding back energy to the grid in times of low PV power. Thus, V2G decreases the dependence on continuous energy production and is more robust against fluctuating energy production. This technology shift results in a significant increase in installed rated power of renewable energy power plants, since more installed rated PV power is required to produce the same amount of energy as off-shore wind turbines.

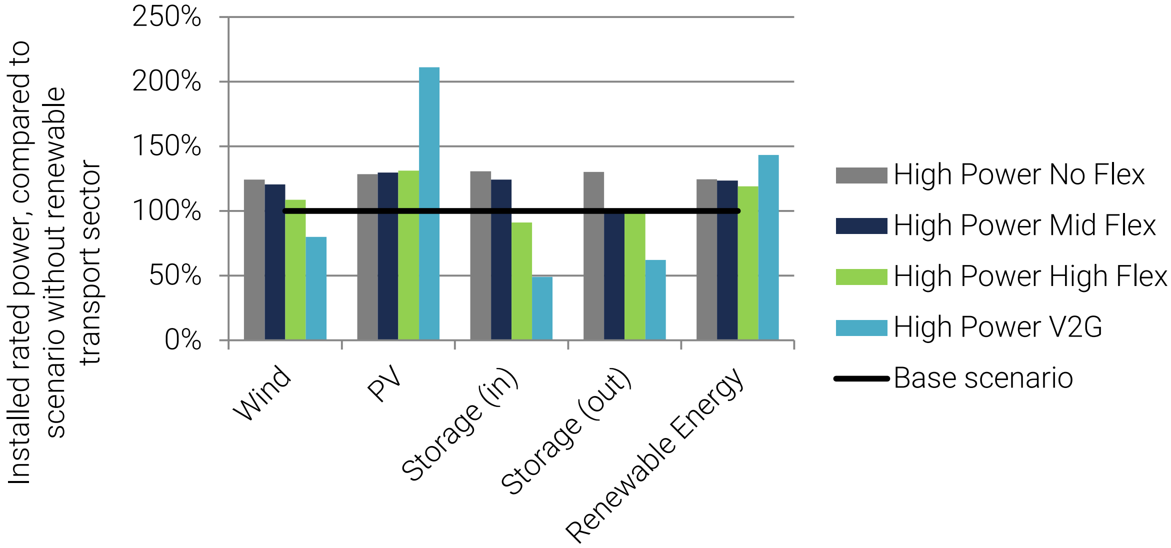

Figure 3: Comparison of charging flexibility in terms of required installed rated powers of storages and RE power plants

Moreover, increasing charging flexibility reduces excess energy and losses. Scenarios with high flexibility and V2G show significant reductions of additionally required energy for transportation, while the total energy demand remains unchanged (see Figure 4). The reduction sums up to ~44 % in scenario "High Power - High Flex" compared to "High Power - No Flex".

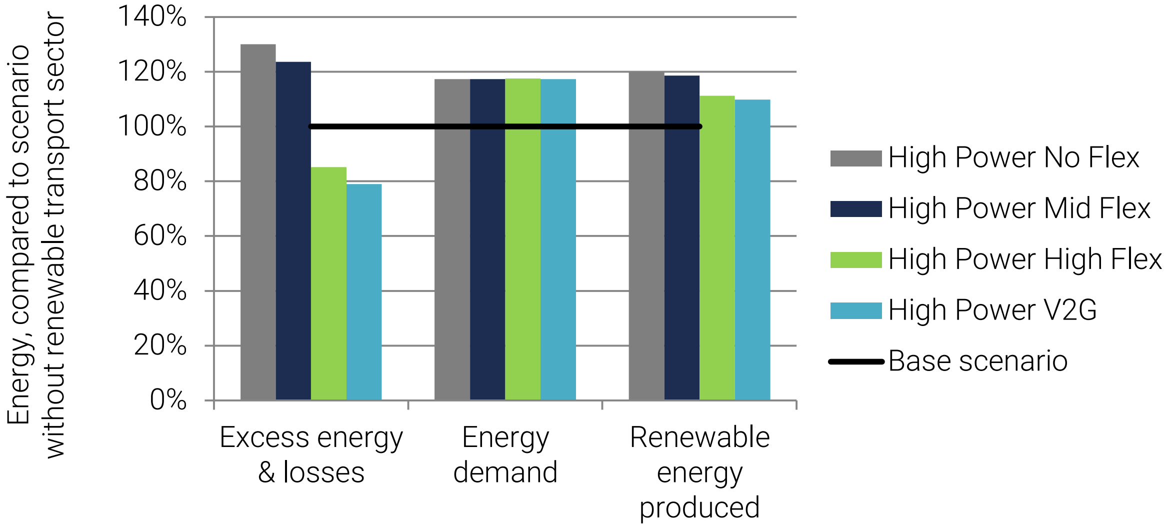

Figure 4: Comparison of charging flexibility in terms of required energy production, excess and losses as well as demand

A comparison of low and high charging power shows negligible influence on results compared to the above discussed influence of charging flexibility (see Figure 5Figure). Charging power's influence on V2G is more significant, since feed-in power is increased as well. In addition to this, technology compilation in V2G scenarios is shifted towards PV to a greater degree, if charging power is high.

