Analysis of Different Sector Coupling Paths for CO_2 Mitigation in the German Energy System under Consideration of Energy Supply Infrastructures

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***Abstract*—In the context of the energy transition in Germany, the share of renewable energies in the electricity generation mix has been the main focus so far. However, if the German government's long-term greenhouse gas reduction targets are taken as a basis, decarbonisation of the heating and transport sectors is crucial. In this context, different sector coupling paths must be evaluated in terms of their suitability to achieve the given climate targets.**

This paper focusses on the use of sector coupling in the transport sector. In particular, it investigates the direct electrification of the transport sector. In addition, an analysis of the influence of the required energy supply infrastructures on the use of sector coupling technologies for decarbonisation of the transport sector in Germany is carried out. The aim is to examine not only the influence of infrastructures on the choice of sector coupling technologies, but also the impact of the sector coupling options on infrastructures.

To this end, in the framework of the German Kopernikus project ENavi, the energy system model TIMES is expanded with regard to the conceivable sector coupling technologies. In order to be able to adequately evaluate these technologies, a simplified representation of the required energy supply infrastructures will also be implemented. By varying the infrastructure parameters, scenario-based analyses will then be carried out to determine to what extent the infrastructures influence the selection of sector coupling paths and thus the possible composition of Germany's future energy system.

The main findings indicate that the potential of sector coupling technologies is very much dependent on the choice of greenhouse gas emission reduction targets. In freight traffic in particular, these options only become attractive when ambitious targets are established. With regard to infrastructures, it can be said that a detailed assessment of the infrastructures has a great influence on the energy system. Furthermore, the impact of the use of sector coupling is far from negligible and requires more detailed research.

I. Introduction

With the Climate Action Plan 2050, the German government has set itself extremely ambitious national climate protection goals. Greenhouse gas emissions, for example, are to be reduced by 55% by 2030 compared to the reference year 1990. By 2050, reductions of 80% to 95% are even set as a goal (see table I).

TABLE I
German National targets for reducing the Greenhouse gas emissions (compared to 1990)[1]

	2015	2020	2030	2040	2050
GHG Emissions	-27.2%	-40%	-55%	-70%	-80% to -95%

In order to achieve these ambitious goals, an almost complete decarbonisation of the entire German energy system is necessary. So far, however, this has mainly taken place in the electricity sector, which accounts for only about 20% of final energy consumption in Germany (source to be included). In order to meet the climate targets, the heating and transport sectors must therefore also be taken into account to a greater extent.

With around 30% of final energy consumption in 2016 [2], the transport sector is an important factor in the German energy system. One of the possibilities to decarbonise this area is the use of renewable energy from the electricity sector. For this "sector coupling", the integrative linkage of the two sectors, however, (partly new) technologies are necessary to utilize the renewable potentials of the electricity sector in the transport sector. In addition, sector coupling can serve as a flexibility option for the energy system and as an energy storage solution: Short-term (e.g. batteries of electric cars) or long-term (power-to-gas). However, since most of these technologies depend on infrastructure, a thorough analysis of sector coupling can only take place under consideration of energy supply infrastructures.

The aim of this work is to analyze the possible sector coupling paths that might be used in the transport sector for system decarbonisation. The focus of the study will be on electric trucks (trolley trucks) for freight traffic and electric mobility for passenger transport. To this end, the TIMES energy system model will be extended to include possible sector coupling technologies. In addition, energy supply infrastructures are implemented in a simplified way in order to investigate their influence on the sector coupling technologies. Scenario analyses will then be used to analyse the effects of decarbonisation in the transport sector.

