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ORIGINAL PAPER

The remaining CO_2 budget: a comparison of the CO_2 emissions of diesel and BEV drivetrain technology

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Abstract
This paper describes the CO_2 emissions of the additional electricity generation needed in Germany for battery electric vehicles. Different scenarios drawn up by the transmission system operators in past and for future years for expansion of the energy sources of electricity generation in Germany are considered. From these expansion scenarios, hourly resolved real-time simulations of the different years are created. Based on the calculations, it can be shown that even in 2035, the carbon footprint of a battery electric vehicle at a consumption of 22.5 kWh/100 km including losses and provision will be around 100 g CO_2/km. Furthermore, it is shown why the often-mentioned German energy mix is not suitable for calculating the emissions of a battery electric vehicle fleet. Since the carbon footprint of a BEV improves significantly over the years due to the progressive expansion of renewable-energy sources, a comparison is drawn at the end of this work between a BEV (29.8 tons of CO_2), a conventional diesel vehicle (34.4 tons of CO_2), and a diesel vehicle with R33 fuel (25.8 tons of CO_2) over the entire useful life.

Keywords BEV technology · CO_2 emissions BEV · Future power supply · CO_2 emissions power grid · Fossil-based energy · Renewable energy

Abbreviations

AMS	Auto motor sport (a German-language automobile newspaper)
BDEW	Bundesverband der Energie und Wasserwirtschaft (German Federal Association for Energy and Water Management)
BEV	Battery electric vehicle
BMU	Bundesministerium für Umwelt, Naturschutz und nukleare Sicherheit (Federal Ministry for the Environment, Nature Conservation and Nuclear Safety)
ETS	European emissions trading system
FAZ	Frankfurter Allgemeine Zeitung (a German-language newspaper)
GW	Gigawatt
GWh	Gigawatt-hour
HB	Handelsblatt (a German-language business newspaper)
IPCC	Intergovernmental Panel on Climate Change
kWh	Kilowatt-hour
PtX	Power to X
TWh	Terawatt-hour
WLTP	Worldwide harmonized light vehicles test procedure

1 Introduction

The contribution of CO_2 emissions from anthropogenic sources, especially from individual mobility, to global warming is discussed more than ever in the public and political spheres. As a result, the European Union has set a climate target that calls for a 40% reduction in greenhouse gases from anthropogenic sources by 2030 compared to the 1990 level [1]. This ambitious target has been even strengthened in the meantime. A new reduction goal of even 55% by 2030 was recently announced [2]. In addition, a long-term climate target of an 80% reduction in greenhouse gas emissions by 2050 was published in 2018 [3]. These requirements are to be implemented by the EU member states in the form of

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the BMU Climate Protection Act [4, 5]. They result from a publication by the IPCC, which describes the remaining CO_2 budget with respect to meeting the 1.5 ℃ global warming target. It is assumed that with a remaining budget of 580 Gt CO_2, the target will not be exceeded with a probability of 50%; with a remaining budget of 420 Gt CO_2, this is assumed with a probability of 66% [6].

2 Simulation and modeling of electric energy supply

The following section depicts the basic procedure for the investigations described in this paper. For future years, the analysis will refer to the forecasts provided by the transmission system operators [7, 8]. Furthermore, it should be noted that the energy balance boundary conditions specifically relevant to Germany were chosen for the analysis. It is assumed that the entire energy is produced in Germany. Excess electricity is exported on a balance basis.

2.1 Reference demand for electricity relevant to the analysis

To be able to perform an hourly resolved simulation for future years, hourly resolved real-time data from a reference year must be available. For the simulation, the data of the transmission system operators for the year 2017 were used [9, 10], which were transferred into a matrix P_{ijk}, in which i denotes the technology (i.e. $i=3$ denotes photovoltaic/solar), j denotes the hour within a year 1:8760 and k references the year. These data are shown in Fig. 1. By comparing them with the integral parameters from 2019, the general transferability of the approach can be confirmed. The power demand is set independent from technology i and can be denoted as D_{jk} for every hour j within a year k.

The figure above depicts the electricity demand, the total renewable electricity generation, as well as the electricity generation from the sources of solar and wind energy for an entire year. The progression shown is characteristic also for future years. It can clearly be seen that at no point in time, the electricity demand in 2017 could be completely covered by renewable energy. However, through further expansion of renewable electricity generation, an increasing share of the demand will be met purely through renewable sources in the future.

2.2 Expansion potential of wind power and photovoltaics

The expansion of wind power and photovoltaic systems is making an increasingly effective contribution to Germany's overall energy balance. This expansion will increase sharply over the next few years. The evolution of the installed power $P_k^{installed\ power,\ i}$ of energy type i, according to Table 5 is shown in Fig. 2.

Expansion and decommissioning of power plants for the years of 2030 and 2035 are based on analyses by the Federal Network Agency of June 15, 2018 and July 26, 2020 [7, 8]. The installed power of the years in between is interpolated linearly in this publication. The percentage expansion of wind power and photovoltaics is shown in Table 1.

It should be noted that the extent to which expansion takes place depends on many factors. The expansion of onshore wind farms is viewed particularly critically despite the CO_2 potential [8]. According to the scenario framework, the shares of renewable installed power are 76% for 2030 and 83% for 2035. The year 2023 is chosen because the last nuclear power plant in Germany will be shut down at the end of 2022. Furthermore, the share of hard coal is assumed to be 0 GW for the year 2035, as according to legal regulations [8, 9].

Table 2 shows the full-load hours of the different renewable-energy sources, which are defined below by the factor i according to Table 5. The full-load hours are calculated for

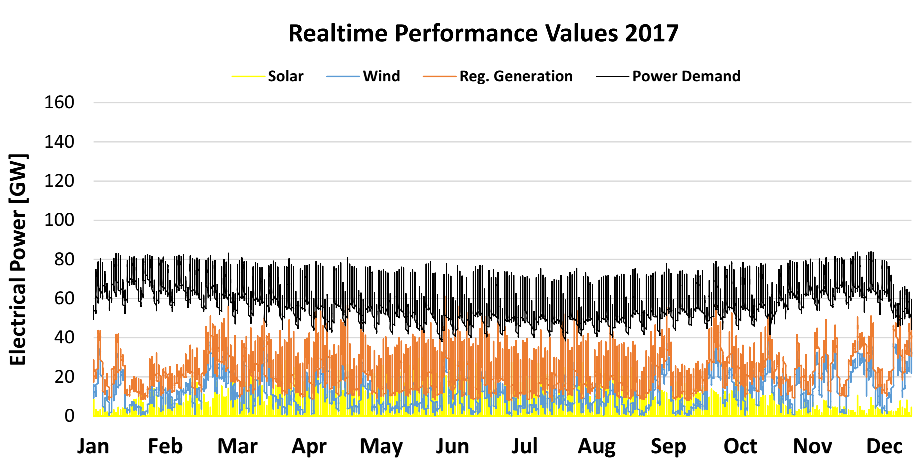


Fig. 1 Evolution of electrical power generation from selected electricity sources P_{ijk} ($i=1$ wind, $i=3$ solar/photovoltaic, sum of $i=1$–4 represents reg. generation) over j hours (within the range $j=1$–8760) for the year $k=2017$; power demand D_{jk} for year $k=2017$

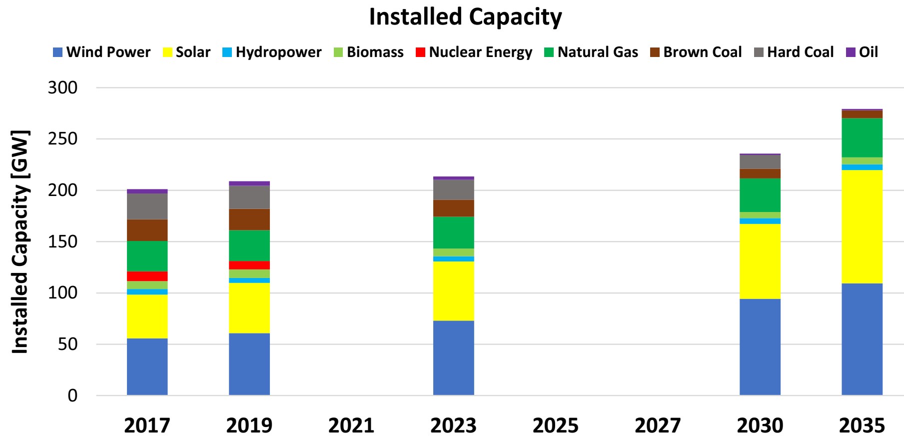


Fig. 2 Installed capacity $P_k^{installed\ power,\ i}$ of power plants and electricity sources (i.e. $i=4$ denotes biomass-based power) for the year k

Table 1 Expansion of installed power $P_k^{installed\ power,\ i}$ of wind power ($i=1$) and photovoltaics ($i=3$)

Period	Wind power, $i=1$ (%)	Photovoltaics, $i=3$ (%)
2030 vs. 2017	69	72
2035 vs. 2017	96	160

Table 2 Full-load hours $h_k^{full\ load,\ i}$ of renewable-energy sources i (defined in Table 5) in the year k

	$k=2017$	$k=2019$	$k=2030$	$k=2035$
Wind power, $i=1$	1904	2072	2724	2735
Hydroelectric power $i=2$	4187	4292	4000	4400
Photovoltaic/solar, $i=3$	931	968	950	950
Biomass, $i=4$	5805	5348	5000	3900

Table 3 Full-load hours $h_k^{full\ load,\ i=1}$ of wind power, analysis (onshore) considers basic/latest wind turbine technology

	2030	2035
Wind onshore	1700/2300	2300
Wind offshore	4300	4000

2017 and 2019 by dividing the electricity generated by the installed power of the respective plant. A comparison with the data from the Federal Association of Energy and Water Management (BDEW) confirms these values [10]. The full-load hours for the future years are projected [7, 8].