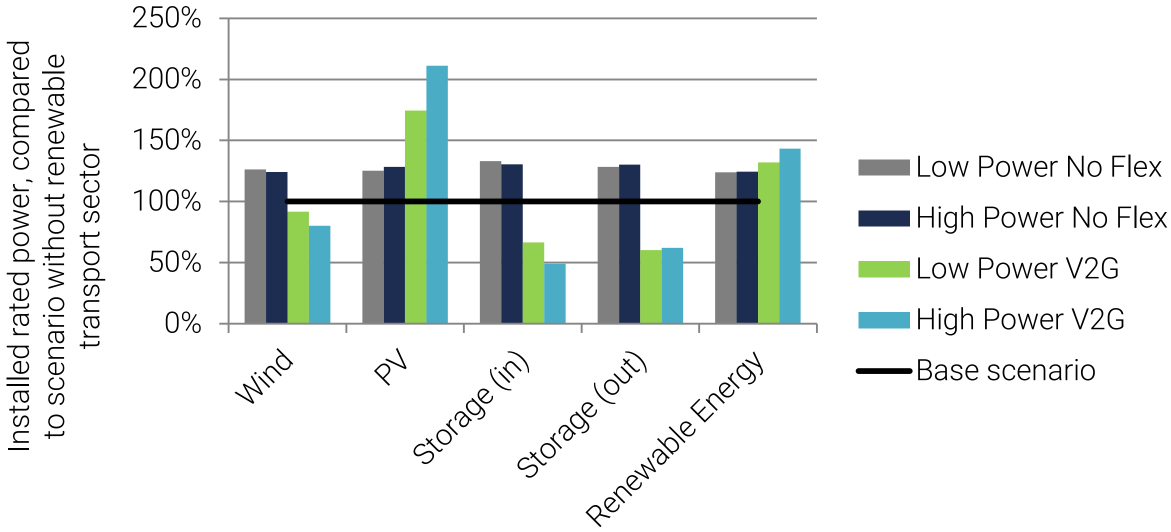

Figure 5: Comparison of charging power in terms of required installed rated powers of storages and RE power plants

In scenarios with 50 % market penetration of FCEVs, the additional demand for electricity is increased from 90 TWh to 169 TWh (+87 %). Concerning the energy system compilation, the influence of FCEVs is dependent on BEVs' charging flexibility. If there is no flexibility, required storage capacity is reduced and the additionally required energy is produced by photovoltaics as well as wind power plants (see Figure 6Figure). On the other hand, if full flexibility and V2G are available, storage demand is slightly increased by FCEVs. Furthermore, less solar and more wind power plants are installed, so technology shift towards photovoltaics is slightly diminished.

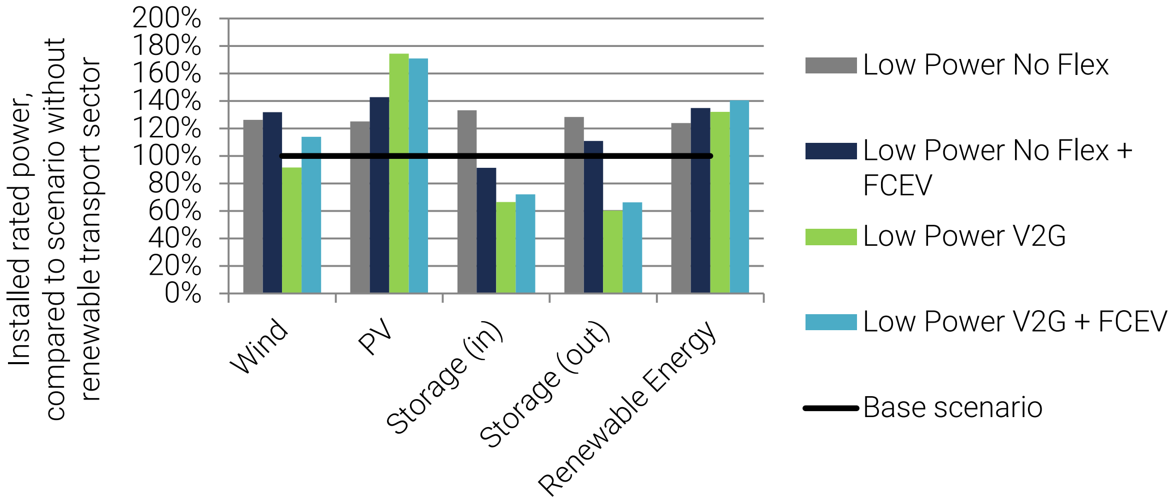

Figure 6: Comparison of different FCEV scenarios in terms of installed rated power of storages and RE power plants

The increase of the transport sectors' energy demand can be explained by the lower efficiency of fuel cell vehicles and the conversion losses during electrolysis. It is interesting to note, however, that the additional production does not necessarily increase proportionally with the demand. As shown in Figure 7, it is only 29 % higher in scenarios without BEV charging flexibility, while demand is 87 % higher. This is due to the fact that the generation and withdrawal of hydrogen can be delayed by efficient hydrogen storage, whereas the demand of BEVs can only be delayed for a limited time. For the electrolysis, a large proportion of renewable energy can be used, while BEVs are a must-run capacity even in times of negative residual load. In scenarios with full flexibility and V2G, required energy production is 122 % higher if FCEVs also need to be supplied, because FCEVs' flexibility is lower than BEVs' flexibility in scenarios with V2G.