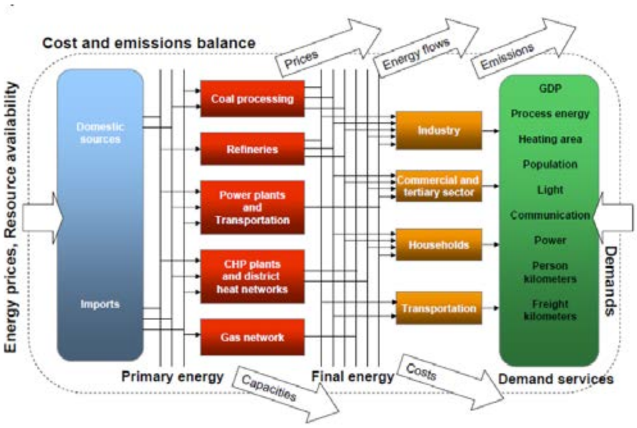

Fig. 1. The TIMES Reference Energy System

II. TIMES Model

The analyses are conducted with the energy system model TIMES-D (The Integrated MARKAL-EFOM System).

A. General modelling approach

The TIMES-D model was derived from the TIMES-PanEU model, which represents the EU plus Norway and Switzerland, and depicts the complete German energy system in great detail. As can be seen in Figure 1, the modelling includes all demands for energy services, the available energy resources and technologies for the conversion and supply of energy. The model is a linear optimization model in which the total discounted system costs are minimized for the entire time horizon. The model assumes complete competition between different technologies or energy conversion paths.

As an energy system model, TIMES covers all sectors involved in energy supply and demand, such as the raw materials supply sector, public and industrial power and heat generation, industry, trade, services, households and transport. Both greenhouse gas emissions (CO2, CH4, N2O) and pollutant emissions (CO, NOx, SO2, NMVOC, PM10, PM2.5) are recorded in TIMES. The aim is to determine the economically optimal energy supply structure for a specified useful energy or energy service requirement, taking into account energy and environmental policy requirements. Results of the model runs include energy prices and flows, technology stocks and capacities, emissions and costs.

The observed model horizon extends from 2010 to 2050, with the interim period being mapped over five-year support years. In order to better capture sector coupling as a flexibility option, the model was divided into 280 time segments of 3 hours each during the year. The time segments are divided into 5 type weeks, one week per season plus a special peak week in autumn, which should represent the high feed-in of renewable energies at this period. This time resolution is used to reflect differences between seasons and times of day in the availability of renewable energies or the distribution of demand.

Fig. 2. Trolley trucks on a test track in Germany

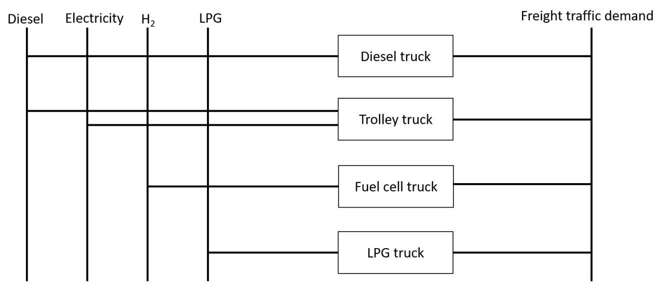

Fig. 3. Excerpt from the modelling of freight traffic

B. Implementation of Trolley Trucks

Trolley trucks are an existing but not yet market-ready technology. These are heavy goods vehicles with electric motors that are supplied with energy via a pantograph. The electricity is supplied via overhead lines (2). Routes without overhead lines are covered by an additional diesel generator or battery. In Germany, there are discussions about electrifying the highways used by long-distance truck traffic. However, since the development of this infrastructure would involve high costs, a differentiated modelling of the technology is recommendable here.

As can been seen in the figure 3 trolley trucks are built into the Reference Energy System as a selectable technology. It is in competition with classic diesel trucks or trucks using other fuels such as biodiesel, hydrogen or liquefied petroleum gas. The selection of the process is associated with acquisition costs and is represented by the investment costs to be incurred by the system. Up to now, the investment costs for vehicles and the construction of the infrastructure have been summarized in a simplified way.

However, there are clear differences in the utilisation of individual motorway sections in Germany. Same specific investment costs imply identical utilization. However, an electrified motorway kilometre on an extremely busy section of motorway can supply a larger number of vehicles than on an underused section. The specific costs of building the infrastructure (assuming that the absolute costs of construction are the same everywhere) therefore depend on the utilisation of the section of track.