It should be noted that one value of full-load hours of wind power $\mathrm{h}_k^{\mathrm{full\ Load},\ i=1}$ is listed in Table 2 for each year. Note that these wind power values are average values considering and distinguishing between onshore and offshore wind performance. In addition, the date of production is essential. Table 3 below shows the full-load hours for wind for the years of 2030 and 2035. The values for onshore wind in 2030 differ due to the date the turbine was installed. 1700 h are assumed for wind turbines installed before December 31, 2017 and 2300 h for wind turbines installed afterwards. For the later calculations, the value of 2300 h is assumed [7].

It is particularly noticeable that the full-load hours for wind increase sharply as compared to 2017 and 2019. This follows the reasoning that more modern low-wind turbines can generate more full-load hours due to larger hub diameters [11]. According to the Federal Network Agency, these values might however be overestimated, since the hub height does not necessarily follow technical ideals [8].

The contribution of renewable energy is analyzed according to Eq. 1 (explained in detail in Sect. 2.3), considering the further ramp up of wind turbines and photovoltaic systems. Integration of P_{ijk} over a complete year of 8760 h leads to the respective energy values W_{ik} for the sources i within a year k, as shown in Fig. 3. In this publication the expression "electricity consumption" is sometimes used although energy cannot be consumed from the thermodynamic perspective. This nomenclature is basically intended to indicate the fact that consumers require electrical energy and that a request from the customer respectively consumer side exists.

The electricity generated from renewable energy cannot be scaled up in an arbitrary order of magnitude as installed power and current weather conditions determine the maximum power output of wind and solar power in contrast to conventional fossil power plants. Only energy generation from fossil fuels can be scaled up flexibly through more use or less use. For the years of 2017 and 2019, the recorded data were used [12, 13]. Furthermore, import and export have been considered. In the analyses for future years, battery electric vehicles (BEV) were not considered in the presentation of the net electricity consumption. In accordance with the expansion scheme, 1.1 million heat pumps were projected for 2030 and 3 million for 2035 [7, 8]. It

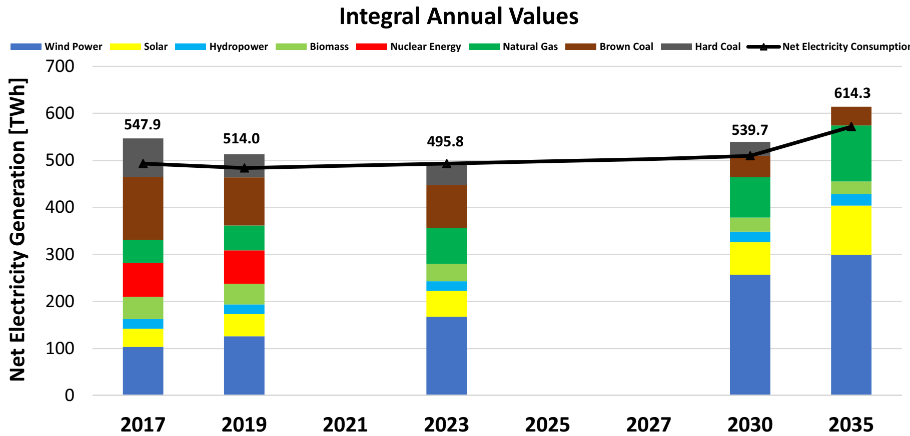


Fig. 3 Evolution of net electricity generation/net electricity consumption W_{ik}

is particularly important to note that in future years, the net electricity demand should be covered and generated completely independently within Germany. Especially in the future, the excess electricity can be stored in batteries, transferred via PtX technology or can be exported. Electric energy storage technology is considered according to assessment by the Federal Network Agency [7, 8]. The boundary conditions of battery storage and PtX technology are explained below in Sect. 2.4.

Net electricity denotes the electricity or the electricity mix as it is actually drawn from the socket, in other words the customers' electricity requirement. Gross electricity also includes the power plants' own consumption and the industry's own generation [14].

It is assumed that the hourly renewable electricity supply is available at every location in Germany. This corresponds to the ideal state referred to as "Kupferplatte Deutschland" (copperplate Germany), which is in line with the idea of the German power grid being a Germany-wide copper plate enabling such ideal state [15, 16]. In the hours where renewable electricity generation is not sufficient, the demand is additionally covered by fossil fuels. If there is sufficient or excess renewable energy, no fossil power plant is operated on balance. Thus, an important condition set for the analysis is that renewable energy, wherever it is generated in Germany, is always transferred to electricity consumers with first priority.

The share of natural gas in the energy mix is expected to rise sharply over the next few years and is thus becoming increasingly important [17]. The percentage shares of non-renewable-energy sources in electricity generation are shown in Table 4.

Due to the varying supply of renewable-energy sources P_{ijk} (for $i=1$ to 4) the remaining electric power to stabilize the net and deliver electric energy for all consumers needs to be supported by non-renewable-energy sources. The share of this non-renewable electric power, which means the percentage of nuclear, gas and coal to overall non-renewable energy, remains the same within every hour of a year k according to Table 4. This will be discussed in more detail in later sections. The future full-load hours of gas were assumed to increase linearly, also according to the analysis by the Federal Network Agency [7, 8]. Lignite and hard coal full-load hours were kept the same as the 2019 h but the installed power is reduced over the years. Due to the decommissioning of coal and the addition of gas-fired power plants, the share of gas will increase additionally and the share of coal will decrease significantly.

2.3 Hourly resolved simulation 2030/2035

The analyses presented for the simulated real-time power values for the years of 2030 (Fig. 4) and 2035 (Fig. 5) are a result of the real-time data of 2017 in combination with the expansion data of the installed renewable capacities and the respective projected full-load hours of the renewable-energy sources [7, 8].

The meteorological conditions of 2017 were set to be standard for this analysis, as the 2017 data were available

Table 4 Share of energy sources in total non-renewable electric energy generation (oil not considered)

	$k=2017$	$k=2019$	$k=2023$	$k=2030$	$k=2035$
Share of nuclear energy, $i=5$	21.4%	25.8%	0.0%	0.0%	0.0%
Share of natural gas, $i=6$	14.6%	19.2%	35.2%	53.2%	75.0%
Share of hard coal, $i=7$	24.2%	18.0%	22.0%	18.3%	0.0%
Share of lignite, $i=8$	39.8%	37.0%	42.8%	28.5%	25.0%

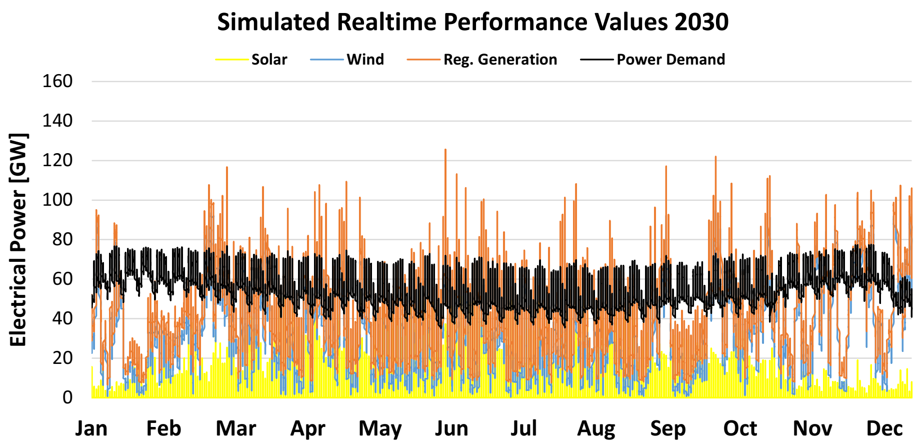


Fig. 4 Evolution of selected electricity sources P_{ijk} over *j* hours ($i=1$ wind, $i=3$ solar/photovoltaic, sum of $i=1$–4; j within the range 1:8760; $k=2030$): simulated performance 2030, based on 2017 analysis; electric power demand D_{jk} without BEV

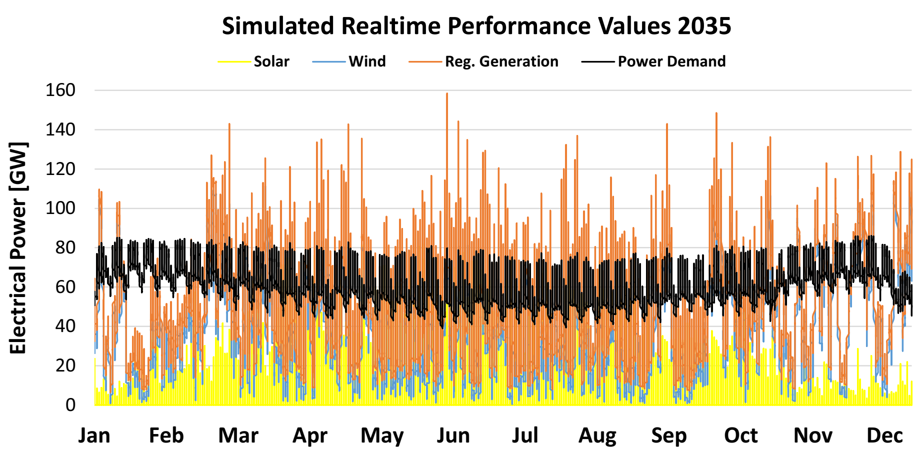


Fig. 5 Evolution of selected electricity sources P_{ijk} over *j* hours ($i=1$ wind, $i=3$ solar/photovoltaic, sum of $i=1$–4; *j* within the range 1:8760; $k=2035$): simulated performance 2035, based on 2017 analysis; electric power demand D_{jk} without BEV

and had been intensively and completely preprocessed in a preliminary work to enable a comprehensive analysis.

