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Carbon-neutral mobility powered by green electricity? How the power sector reacts to alternative mobility solutions

An assessment of energetic and regulatory effects on the CO_2 emissions of alternative powertrain technologies and energy sources

Carbon-neutral mobility powered by green electricity?
How the power sector reacts to alternative mobility solutions

This **orientation study** was conducted on behalf of the FVV (project number: 1430, duration: 01.10.2020 - 30.03.2021) by **Frontier Economics Ltd.** and the **Kiel Institute for the World Economy (IfW)**.

The impact of additional electricity demand from carbon-neutral mobility on the European power sector (EU ETS) is an important part of a comprehensive LCA system analysis. This document is therefore intended as a complementary study to **Research Association for Combustion Engines (FVV): Cradle-to-Grave Life-Cycle Assessment in the Mobility Sector - A Meta-Analysis of LCA Studies on Alternative Powertrain Technologies**. Issue R595 | Frankfurt/M., 2020

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CARBON-NEUTRAL MOBILITY POWERED BY GREEN ELECTRICITY? HOW THE POWER SECTOR REACTS TO ALTERNATIVE MOBILITY SOLUTIONS

AN ASSESSMENT OF ENERGETIC AND REGULATORY EFFECTS ON THE CO2 EMISSIONS OF ALTERNATIVE POWERTRAIN TECHNOLOGIES AND ENERGY SOURCES

A Study for the FVV e.V.

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ABSTRACT

The remaining global CO_2 budget that is available in order to limit the rise of global temperatures to 1.5 °C above pre-industrial levels is limited and could be used up within the next decade or two. In its Green Deal, the European Commission has increased its ambitions to reduce CO_2 emissions in Europe until 2030 by at least 50% compared to 1990. The transport sector currently accounts for ¼ of EU CO_2 emissions and its share has been growing in recent years. Hence, the decarbonisation of the transport sector and specifically the road transport represents a big challenge and an effective use of the remaining CO_2 budget is indispensable. In a recently published meta-study on behalf of FVV, we prove that a fair comparison of powertrains needs to consider the whole life cycle of a vehicle in order to determine the most effective emission reduction option for road transport. In this study, we expand this work and specifically focus on the interaction of energy-related CO_2 emissions resulting from the additional power generation to charge electric vehicles with the rules and regulations of the power sector and its central instrument of climate change, the EU Emission Trading System. By using detailed modelling of the EU power market and the EU ETS, we conclude that charging needs of electric vehicles will, in the foreseeable future, lead to additional emissions in the power sector. The EU ETS under its current rules will to a certain extent dampen but not prevent this increase in power-related CO_2 emission. Further, we show that synthetic or renewable fuels of non-biological origin (RFNBO) face much stricter regulation under RED II related to the effective emission reduction and hence represent a more effective and more reliable emission reduction option under current regulation. We identify the regulatory treatment of the carbon source required for the production of RFNBO as field for further research.

SUMMARY

In various research projects, the FVV deals with the contribution that alternative propulsion technologies (e.g. based on combustion engines in combination with CO_2-neutral fuels, the use of fuel cell technology, or through electrification) can make to achieving a long-term defossilised transport sector.

Remaining CO_2 budgets must be used efficiently

To limit climate change, a reduction in greenhouse gas emissions is necessary in all areas of the economy and life. The remaining amount of CO_2 that may still be emitted into the atmosphere without causing an excessive increase in the global temperature is limited - for example, according to the IPCC report, the remaining CO_2 budget on 1 January 2018, until the 1.5 °C target is reached corresponds to approx. 420-580 Gt. CO_2[1], which would be reached in about 10-15 years at current global emissions. Against this background, the choice of technology that provides the greatest benefit with the lowest CO_2 emissions is crucial. This principle naturally also applies to the choice of powertrain technologies and fuels. In the transport sector in particular, the complex value chains mean that it is important to analyse and evaluate the carbon footprint on the basis of the entire life cycle.

In this context, Frontier together with FVV recently prepared a study[2] in which the various contributions of individual technology options were summarised on the basis of a meta-study of life cycle analyses (LCA). The result shows that a large part of the climate benefits attributed to battery electric vehicles ("BEV") in the context of the political discussion are based on only a partial, limited view. Only in the context of a "tank-to-wheel" analysis significant CO_2 advantages can be observed, which are, however, largely offset by additional emissions in other phases of the vehicle's life cycle compared to internal combustion engines.

Distortions of technology choice by regulatory frameworks must be avoided

The life cycle analysis meta-study contributes to a transparent assessment of different technology options. However, certain aspects of individual technologies could not be fully captured, such as the influence of GHG regulation in the power sector on the emissions balance of alternative powertrain technologies: The supposed CO_2 benefits of electromobility are largely based on a shift of emissions from the transport to the power sector, as the shifted emissions caused by charging energy are valued at zero in the current fleet regulation.

With our current study, we contribute to the understanding of the feedback effects of an increase in power demand due to charging energy, also taking into account the CO_2 regulation of the EU Emissions Trading Scheme (EU ETS), which limits the annual CO_2 emissions in the power sector and energy-intensive industries. We

[1] IPCC (2018), Special Report - Global Warming of 1.5 °C, Table 2.2, range based on 50th and 67th percentiles, time remaining derived based on global CO_2 emissions of 36 Gt.CO_2 per year (as of 2019).

[2] Frontier Economics (2020), Cradle-to-grave life-cycle analysis in the mobility sector; a meta-analysis of LCA studies on alternative powertrain technologies, study for the FVV e.V.

investigate how the mix of energy sources in the power system changes due to the increase in demand and how the instruments of the EU ETS respond to this.