For this reason, the costs for the construction (and also maintenance) of the overhead line infrastructure are

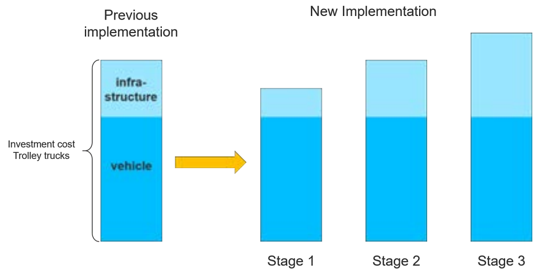

Fig. 4. Disaggregation of Invest costs

distributed (see fig. (4)). For this purpose, the truck process was divided into three processes. All of them have the same vehicle costs, but the infrastructure extra charges (in €/vehicle) are distributed differently. To this end, the costs for the complete electrification of the German motorway network are distributed unevenly among the individual processes, whereby the maximum capacity of the individual processes is limited. The aim is to simulate that the first sixth of the motorway network can already supply around a third of overhead line trucks. The last third of the vehicles is therefore less economical to supply.

Finally, the maximum potential of the three new processes must be determined, i.e. what proportion of the demand for the transport of goods can be met by overhead line technology in the best possible case. Since, as described, only the German motorways are to be equipped with overhead contact lines, this share is limited.

According to a study conducted by Fraunhofer ISI [3], the trolley truck can provide long-term electrification for all long-distance truck traffic. This technology is therefore not suitable for local freight transport (such as package cars or small delivery vans). According to [4], local truck traffic accounts for 9.8% of overall truck traffic. The maximum potential of the trolley truck is therefore 90.2% of the total freight traffic.

C. *E-mobility*

In this paper, the term e-mobility refers to all technologies in the transport sector that are operated electrically. This does not apply to heavy goods traffic or trains. This means that not only electric cars are at issue, but also, for example, electrically powered light duty vehicles.

E-mobility is mapped in the model using the approach shown in the figure 5: The vehicle battery is charged via the charging infrastructure. The electricity for this is obtained from the distribution grid. To enable the vehicles to be charged, the model must build up sufficient capacity for the charging infrastructure. The electricity stored in the battery can then either be used by the vehicle process to meet the demand for mobility or fed back into the grid. In the latter case, the battery functions as a power storage for the system.

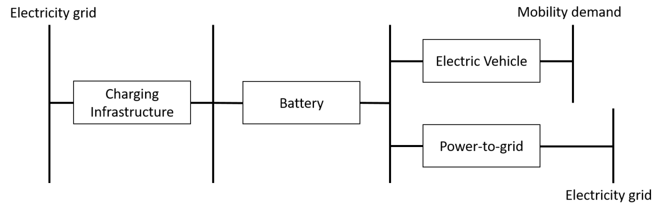

Fig. 5. Depiction of e-mobility in the model

TABLE II
GHG REDUCTION TARGETS FOR THE SCENARIOS

		Years		
	Scenarios	2020	2030	2050
Reduction of GHG emissions	S80	-40%	-55%	-80%
	S90	-40%	-55%	-90%
	S95	-40%	-58%	-95%

D. *Scenario Analyses*

As a framework for all scenario analyses, GHG emissions are gradually reduced in accordance with the data in the table I up to 2050 (see table II). Since the German government has formulated a target area rather than a concrete target for 2050, three scenarios are defined. The scenarios differ widely in terms of the final target for 2050 and not so much in the intermediate targets.

For the trolley trucks, in addition to the three standard reduction scenarios, scenarios with and without disaggregation of the infrastructure are performed to investigate the influence of the new modelling. For this purpose, the reduction scenario S90 is calculated once with the old modelling and once with the split infrastructure modelling (as shown in Fig. 4).

For the analysis of e-mobility, a special investigation of the influence of the charging infrastructure is also carried out. To this end, the share of the charging infrastructure that can be used simultaneously is limited. The availability of the infrastructure in the scenarios is set to 10%, 30%, 50% and 90%.

III. Results of the Scenario Analyses

A. *Freight Traffic*

First, the potential of the trolley truck is to be investigated. For this purpose, the 3 emission reduction scenarios are evaluated with regard to the share of trolley trucks in meeting the demand for freight transport.