In a first step, the contribution P_{ijk} was defined and the renewable electricity generation P_{ijk} ($i=1$–4) of the respective energy sources were analyzed for the year $k=2017$, as already shown in Fig. 1. Since the full-load hours of the various energy sources ($i=1$–8) are forecast to rise or fall at different rates in the future, the corresponding analysis and boundary conditions must be accounted for in the calculation. The following Eq. 1 can be used to calculate the regenerative power generated for each hour of the future years based on the data from 2017.

$$P_{ijk} = P_{ij2017} \times \frac{P_k^{installed\ power,\ i}}{P_{2017}^{installed\ power,\ i}} \times \frac{h_k^{full\ load,\ i}}{h_{2017}^{full\ load, i}} \quad i = 1 - 4 \qquad (1)$$

$$W_{ik} = \int_0^{\Delta t} P dt = \sum_{j=1}^{8760} P_{ijk} \qquad (2)$$

Subsequently the integral of power P is evaluated over the total time Δt of a year *k*, leading to W_{ik} according to Eq. 2. A total amount of energy of the respective regenerative energy carrier i can be calculated [18].

Figure 4 and Fig. 5 clearly show that the electricity demand can be completely covered by renewable-energy sources ($i=1$–4) during many hours of the year. However, it can also be seen that especially in months with little sunshine, the electricity generated from renewable sources is not sufficient and, as mentioned above, the demand must also be covered by fossil fuels [19]. The remaining difference between future energy demand and regenerative power P_{ijk} ($i=1$–4) in most hours of the year is the non-regenerative power plant supply P_{ijk} ($i=5$–8). The share of energy contribution within every hour of nuclear, gas, and coal has been defined according to Table 4. The European Emission Trading System ETS might influence the corresponding share of non-regenerative power plant supply of the future. It must be emphasized however, that the impact of the ETS tool must be assessed and adapted to future boundary conditions with an increased electricity demand D_{jk} on the one hand, and partially increasing gap and increased necessity of non-regenerative power plant supply P_{ijk} ($i=5$–8) on the other hand. The impact of ETS is slightly more detailed in Sect. 4.4.

The minimum total renewable power is 7 GW for the year 2030 and 6 GW for the year 2035. The renewable peak total power is 126 GW for the year 2030 and 158 GW for the year 2035. The lower minimum total power of 2035 compared to 2030 is due to the lower full-load hours of biomass, despite further expansion of electricity generation from renewables, as it forms a constant base throughout the year. It is also obvious that renewable electricity generation often significantly exceeds electricity demand. In this case, there is a need for battery storage [16, 20, 21] or other energy storage technologies. Power to X (PtX) plants, which generate methane, hydrogen, or heat from excess electricity, can be operated at these times [22–24].

2.4 Energy balance and storage

As mentioned before, there is a need for significantly increased storage capacities [7, 8]. The scheduled storage energy is shown in Fig. 6.The energy balance of the regenerative surplus and the lack of energy to be filled are also shown.

Figure 6 (left) illustrates the integrated regenerative energy surplus (orange) in the years $k=2030$ and $k=2035$. The orange columns represent the integral over those hours j, when the regenerative contribution ($i=1$–4) of P_{ijk} is greater than the electric energy demand D_{jk}.

Furthermore, the gray columns represent the integral of all hourly gaps, when the total regenerative contribution ($i=1$–4) of P_{ijk} is smaller than D_{jk}.

Although the installed regenerative power $P_k^{installed\ power,\ i}$ ($i=1$–4) will significantly increase from today to the year $k=2030$ to $k=2035$, the gap (gray column) remains almost constant due to the increasing demand for electricity (increased number of heat pumps i.e.).

Figure 6 (right) shows the projected battery storage capacities. It is particularly interesting to note that in the forecasts for battery storage in 2030, only 0.5 TWh of the excess electricity can be stored over the entire year and used again when there is too little renewable electric energy generation. This assumes that any storage is available regardless of location. For the year 2035, a maximum of 3.7 TWh of surplus electricity can be stored. This analysis confirms that, despite the important expansion of renewables, 160.5 TWh will still have to be provided by fossil fuels in 2030 and 155.7 TWh in 2035 (blue), assuming electric power generation within the area of Germany (corresponding to Table 4 for the respective year). It should also be noted here that no BEV fleet is considered in Fig. 6. Please note that also the PtX potential according to the currently scheduled PtX expansion has been analyzed. However, based on today's strategy, the PtX influence is of minor impact.

2.5 Balance analysis

Figure 7 shows the distribution of fossil electricity generation in relation to renewable electricity generation. As already described in Sect. 2.2, the share of renewable energy is increasing strongly.

This distribution does not consider BEVs, either. Additional consumers (BEVs) change the distribution to more fossil electricity generation, since renewable electricity generation cannot be increased following the demand. Even in 2035, the fossil share of net electric energy generation is at least 25%. Table 5 shows the different carbon footprints indicating how many grams of CO_2 per kilowatt-hour (kWh) of electrical energy are produced for each energy source.

Of course, renewable electricity generation causes significantly lower CO_2 emissions. However, CO_2 emissions also

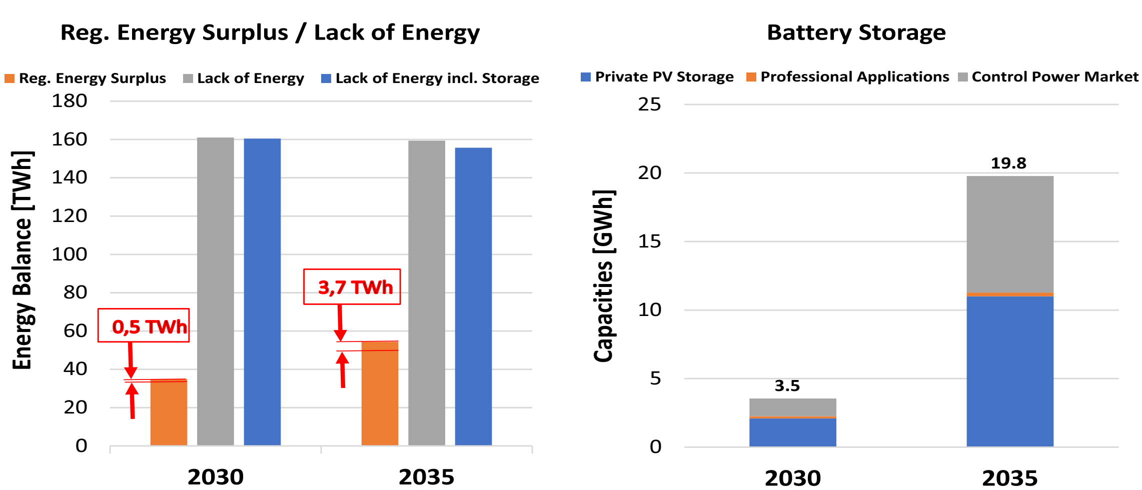


Fig. 6 Evolution of electricity performance: energy balance, evolution of battery storage capacities

Fig. 7 Shares of non-regenerative and regenerative power of net electrical energy generation

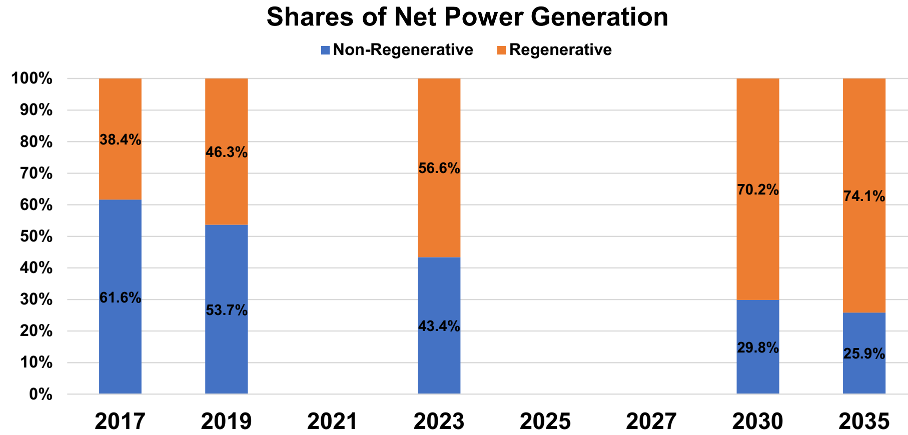


Table 5 Average CO_2-equivalent emissions of different electricity generation technologies [25]

Technology	g CO_2/kWh
Wind power onshore/offshore, $i=1$	18/5
Hydroelectric power, $i=2$	23
Photovoltaics, $i=3$	50
Biomass, $i=4$	70
Nuclear energy, $i=5$	24
Natural gas, $i=6$	499
Hard coal, $i=7$	830
Lignite $i=8$	1075

Table 6 Carbon footprint of the electricity sector in Germany for different years

	2017	2019	2023	2030	2035
Footprint of electrical energy g CO_2/kWh	412	363	370	244	198

occur with this electricity generation on a low level, because of production, maintenance and disposal issues [26, 27].

Based on the respective share of the energy sources in electricity generation and the carbon footprints, an average footprint of electrical energy is calculated for the respective years (see Table 6).

The ever-increasing share of renewable energies is also steadily reducing the average carbon footprint. It should be noted that the carbon footprint will increase again in 2023, when the last nuclear power plant will be taken off the grid at the end of 2022, as nuclear power emits significantly less CO_2 than coal-fired power (see also Table 5).

Charging a BEV with an electricity mix of 198 g CO_2/kWh in 2035 will result in a theoretical value of 45 g CO_2/km if one assumes a consumption of 22.5 kWh/100 km and an average value calculation based on Table 6, which is however rather misleading. Indeed, such electricity mix cannot be used to charge a BEV fleet of several million vehicles, as the energy required for these consumers must be provided additionally. Since renewable electricity generation cannot be further increased to a higher extent than depicted in (Table1/Table 2), the additional electricity consumption basically needs to be covered by fossil fuels, which in turn worsens the electricity mix.

3 Vehicles

This section describes the vehicles used in our analyses. For each of the studies, we selected a VW ID.3 BEV and a VW Golf 8 2.0 TDI diesel vehicle in the compact class. Figure 8 shows the different fuel tests and energy demand values published.