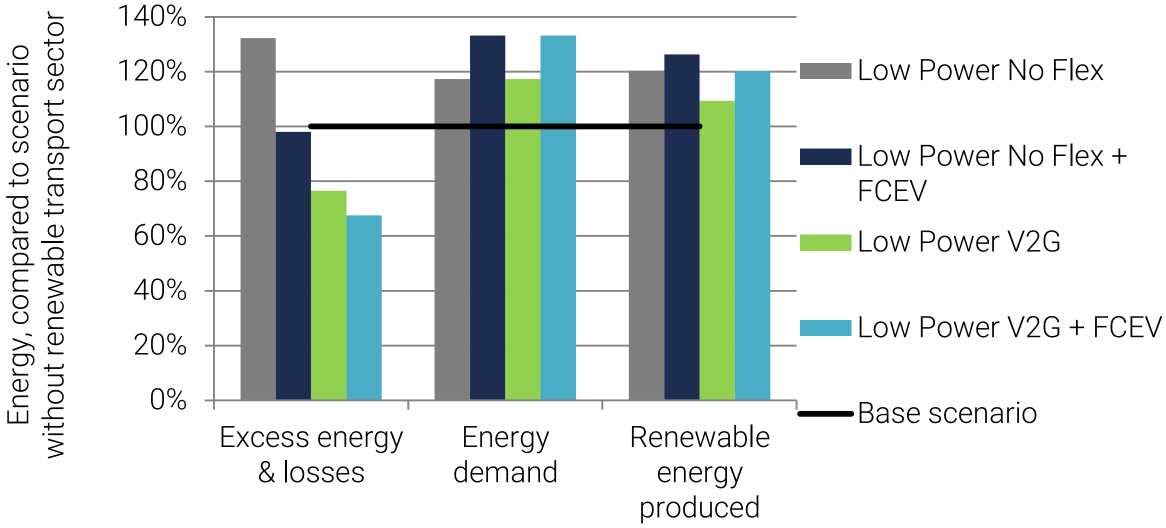

Figure 7: Comparison of different FCEV scenarios in terms of required energy production, excess and losses as well as demand

4 Conclusion and outlook

Decarbonizing the German transport sector is an ambitious goal, albeit technically feasible. Assuming today's e-mobility technologies and introducing a few scenarios for future charging infrastructure and vehicle roll-out, a transport sector based on 100 % renewable energy can be achieved. The analyses performed by the Reiner Lemoine Institute show the effects of the two investigated technologies – battery-electric and hydrogen-powered vehicles – on the energy system. For a full passenger vehicle market penetration of BEVs, the electricity demand increases by ~90 TWh. Depending on flexibility options available, it is possible to utilize energy that is otherwise curtailed. Therefore, additional energy production varies between ~60 TWh and ~130 TWh. If the share of FCEVs reaches 50 %, energy demand increases to ~170 TWh while additional energy production amounts to between ~130 TWh and ~170 TWh.

Flexibility options also have a strong influence on storage demand. An energy system based entirely on renewable energy requires high flexibility due to the fluctuating energy production of the most dominant energy sources wind and solar energy. This flexibility can be introduced to the system by either storages or flexible demand. Our analyses have shown that the storage demand can be reduced further and further with growing flexibility of BEVs. Furthermore, a fully flexible BEV demand with V2G allows a technology shift from an expensive but steadier

energy production from off-shore wind power plants to a cheaper but highly fluctuating energy production from photovoltaic systems.
Charging power has a negligible influence in general. Only if V2G options are available, higher charging power amplifies the tendency of a technology shift towards solar power plants.

If BEVs are not fully flexible, FCEVs reduce the required storage capacities. Their lower efficiency leads to higher energy demand (+87 % for 50 % FCEV share). But due to high flexibility in hydrogen production, renewable energy can be used that would otherwise be considered excess energy. Accordingly, the required additional electricity production is increased by only 29 %. Therefore, the FCEVs' disadvantage of lower efficiency is partly compensated by their flexibility from a system's point of view. On the other hand, if the required flexibility can already be provided by BEVs (in scenarios with full flexibility), FCEVs showed no energy system related advantage over BEVs.

The RLI is pursuing this research by integrating all sectors for a successful transformation of our energy system. In the future, the heat sector must therefore be included. Also, for now we use a copper-plate assumption of the electricity system which certainly does not hold in reality and should be replaced by a capacity-based grid model in future studies. By using a higher temporal simulation resolution, the impact of vehicles' charging power on additional capacities could be further investigated.

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