As figure 6 shows, the trolley truck will not be used until 2040; in none of the scenarios is the pressure to reduce emissions high enough to use the technology. From 2045, however, the massive use of the technology will begin in some scenarios. While the trolley truck is still not used in the S80, it covers almost 57% of freight transport demand in the S90. In the S95, the reduction pressure is even so high that it is used up to the maximum of 90.2%.

From this it can be concluded that from a purely economic point of view the use of trolley trucks makes little sense.

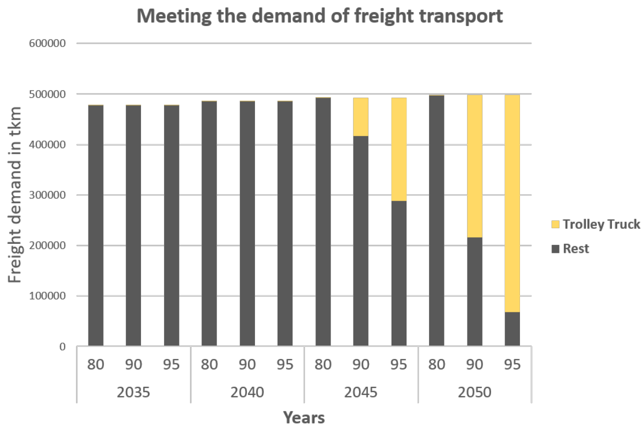

Fig. 6. Share of the trolley truck of the coverage of freight transport demand for different scenarios

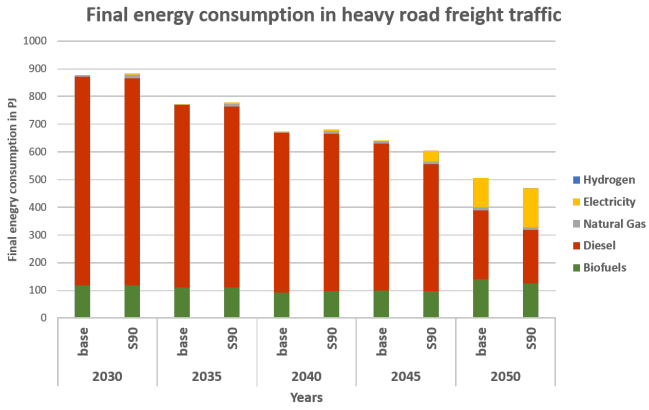

Fig. 8. Final energy consumption in Heavy duty Freight Traffic

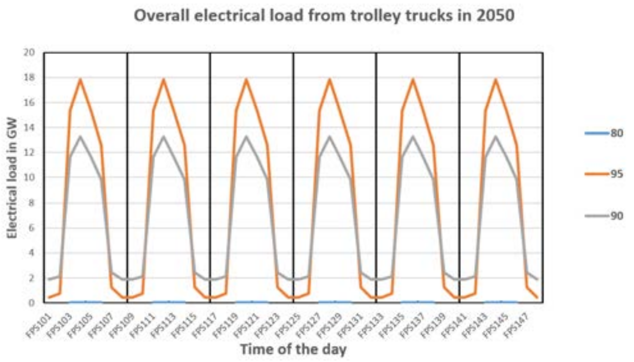

Fig. 7. Load curve of Trolley Trucks in 2050

Even at 80% GHG reduction, the more economic GHG savings potentials seem to lie in other sectors of the energy system. Only when these potentials are exhausted and the reduction targets become even more ambitious, the use of this technology is recommended. The potential of the trolley truck is therefore massively dependent on the selection of GHG reduction targets.

If one of the more ambitious goals is now assumed, it is worth taking a closer look at the effects of using the trolley truck, especially on the infrastructure. As shown in the illustration 7, the use of electric trucks can create heavy additional loads for the grid.

With maximum coverage (90.2%), the additional load for the grid is 18 GW, with 57% coverage in the S90 scenario, this value is still 13.3 GW. Due to the direct connection of the vehicles to the grid, these peaks are also located exactly during the peak times of freight traffic; the load is directly dependent on driving behaviour.