The average WLTP certification value for the BEV ID.3 is 16.1 kWh/100 km, and 4.4 l/100 km for the selected Golf 8 diesel vehicle [28]. Equivalently, to better represent real-world consumption, an additional consumption of 14% compared to the WLTP values is assumed for both vehicles. These 14% are an approximate average of the real-world consumption compiled from various test magazines. This value results in a consumption of 18.4 kWh/100 km for the ID.3 and of 5.0 l/100 km for the Golf 8 diesel vehicle.

Figure 9 in addition shows the electricity losses that occur during use. Furthermore, the CO_2 impact of the diesel vehicle is shown for tank-to-wheel and well-to-wheel considerations.

Grid losses are physically induced energy to heat transfer losses in the power grid that occur for example during transport, transformation, and distribution. For our analyses, these are assumed to be 6% [29] leading to an increase in electricity demand from 18.4 to 19.5 kWh/100 km. Low-voltage losses, assumed to be 2%, increase the demand to 20.0 kWh /100 km. Low-voltage losses include local grid and in-house losses, which are predicted to increase further

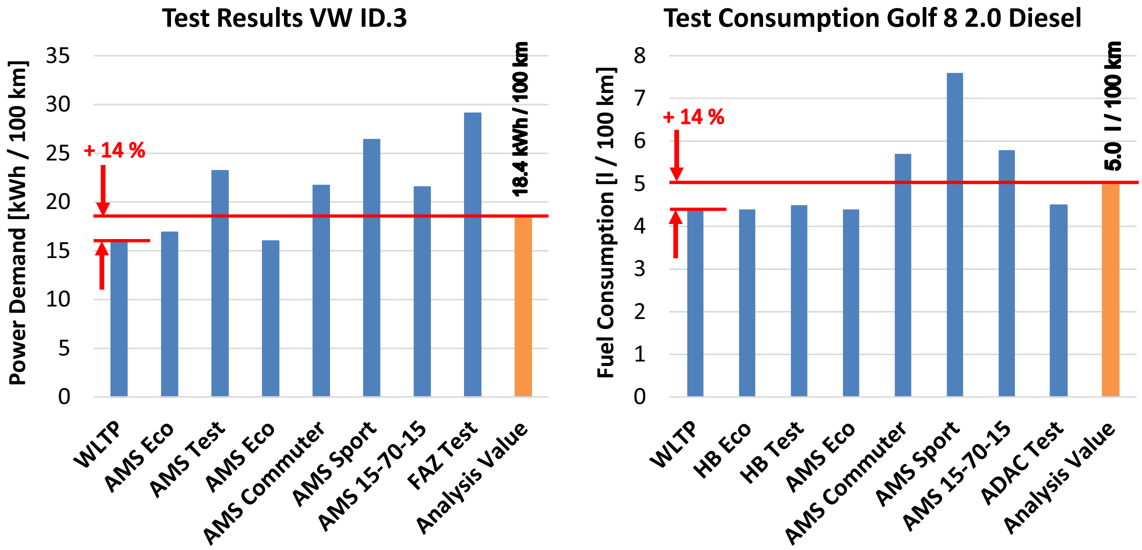


Fig. 8 Energy demand respectively fuel consumption of reference vehicles VW ID.3 (left) and VW Golf 8 (right)

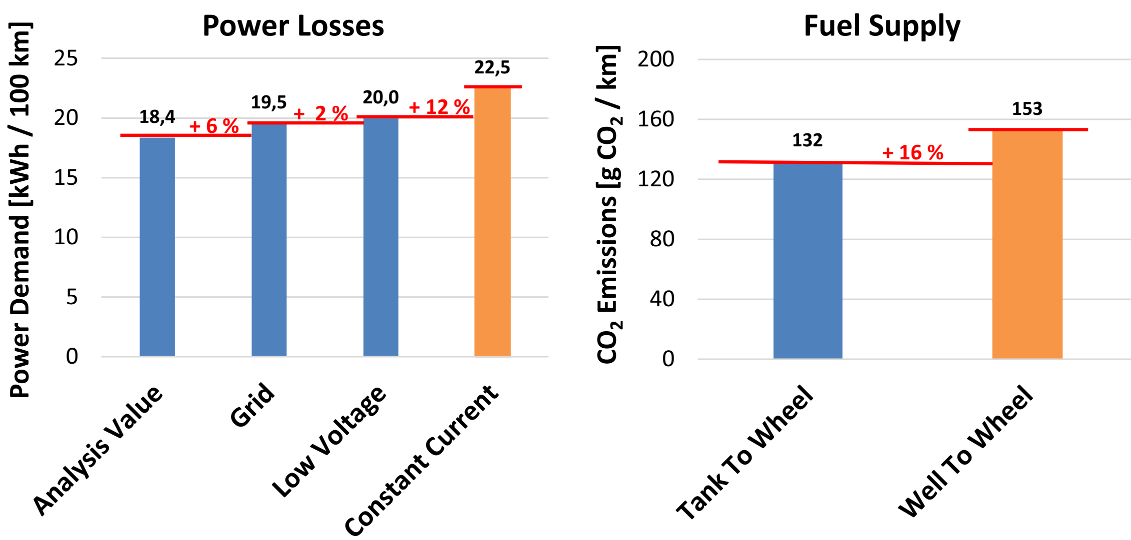


Fig. 9 Analysis (left) of increased electrical energy demand (i.e. power losses) and diesel impact on CO_2 emissions (right)

in the future. In addition to the grid-side losses, there are also losses during operation. BEVs discharge at vehicle standstill. These losses are referred to as constant current losses. It is assumed that this discharge is a constant 40 watts [21, 30]. It is assumed that the vehicle is stationary for 8500 h per year. Conversely, this means that the vehicle is moved 260 h a year, which corresponds to a driving time of approx. 40 min per day. This results in an additional demand of 340 kWh. Adding the latter to the total energy required and putting it into perspective, an additional electricity demand of 12% is obtained, which means that a total electricity demand of 22.5 kWh/100 km can be assumed. This value is used for all subsequent calculations.

It should be noted that fast-charging losses, wall-box losses, battery heating losses, vehicle temperature losses in the charging mode, operation in winter, and charging station infrastructure issues are not taken into account in these considerations!

The fuel supply of diesel vehicles also needs to be considered. A CO_2 impact of 2650 g CO_2/l during use is assumed. Production, transport, and distribution are supposed to increase the CO_2 impact by 16% to 3074 g CO_2/l [31]. These assumptions result in tank-to-wheel emissions of 132 g CO_2/km and well-to-wheel emissions of 152 g CO_2/km. The well-to-wheel emissions are used for the calculations below.

4 Overall electric energy system analysis

In the following section, among other things, the boundary conditions of the analyses for future years are described in more detail. The total CO_2 emission balance is presented, together with the resulting impact on CO_2 emissions caused by BEVs over the use phase.

4.1 Analysis

Figure 10 shows a simulated course of the day of July 23, 2030 with and without BEVs, as also shown in Fig. 4 and Fig. 5, complemented by an additional BEV charging influence.

The orange curve shows that during many hours, more renewable electricity is produced than is actually required (blue graph). In this example, this is particularly obvious around noon. It can also be seen that especially at night, renewable electricity generation is not sufficient to cover the demand. The blue curve already takes into account electrification forecasts, e.g. from heat pumps according to [7, 8]. BEVs, on the other hand, are not included in this curve. As already mentioned, the generated electricity is assumed to be available at any location in Germany (assumption: "copperplate Germany"). In the model calculation, in the case of excess renewable electricity, the battery storage systems are charged first based on their available capacities (see Fig. 6 right). If there is insufficient renewable supply, the storage batteries are emptied as thoroughly as possible before the fossil power plants are started.

Figure 10 (right) in addition represents the curve with ten million BEVs, which results in a higher electricity demand. The simplified assumption is made that all BEVs are charged constantly 24 h a day over 365 days (31.5 TWh of additional energy required for 10 million BEVs results in an hourly additional demand of approx. 3.6 GW). Indeed, a battery charging is typically recommended during noon but on the other hand, many vehicles must operate during the daytime. Therefore, a constant charging rate has been assumed.

To calculate the impact of the charging strategy on the CO_2 footprint, an analysis has been performed for different charging times. Due to latest political demands to realize a 15 million BEV fleet already in 2030, this is shown as an example in Fig. 11. Two strategies are distinguished. First, the assumption is made that vehicles only charge during the day from 9 am to 6 pm (blue) and second, that vehicles only charge at night from 8 pm to 6 am (orange). The assumption that the vehicles charge around the clock is also shown in gray. It can be seen that the charging time did not have any influence in past years due to a lack of renewable energy. In future years, the charging time will have an increasing influence. Ideally, the vehicles would have to be charged during the day to take advantage of the peak of renewable generation around midday due to the increasing solar expansion. On the other hand, it can be clearly seen that the CO_2 footprint deteriorates significantly if the vehicles are only charged at night. Based on this, the average 24/7 charging assumption seems to be a realistic scenario.