18 GW additional electrical load in the extreme case must not be neglected, especially since this load may be distributed very unevenly across regions. Particularly, the focus of the load is likely to occur on motorways in the vicinity of large conurbations. It is therefore essential to investigate the necessity of grid expansion there.

Finally, the influence of the disaggregated modelling of the overhead contact lines on the results will be investigated. Figure 8 shows the final energy consumption for heavy goods traffic. One for the normal scenario S90, and one for a 90% reduction target without detailed modelling of the infrastructure (base).

It can be seen that a new distribution of infrastructure costs alone increases the share of electricity in final energy consumption from around 21% in the baseline scenario to around 30% in the S90 scenario. The share of the trolley truck therefore also depends strongly on the infrastructure. It seems logical that for the use of this technology it is recommended to first overlay the most frequented routes.

B. E-Mobility

This section will examine both the potential of electromobility and the effects of an increased use of electric vehicles.

Figure 9 shows the coverage of the demand for mobility that can be provided by electric vehicles. The results for the scenarios are almost identical until 2035, different long-term targets have no effect on the share of electric vehicles up to this point.

From 2040, there will be major differences between S95 and the other two scenarios. The share in S95 increases from around 15% in 2035 to over 75% in 2050, differences between S90 and S80 appear after 2045, but the difference in 2050 is not immense. The shares of electric vehicles are 35% (S90) and 21% (S80) respectively.

As with the trolley trucks, the choice of the long-term target for GHG emission reduction has a major impact on the potential of e-mobility. Similar to freight transport, differences occur in particular with very ambitious targets, where the GHG reduction pressure on the system is enormously high.

In addition to the potential of electromobility, the effects of using electric vehicles on the system are now to

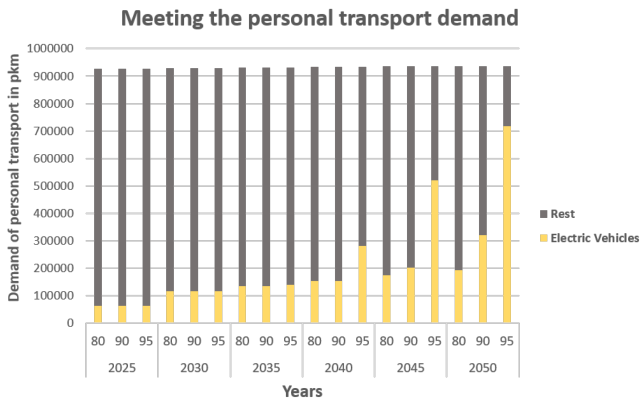

Fig. 9. Share of electric vehicles of the coverage of personal transport demand for the different scenarios

be investigated. To this end, the additional electricity consumption of electric vehicles compared to other sectors in the system is examined first.

As shown in Figure 11, the share of total electricity consumption in all scenarios in 2040 will be less than 10% of total electricity consumption. Scenario S95 has the highest electricity demand of 120PJ.

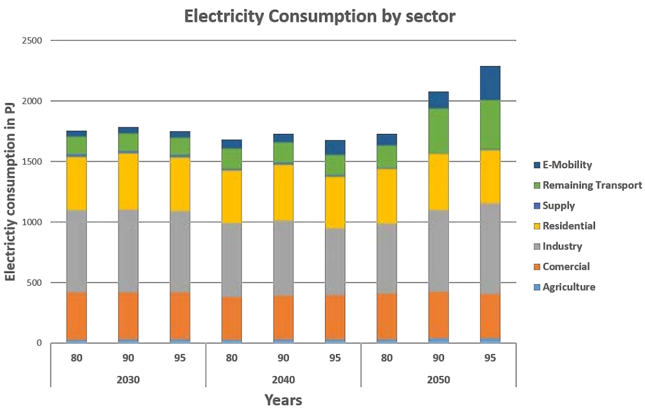

Fig. 11. Electricity consumption in the sectors of the energy system for the different scenarios

In 2050, e-mobility accounts for slightly more than 10% of the total electricity consumption in scenario S95 (corresponds to an extra 280 PJ). For scenario S90, this share is around 7%. Even in S95 with 75% coverage of the demand for transport, e-mobility only accounts for just over 10% of the total electricity demand. However, the entire transport sector (including trolley trucks and railways) is responsible for 30% of the overall electricity consumption. In comparison to the S80 scenario, in scenario S95 an additional electricity demand of 190PJ results from electromobility.

Finally, in addition to the total electricity consumption, an analysis should be carried out to what extent the charging of electric vehicles has an effect on the system. To this end, the electrical load caused by e-mobility is examined in more detail below. Figure 10 shows the load curves by E-mob in 2050 for the S90 scenario, once for 10% and once for 50% availability of charging infrastructure as well as the curve of mileage as additional information (which is the same for all scenarios).

If the simultaneousness of the charging process is limited to 10%, the electrical load will never exceed 15GW. In return, however, charging is more frequent within a week. In the case of a 50% limit, loading is less frequent but significantly greater. The resulting peak load is barely less than 40GW.

Figure 12 shows in more detail the load curve for 50% availability and the residual load of the entire system. The residual load here is the total electrical load in the system (with the exception of e-mobility for this consideration) minus the feed-in of renewable energies and generation that cannot be switched off (heat-guided CHP). Negative residual loads therefore mean a surplus of renewable energies in the system at this point in time.

As Figure 12 shows, these extreme load peaks are in time segments of extremely high negative residual loads. So if you give the system a great degree of freedom as to when it charges electric vehicles, it will systematically select the time segments in which large quantities of regenerative electricity are available. In principle, this scenario represents maximum system-oriented, controlled loading. In this case, electromobility serves as an additional flexibility option for the system.

The disadvantage of this system serviceability is the burden on the distribution network. At its peak, the additional load is almost 40GW, it is questionable whether such a load can be absorbed without expanding the grids. Especially since this burden will be unevenly distributed regionally. The hotspots of the demand are likely to be in the vicinity of conurbations.

It should also be borne in mind that the 40GW already occur in the S90 scenario, where only 35% of mobility needs are covered by electric vehicles, and not in the S95 scenario. In this case, the electrical load is likely to be significantly higher if charging is not limited in some way.

IV. Conclusion

- The contribution of the trolley truck is heavily dependent on the choice of emission reduction targets. It will only have a significant share in freight traffic beginning at 90% GHG reduction in 2050.
- At the maximum, using the trolley truck would cause an additional electrical load of 18 GW, which is likely to vary significantly from region to region.
- In addition, it was shown that detailed modelling of the required infrastructure has a significant influence on the use of the technology. The difference here is about an additional 50% of the trolley truck's final