For the year 2030, without BEVs, the fossil-based electric energy demand will be about 161 TWh (demand minus regenerative generation). In the case of a BEV fleet with

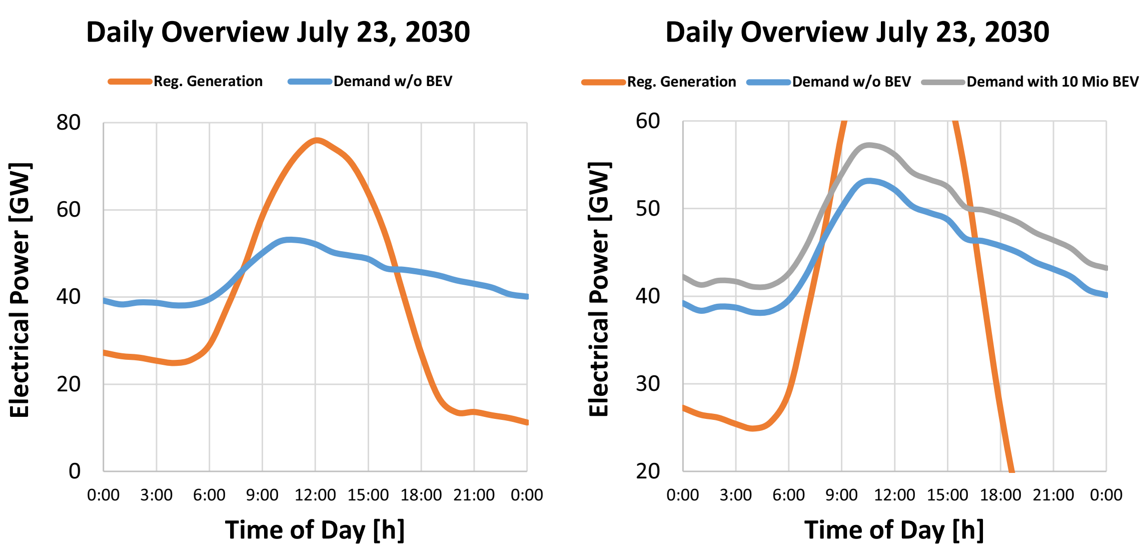


Fig. 10 Daily overview July 23, 2030 without (left)/with (right) contribution of BEV fleet, evolution of selected electricity sources P_{ijk} over j hours (orange, regenerative power: sum of $i=1$–4, $k=2030$): electric power demand D_{jk} with $k=2030$ and without BEV (left), with and without BEV (right)

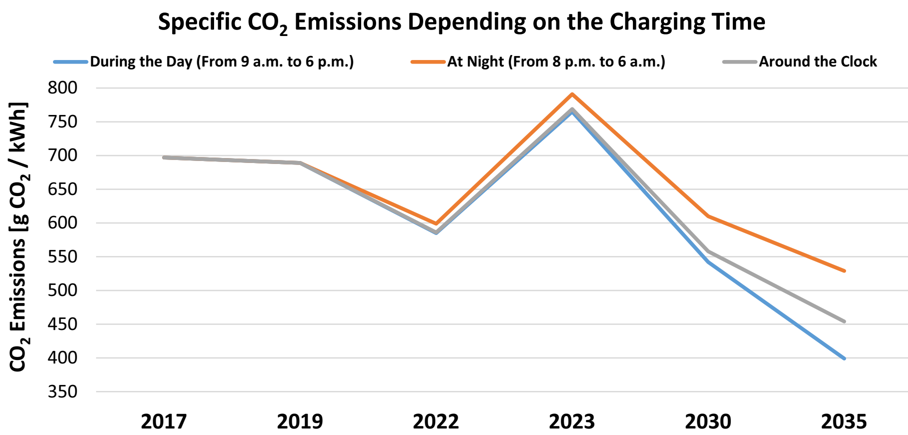


Fig. 11 Specific CO_2 emissions due to different charging strategies in different years for 15 million BEVs

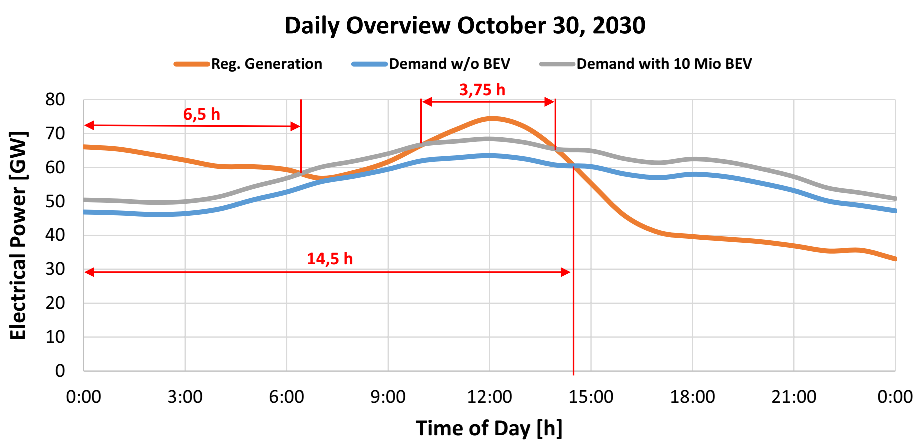


Fig. 12 Example of the daily evolution of regenerative electrical power generation, similar as Fig. 11

ten million vehicles, it would increase to 185 TWh. Due to additional consumers, be they BEVs or others, more fossil energy is needed, since renewable electricity generation cannot be increased ad hoc. Another effect of additional consumers is the increase in the time share with the requirement of fossil energy-based grid support (see Fig. 12). The example reveals that without BEV fleet, the electricity demand can be met purely from renewables for 14.5 h per day. With an additional BEV fleet of ten million vehicles, the electricity demand can only be covered purely from renewables for 10.25 h. Moreover, the volatility of the electricity market increasingly leads to transient partial-load operation of fossil power plants with consequent efficiency deterioration. The additional CO_2 increase resulting from this issue is however not accounted for in this analysis.

4.2 Average daily data 2030/2035

Figure 13 shows the average daily run of electric power data for the year 2030 (left) and for the year 2035 (right). The average of all 24-h time intervals (00.00–01.00; 01.00–02.00; …; 23.00–24.00) of 365 days has been calculated on the basis of P_{ijk}. Furthermore, the minimum and maximum curves of electricity demand, total renewable electricity generation, and the contributions from wind and solar energy are plotted. The minimum and maximum curves do not reflect the curve of a single day, but only the extreme values of individual hours. The curves also reflect the demand without BEVs.

Based on the minimum and maximum course (dashed lines) for wind, for example, it becomes clear that during some hours of the year, neither wind nor sun are available. On the other hand, more than 2200 h of surplus renewable energy are expected in 2030. Therefore, storage options like battery electric energy storage or PtX applications are required.

It is evident that on average for the year 2030, renewable electricity generation is not sufficient to cover the electricity demand at any time of the day. It is around noon that renewable electricity generation is highest due to solar energy. In 2035, on average, renewable electricity generation around noon is sufficient to cover the energy demand. It is particularly clear that renewable electricity generation at night and in the late evening is insufficient to meet the demand. From this, it is obvious that both in 2030 and 2035, the average

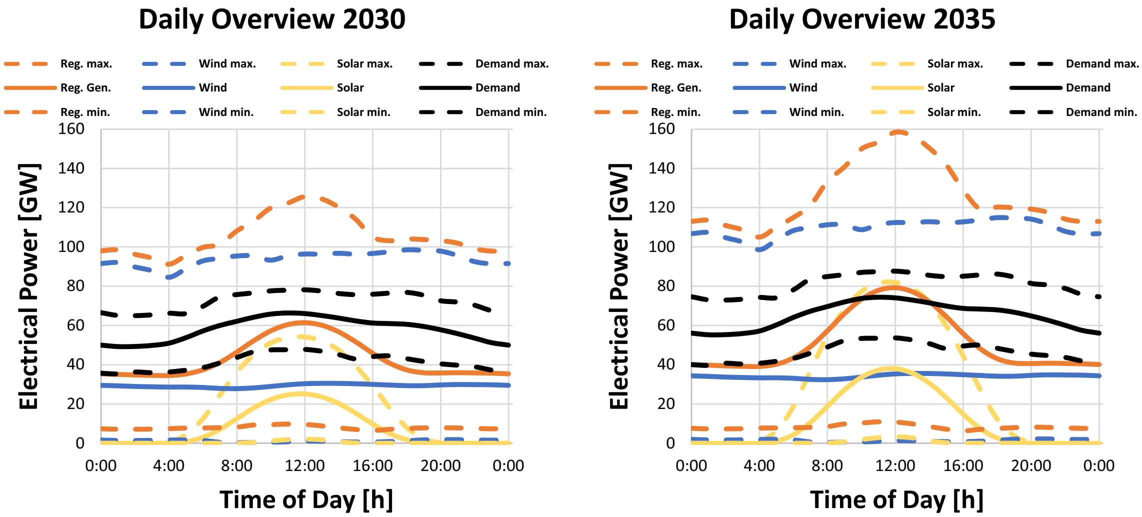


Fig. 13 Contribution by different electrical sources: daily average courses in the years 2030 (left) and 2035 (right), min/max situation within a complete year depicted for 2030 and 2035

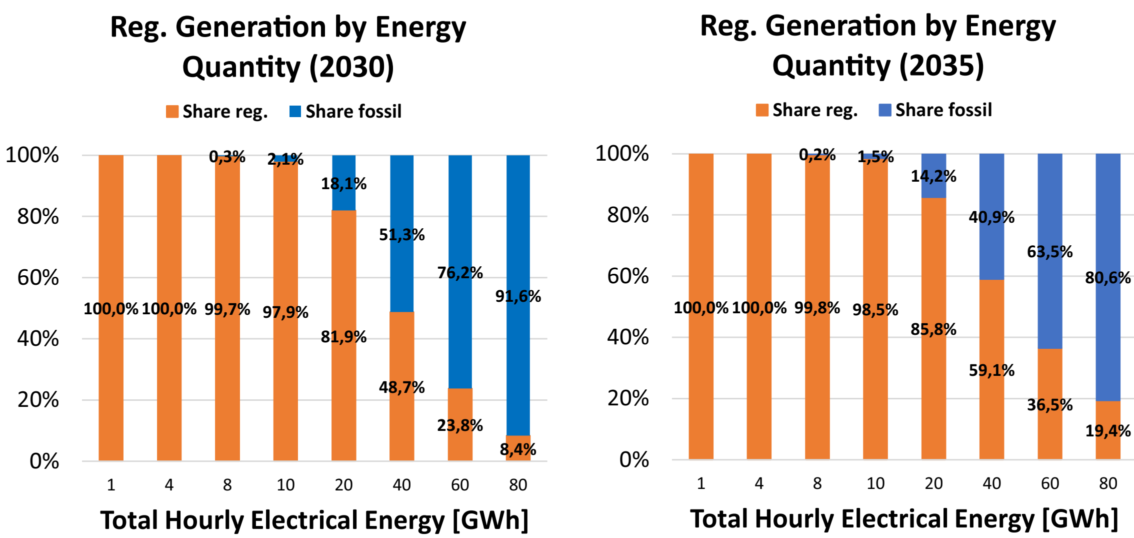


Fig. 14 Shares of available time of non-regenerative (fossil, blue) and regenerative power (orange) in the years 2030 (left) and 2035 (right), the unit is GWh per hour, which is equivalent to an average power level in GW

renewable electricity generation is even slightly below the minimum demand.