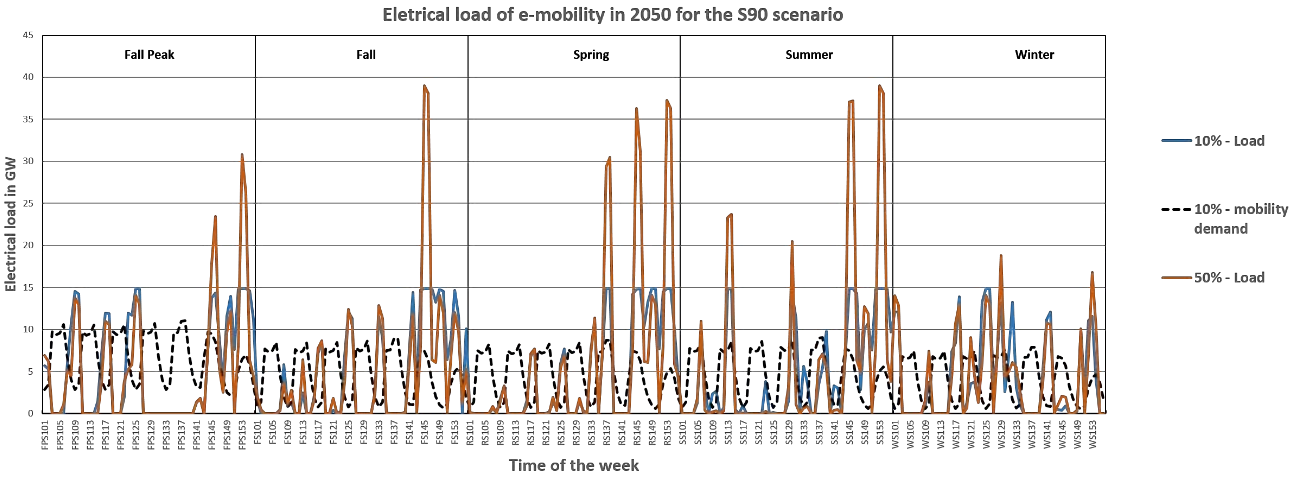

Fig. 10. Electrical load of e-mobility for different charging infrastructure availabilities

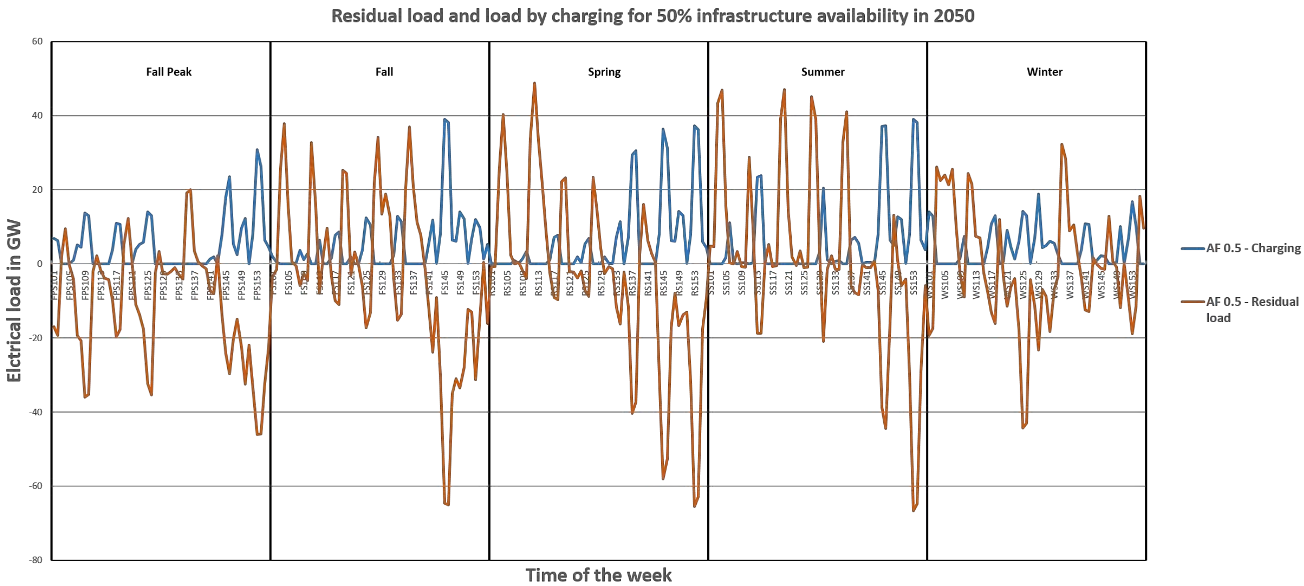

Fig. 12. Residual load and load by charging of e-mobility for 50% infrastructure availability in 2050

energy consumption.

- As with the trolley trucks, the choice of the long-term target for GHG emission reduction has a major impact on the potential of e-mobility. Depending on the reduction target for 2050, the share of electric vehicles vary between 21% and 75% of the coverage of personal transport demand.
- The load caused by charging the electric vehicles can be regulated by limiting the availability of the charging infrastructure. In this case, however, electromobility is only available to a very limited extent as a flexibility option for the overall system.
- If the use of the charging infrastructure is not limited, electromobility can serve as a useful flexibility option in times of high regenerative feed-in. In this case, however, the electrical distribution grid is exposed to large additional loads of up to 40 GW.

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