4.3 Availability of renewable electrical energy

Figure 14 gives an overview of how much renewable electric energy is permanently available in 2030 and 2035.

The illustrated distribution indicates during how many hours of the year the respective regenerative total energy is available, depending on the electricity demand. The example of 2030 (left) depicts that 1 GW and 4 GW of renewable energy are available at all hours of the year (8760 h equivalent to 100%). On the other hand, 60 GW are only available during 23.8 percent of the annual hours. In other words, during 2085 h per year, 60 GW are completely available as renewable electricity. For the rest of the time, additional fossil energy must be provided to reach the required amount of energy. The average amount of energy required per hour is 58.2 GW (57.6 GW without PtX plants) for the year 2030 and 65.3 GW (64.0 GW without PtX plants) for the year 2035. As a result of the further expansion of renewable electricity generation, the proportion of hours with purely renewable-energy supply will increase, for instance from 23.8 to 36.5%, if the

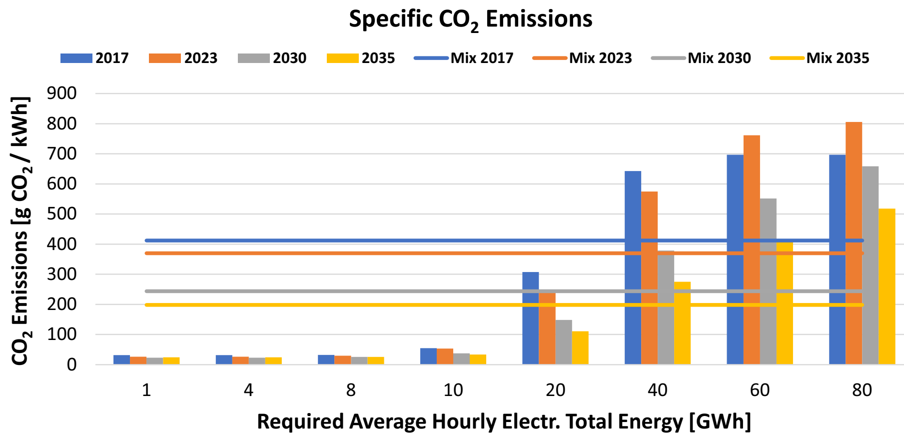


Fig. 15 Electricity CO_2 average footprint and increase in CO_2 emissions as a function of additional required total electrical energy (hourly average), the unit is GWh per hour, which is equivalent to an average power level in GW

Table 7 Renewable/non-renewable-energy mix of the different years k

Energy mix	$k=2017$	$k=2023$	$k=2030$	$k=2035$
Renewable g CO_2/kWh	31.6	26.4	23.2	24.5
Non-renewable g CO_2 kWh	697.0	807.4	716.6	636.5

Table 8 Periods of time [h] covering electricity demand with renewable or fossil energy carriers in 2030

Electrical energy supply 2030	BEV 0	BEV 1	BEV 5	BEV 10
Purely renewably [h]	2324	2299	2154	1983
Fossil fuel supplement [h]	6436	6461	6606	6777

electricity demand remains constant at 60 GW. On the other hand, an increase in electric energy demand reduces this share of hours with purely renewable-energy supply from 23.8 to 8.4% in 2030, in case the demand increases from 60 to 80 GW.

It should be emphasized that the proportions of fossil and regenerative hours reflect the mix of additional energy consumers. This means that in 2030, assuming an average basic requirement of 60 GW, the mix of additional consumers will consist of 76.2% fossil and 23.8% regenerative components.

4.4 CO_2 Emissions from electrical energy

Based on the considerations presented in Sect. 4.3, the CO_2 emissions per kWh resulting from the generation of electricity out of the mix of renewable and fossil energy can be derived. Using this approach, the emissions for 2017, 2023, 2030, and 2035 are calculated. This is shown in Fig. 15. The average energy mix for the respective years is also shown.

The calculation of the CO_2 emissions of additional consumers requires the percentage shares of renewable and fossil generation according to Fig. 14. These shares have to be multiplied by the CO_2 emissions of the renewable and fossil energy mix. This mix of fossil and renewable energy differs each year depending on the share of the respective energy sources (Fig. 3). The shares of fossil energy sources for the respective years have already been shown in Table 4. The mix for fossil and renewable energy is listed in Table 7.

Table 9 Periods of time [h] covering electricity demand with renewable or fossil energy carriers in 2035

Electrical energy supply 2035	BEV 0	BEV 1	BEV 5	BEV 10
Purely renewably [h]	3199	3172	3041	2854
Fossil fuel supplement [h]	5561	5588	5719	5906

The calculations of the fossil energy mix including nuclear power until 2022 has already been presented in Table 4. It must be emphasized again that the European Emission Trading System ETS might influence the corresponding share of non-regenerative power plant supply in the future, but it remains an unanswered challenge how an ETS-regulated energy system must be adapted, especially in the case of a significant gap of electric power supply in the future, and which economic consequences result. Additionally, the security of supply issues in the case of low renewable electric energy supply influences the power share in the future.

Indeed, the impact of ETS is intensively discussed among economists as the interaction with the electric energy system is complex. In the case of Germany, a clear ambition to further strengthen photovoltaics and wind power is obvious, but, as analyzed, the gap and requirement of additional fossil energy will remain as shown in Table 8 and Table 9 below. There is a clear evidence, that for markets with limited renewable electric energy like Germany on the one hand and increased electricity demand in the future due to enforced electrification on the other hand, the price of electricity will have to rise significantly [32].

There also seems to be a clear evidence, that the main impact of ETS as a consequence of higher penalties for emissions and related rising electricity costs will be the displacement, externalization and relocation of energy-intensive industry.

In other words, a shift of industry towards regions of the world with a non-ETS-controlled electricity market has been identified as a critical impact [32]. Overall, the main impact of ETS is partly a shift of the energy mix but predominantly an increase in electricity prices in combination with a relocation of industry. The requirement of additional fossil power or additional alternative CO_2-optimized technologies like further increased biomass, nuclear, water-power or storage-(such as pumped hydro, batteries or power-to-gas-to-power) based electricity supply basically remains indispensable in the case of increased electricity demand as analyzed in this publication.

Figure 15 illustrates that with less total energy required, lower specific CO_2 emissions are emitted for all years. With increasing energy demand, the specific CO_2 emissions also increase as a result of the decreasing periods of time with completely renewable electricity generation as well as necessary increased fossil power generation.

Due to the expansion of renewable electricity generation, the annual emissions are significantly lower for future years. The exception is the year 2023, where the specific CO_2 emissions are higher than in 2017. The further expansion of photovoltaics and wind power in the subsequent years will counteract the phase-out of nuclear energy. Without BEVs, the hourly average electric energy demand is between 55 and 65 GWh. The example of the year 2035 demonstrates that due to higher grid loads, the specific CO_2 emissions will also increase in the future (Fig. 15).

Figure 16 plots the average CO_2 emissions and the CO_2 emissions of an additional consumer, such as a BEV.

The average energy mix already shown in Table 7 is displayed on the abscissa. On the ordinate, the additional CO_2 emissions of each additional consumer are plotted. Zero BEVs are assumed (blue line). The blue dots represent the values for the different years. The average energy mix decreases through 2022, increases again in 2023 due to the nuclear phase-out described above, and then once more decreases. In line with this, the additional CO_2 emissions rise and fall as well. By theoretically adding a fleet of five million BEVs, the average energy mix also deteriorates. This is illustrated here in red color for the years of 2030 and 2017. The more vehicles are added in 2030, the more the CO_2 emissions from the additional consumers increase. This is due to the fact that more fossil-based electric energy has to be provided. For the year 2017, it can be seen that the CO_2 emissions for additional consumers would have remained constant. The reason for this is that for the five million BEVs assumed theoretically for 2017, the energy supply would have had to be completely fossil-based because complete renewable coverage did not exist during any hour of that year [12].

4.5 Balance analysis 2030/2035

This section deals with the CO_2 balance of German electricity generation for the years of 2030 and 2035 and discusses how it changes by adding differently sized fleets of BEVs. A distinction was made between fleet sizes of one, five, and ten million vehicles. The CO_2 emissions for the year of 2030 are shown in Fig. 17.

For the analyses, CO_2 emissions are calculated first for a scenario without any BEVs (BEV 0). For this purpose, the amount of energy of the respective energy source is added up for each hour according to Fig. 3. All boundary conditions presented in Sect. 4.1–4.4 were considered for the calculation. At the end of the year, a total energy amount is obtained for each energy source. For the year of 2030, the total CO_2 emissions of the electricity sector amount to 123.5

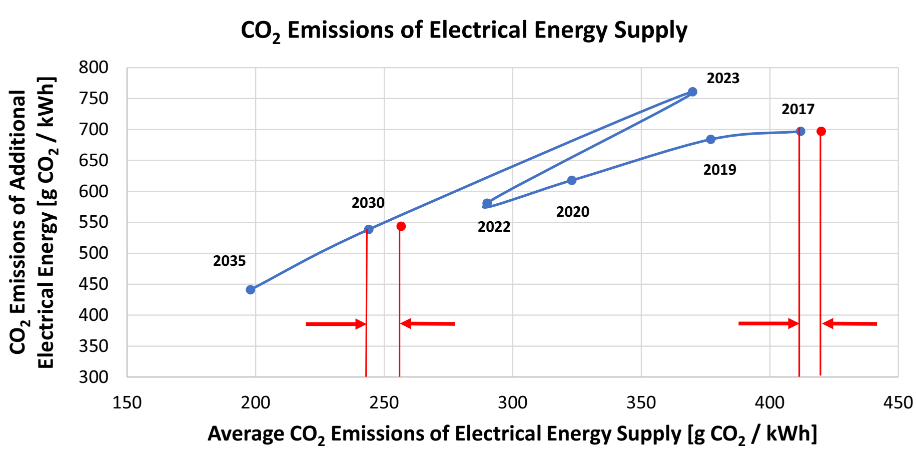


Fig. 16 Evolution of CO_2 emissions of additional electrical energy and average CO_2 emissions of electrical energy supply

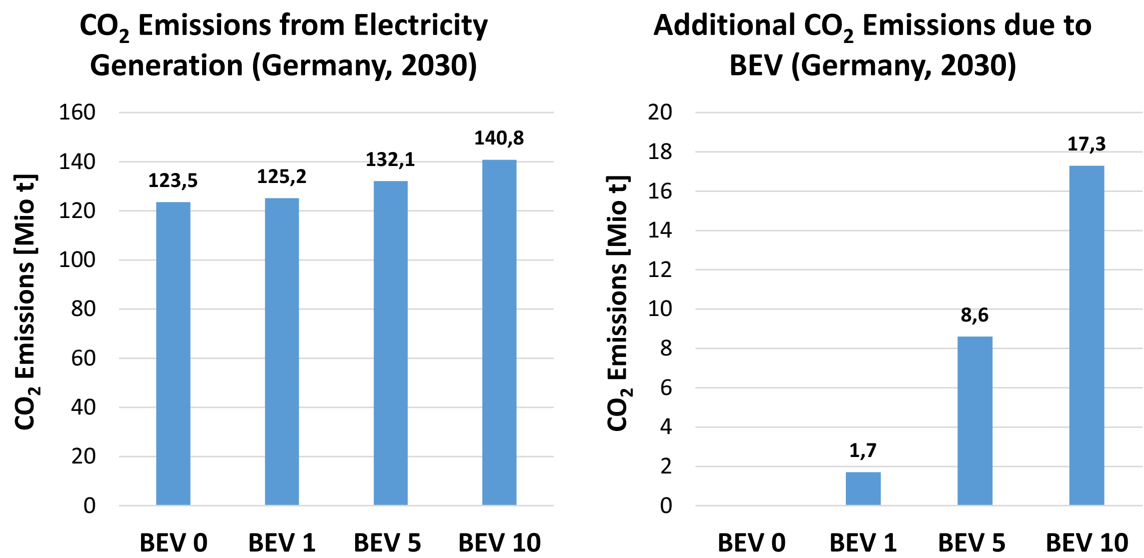


Fig. 17 CO_2 Emissions of the electricity sector in 2030 (left), delta analysis of BEV fleet (right) (i.e. "BEV 5" indicates a scenario with 5 million BEV vehicles in 2030)

metric tons (t) excluding BEVs. Of course, battery storage technology as in Fig. 6 has also been taken into account.

For the BEV fleet, the required additional electricity demand is calculated based on the assumed demand of 22.5 kWh/100 km, an annual mileage of 14,000 km, and the respective size of the fleet. The resulting demand is distributed homogeneously over the year, as illustrated in Fig. 10 (right) or Fig. 12. As mentioned above, an intelligent charging strategy, favoring charging at noon, might improve the situation, but on the other hand, many vehicles operate during the daytime and can only be charged at night. Therefore, an overall constant charging rate has been set.

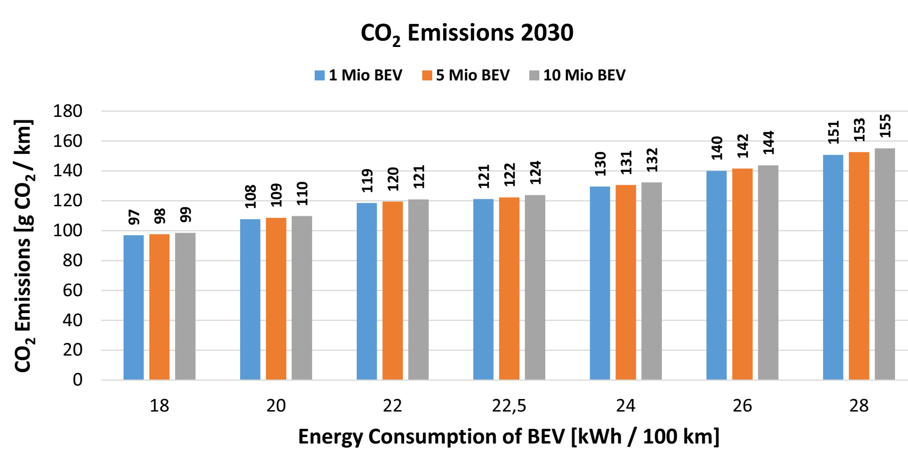
Following the same methodology as previously described for the scenario without BEVs, the absolute CO_2 emissions are calculated. The resulting CO_2 emissions are shown in Fig. 17 (left). The respective difference to zero BEVs (BEV 0) is shown in Fig. 17 (right).

In 2030, the additional CO_2 emissions from the electricity sector are 1.7 t for one million vehicles, 8.6 t for five million vehicles, and 17.3 t for 10 million vehicles.

As already described in Sect. 4.3, the increase in the number of consumers also changes the number of hours during which the electricity demand can be covered purely by renewable energy. This is shown for the different BEV fleet sizes in Table 8. The demand without any BEVs (BEV 0) can be covered completely from renewables during 2324 h. The total electric energy demand with 10 million BEVs can only be covered completely from renewables during 1983 h. Please note that non-renewable electrical energy is equivalent to fossil-based electrical energy, as nuclear power will not be offered in 2030.

The average BEV-induced CO_2 emissions per kilometer clearly depend on the electricity demand of the electric vehicles. As a consequence, the real CO_2 emissions of a BEV

Fig. 18 Specific CO_2 emissions per km of BEV (w/o production) as a function of BEV electricity energy demand 2030



are influenced by the consumption of electrical energy of the vehicle on the one hand and the total electrical energy demand of the electricity system on the other hand.

This is basically illustrated in Fig. 18. An increase in BEV, as described in Sect. 4.4, worsens the energy mix due to additional consumers and less pure renewable-energy periods. For an electrical demand of 22.5 kWh/100 km and a BEV fleet of one million vehicles, this results in CO_2 emissions of 121 g CO_2/km. Consequently, the CO_2 emissions increase with a higher electrical energy demand and decrease with a lower demand.

The same considerations are made below for the year of 2035. Again, the values for a fleet without and with 1, 5, and 10 million BEVs are calculated. The mileage as well as the electricity demand remain the same as in 2030. The CO_2 emissions are shown in Fig. 19.

The additional CO_2 emissions from the electricity sector in 2035 are 1.4 t for 1 million vehicles, 7.0 t for 5 million vehicles, and 14.1 t for 10 million vehicles. It can be seen that in 2035, the additional CO_2 emissions have decreased compared to 2030 (i.e. BEV 5 scenario: 2030: 8,6 Mio t vs. 2035: 7,0 Mio. t). This is due to the further expansion of renewable-energy sources. As a result, the number of hours with purely renewable-based electric energy supply also increase from 2030 to 2035 (see Table 9).

As in 2030, the CO_2 emissions per kilometer in 2035 vary depending on BEV energy demand and the supply status of the electricity sector. The specific emissions are shown in Fig. 20.

For an electricity consumption of 22.5 kWh/100 km and depending on the size of the BEV fleet, the CO_2 emissions are between 98 and 101 g CO_2/km. Consequently, a higher electrical energy demand of BEV again increases the CO_2 emissions, while a lower demand causes them to fall.

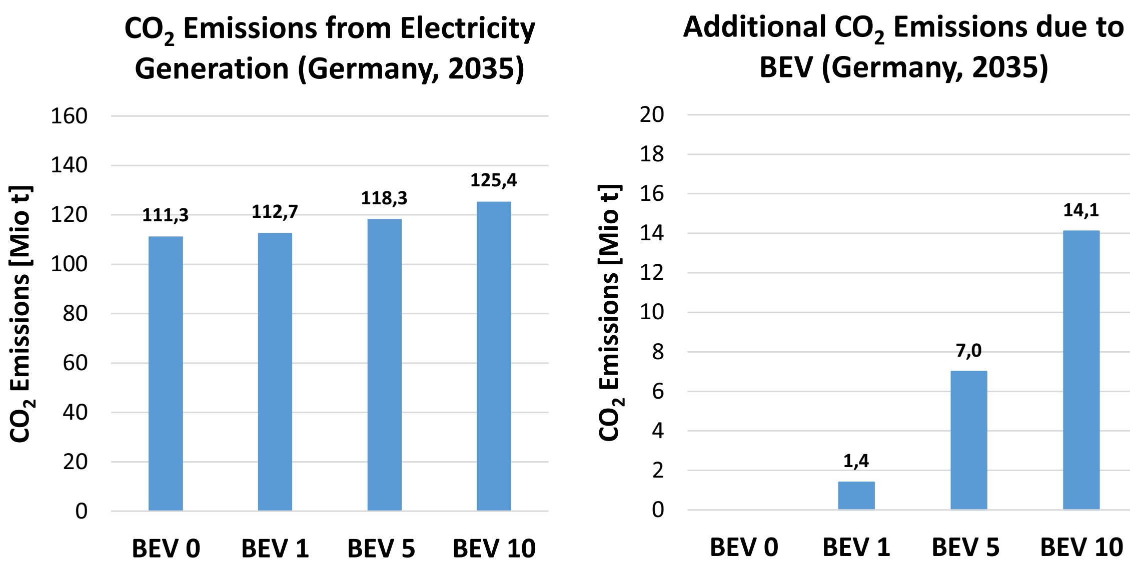
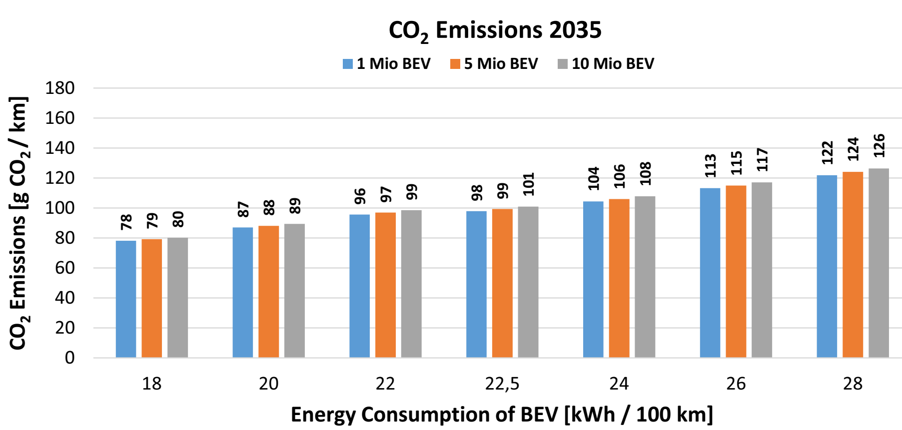


Fig. 19 CO_2 emissions of the electricity sector in 2035 (left), delta analysis of BEV fleet (right) (i.e. "BEV 5" indicates a scenario with 5 million BEV vehicles in 2030)

Fig. 20 Specific CO_2 emissions per km of BEV (w/o production) as a function of BEV electricity energy demand 2035



In the current fleet regulations, the CO_2 emissions are nevertheless set to be 0 g CO_2/km. A comparison of the use phase of different vehicles is presented in Sect. 4.6.

4.6 CO_2 Emissions throughout the useful life

This section presents the total CO_2 emissions of vehicle technologies over a useful life of 16 years and an annual mileage of 14.000 km. A BEV calculation of simply multiplying the electrical energy demand of BEV with the average footprint of the electricity sector (Table 6) is plotted in green color. As this calculation is misleading and inadequate, the real CO_2 impact as presented in Sect. 4.1–4.5 is illustrated (blue line). The CO_2 impact of a conventional diesel vehicle (gray color) has been defined according to the well-to-wheel analysis of Fig. 9. Also, the impact of a R33 diesel fuel blend is presented. Figure 21 shows the progression from January 1, 2020 to December 31, 2035 taking into account the pure phase of use while neglecting the influence of production, a possible battery replacement, or recycling issues.

As already pointed out in Sect. 3, a diesel consumption of 5.0 l/100 km and, thus, a carbon footprint of 153 g CO_2/km including provision is assumed for the calculations [31]. The consumption remains constant over the considered 16 years and generates a total of CO_2 emissions of 34.4 t. The diesel vehicle running on R33 fuel is assumed to have a CO_2 reduction potential of 25% in comparison to pure fossil fuel. R33 utilization results in a carbon footprint of 115 g CO_2/km. Fuel consumption is still 5.0 l/100 km. The CO_2 emissions in this case amount to 25.8 t after 16 years.

R33 consists of 26% paraffinic diesel and 7% rapeseed oil methyl ester (RME), so 26% of fossil fuel have to be blended additionally [33, 34]. Paraffinic diesel can be produced via the Fischer–Tropsch path or via a biomass-based path. In the year 2020, Germany's diesel fuel consumption (passenger cars and heavy-duty transport) amounted to roughly 34 million tons per year. The total fuel demand including gasoline, jet fuel, and marine fuel is around twice as high. Assuming a reduction of 20% in the future due to improved efficiency, hybridization, electric vehicles, and additional measures, only the diesel fuel consumption would be reduced to 27 million tons per year in 2030. Substituting 26% of fossil diesel would require roughly 7 million additional tons of paraffinic diesel per year in 2030, which is equivalent to 288 PJ. The existing HVO production capacities in Europa of NESTE are 2.4 million tons per year and will be further increased. Also, co-processing offers additional potential to substitute 5% of fossil fuel.

Co-processing technology means that biomaterial is fed into refinery units together with fossil feeds. Depending on its source and pre-treatment there are several possible entry points for the bio-feedstock. Different publications define a significant potential to substitute fossil fuel by biomass-based energy [35–40]. The biofuel potential, and thus the sustainable biomass potential, is discussed controversy in literature. However, with conservative assumptions some reasonable estimates can be found in different publications, defining significant potential to substitute fossil fuel by biomass-based energy. If the currently un- or under-used potential of sustainable biomass was added to the todays bioenergy share, this would provide another 390–680 PJ in Germany [38]. As the available biomass is valuable but limited, there is an additional demand for renewable fuels, which may be produced via synthesis gas obtained from other carbon sources and even from CO_2, which needs to be "activated" by renewable hydrogen, produced from electrolysis of water.

For the BEV technology, an electricity demand of 22.5 kWh/100 km is assumed as explained above. The specific CO_2 emissions over the different years are interpolated from 2023 to 2030 and from 2030 to 2035 using the previously calculated values. The specific CO_2 emissions from 2020 to 2022 were also calculated. For the CO_2 emissions after 16 years of use, the value for the CO_2 footprint of BEV charging, only derived from the German energy mix according to Table 6 and not taking into account the real impact

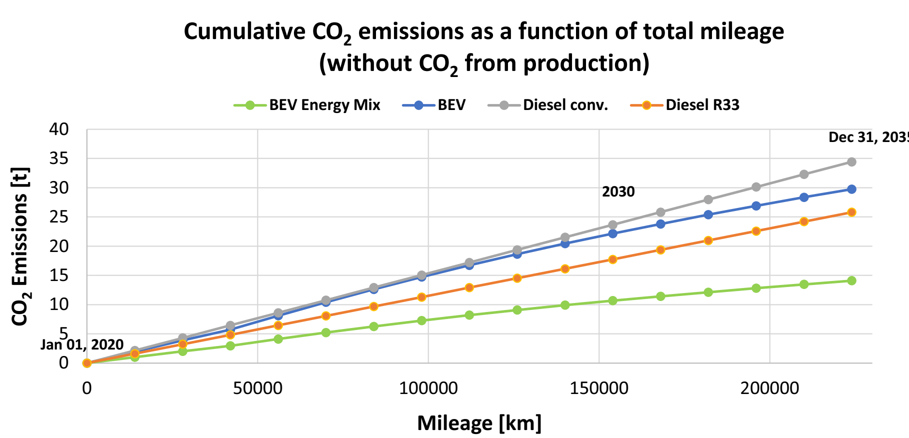


Fig. 21 CO_2 impact of the use phase (w/o production, w/o recycling etc.) of different technologies

as explained above, is 14.1 t. Considering the electricity net behavior, however, leads to real CO_2 emissions of the BEV of 29.8 t.

Charging a BEV and analyzing the CO_2 footprint with the help of the German energy mix appears very favorable at first glance. However, as already pointed out in the previous sections, this does not represent the energy mix with which an entire BEV fleet can be charged. The curve drawn in blue in Fig. 21 depicts the real impact on increasing CO_2 emissions. Already using an R33 fuel with a CO_2 reduction potential of 25% enables significantly reduced overall CO_2 emissions over the entire use phase of vehicle lifetime in comparison to BEV technology in Germany.

Another efficient way of reducing CO_2 emissions is to use an optimized and hybridized 48 Volt P2 diesel drivetrain including additional technical measures with a further reduction potential of around 30% [41–43]. A combination of R33 fuel plus latest hybridization technology sums up the CO_2 saving potential close to 50%, which is not illustrated in Fig. 21, but means that only 18 t of CO_2 after 16 years of operation are possible.

5 Summary

The analyses presented in this paper have revealed that, despite the continuous expansion of renewable-energy sources, additional electrical consumers will have to be supplied with fossil additional power plants for a large part of the annual hours also in the future. This additional impact will be partly based on a fossil one and the CO_2 emissions of the electricity sector will increase as a consequence. This extra burden caused by the electricity sector is currently hardly discussed in any public analysis. Most analyses calculate the CO_2 impact applying only the average energy mix, which amounts to approx. 244 g CO_2/kWh in 2030. This results in a BEV operating value of less than 50 g_{CO2} / km. However, the analyses have shown that even in 2030, the mix of additional electrical energy amounts to approx. 550 g CO_2/kWh (Fig. 16) and that fossil support is necessary for more than 6000 h per year (Table 8). For the CO_2 balance of the useful life (224.000 km) with a registration on January 1, 2020, a BEV vehicle was analyzed with 29.8 t CO_2 in comparison to a standard diesel vehicle with 34.4 t of CO_2 emissions.

In this analysis, only the energy required and the emissions generated during the use phase were taken into account. The production of the vehicles and all other influences were not considered. In addition, the assumption was made that renewable energy is available at any location in Germany regardless of where it is generated. The uniformly constant charging activity of BEV throughout the year was a prerequisite, although this does not correspond to reality. Charging only during daytime improves the situation (shown in Fig. 11). The possible impact of an emission trading system (ETS) has been discussed briefly. However, the market response in the case of a significant lack of electric power supply and an increasing energy demand is part of intensive discussion among economists.

Using a vehicle fueled with R33 diesel fuel instead of standard diesel revealed a result of 25.8 t CO_2 emissions, leading to a saving in comparison to a BEV of approx. 4 t of CO_2. Consequently, no advantage of the use of BEVs over the use of R33-fueled diesel vehicles can be established in terms of CO_2 emissions. A combination of a low-CO_2 fuel with hybrid diesel technology enables very low-CO_2 emissions of 18 t after 224.000 km. Hopefully, legislation will allow an open and technology-driven competition of different drivetrain technologies to ensure the best possible benefit for the environment.

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