Finally, we analyse which regulatory requirements exist outside the power sector that influence the advantageousness of various powertrain technologies. In particular, we look at the requirements of the Renewable Energies Directive[3] on the emissions balance of synthetic fuels.

Charging energy will lead to additional physical emissions in the power sector in the foreseeable future

68 gCO_2/km

"Well-to-wheel emissions of a BEV in 2030

The increase in power demand due to the ramp-up of electromobility in Germany will lead to an increase in emissions in the power sector for the foreseeable future. Although the additional demand will also lead to an increase in investments in renewables, a large part will be met by existing gas-fired and, in the short term, coal-fired power plants. Our detailed electricity market modelling shows, even taking into account a renewable quota in the power sector of 65% as well as other current framework conditions in the German and European electricity market (e.g. coal phase-out), that the CO_2 intensity of charging energy will still be around the level of a gas-fired power plant (approx. 350 gCO_2/kWh) in the medium term until 2030. Assuming an average electricity consumption of 19 kWh per 100 km, this results in a specific emission of 68 gCO_2/km. We refer to this emission value as the *physical emission of electromobility,* since they are directly associated with the grid offtake of charging power and the energy consumption in a "well-to-wheel" consideration. A value that in itself is above the fleet target for the year 2030.[4]

The EU ETS leads to a dampening of additional emissions, but CO_2 neutrality is not achieved

Emissions from the power sector are subject to European emissions trading and thus to an absolute cap. However, reform of the EU ETS in recent years has softened this absolute cap. Simply put, the supply of allowances now responds to demand, which means that under certain circumstances additional demand also leads to additional emissions. This is exactly the situation in which the EU ETS currently finds itself: the supply of allowances exceeds demand and, as a result, there would be a reduction in supply and thus fewer absolute emissions in the power sector. If the demand increases due to charging energy, the excess supply is reduced and the correction of the supply quantities is smaller - compared to a situation without charging energy, the absolute emissions in the power sector increase. It can therefore be assumed that the regulation of the EU ETS has a

[3] Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from renewable sources.

[4] The EU fleet regulation (Regulation (EU) 2019/631) provides for a 37.5% reduction in fleet limits by 2030 compared with the starting value in 2021. If this is assumed to be 95 gCO_2/km, the limit value for newly registered vehicles will drop to 59.4 gCO_2/km.

dampening effect on the *physical emissions* of electromobility, i.e. the *de facto emissions* after taking into account the effect of the EU ETS deviate from the physical ones.

The relationship of physical and de facto emissions remaining in the system is not 1-to-1, as a certain share displaces other emitters. Depending on the consideration of the expectations of market participants in the EU ETS, the share of remaining emissions in our central scenario is between 30% and 40% of the physical "well-to-wheel" emissions, i.e. about 20 to 30 gCO_2/km.

20-30 gCO_2/km

Remaining emissions after correction by the EU ETS

Compared to electromobility, synthetic fuels offer much more reliable emission savings due to the strict regulatory requirement of additionality

With our study, we show that - despite regulation of emissions in the power sector by the EU ETS - the assumption of zero emissions for battery electric vehicles does not reflect the real emissions of the vehicle during the use phase. This contrasts with the regulation of synthetic fuels by the Renewable Energy Directive II (RED II): Due to the fact that the so-called "sustainability criterion" of RED II applies to domestically produced synthetic fuels, but this criterion is not prescribed for domestic (German or European) charging energy, the physical emissions of an approved synthetic fuel (incidentally also those of an approved biofuel) are currently and in the medium term significantly below the emissions of European electricity production for the charging energy of BEVs.

1 BACKGROUND AND OBJECTIVE: WELL-TO-TANK CO_2 EFFECTS AS IMPORTANT PARAMETERS FOR LIFE CYCLE ANALYSIS

1.1 A choice of technology from the point of view of climate protection calls for a consideration of the entire life cycle

As long as there is no comprehensive greenhouse gas regulation, it is necessary to take into account all direct and indirect effects in all upstream and downstream stages of the value chain in order to evaluate technology options sensibly and selectively with regard to their climate effects and other sustainability effects. The perspective should be broadened in the direction of a holistic life cycle analysis of all phases of a product's life - or, with regard to a complete recycling economy that is ultimately to be strived for, even up to its reintroduction into the raw material cycle. This requires an approach based on a cross-sectoral, global and temporally unrestricted system boundary:

- **CO_2 emissions must be minimised overall across all sectors.** For a comprehensive comparison of technologies, emissions caused by the vehicle in other sectors - such as the energy sector in the production of drive energy - should also be considered. Focusing solely on the transport sector is not conducive to achieving the overall goals - especially in times of sector coupling and integration.
- **The climate impact of CO_2 is global**, as only a certain budget of greenhouse gases may be emitted worldwide to meet the climate target of 1.5 °C or 2 °C temperature increase. This means that it is irrelevant for the impact on the greenhouse effect where the emissions originate. Thus, not only the **CO_2 emissions** associated with the production of the vehicles in Germany or the EU, but also those in supplier countries such as China must be taken into account. Unilateral climate policies, or those with varying degrees of stringency in reducing greenhouse gas (GHG) emissions, thereby create an incentive to shift emissions-intensive processes to less regulated countries rather than minimizing emissions overall.
- **The climate impact is independent of the timing of the emissions.** What is relevant are the absolute amounts of CO_2 emitted. This means that downstream emissions - such as emissions during recycling or scrapping - must not be disregarded.

Against this background, with regard to climate policy instruments, technology-open approaches are particularly suitable for ensuring effective GHG savings.

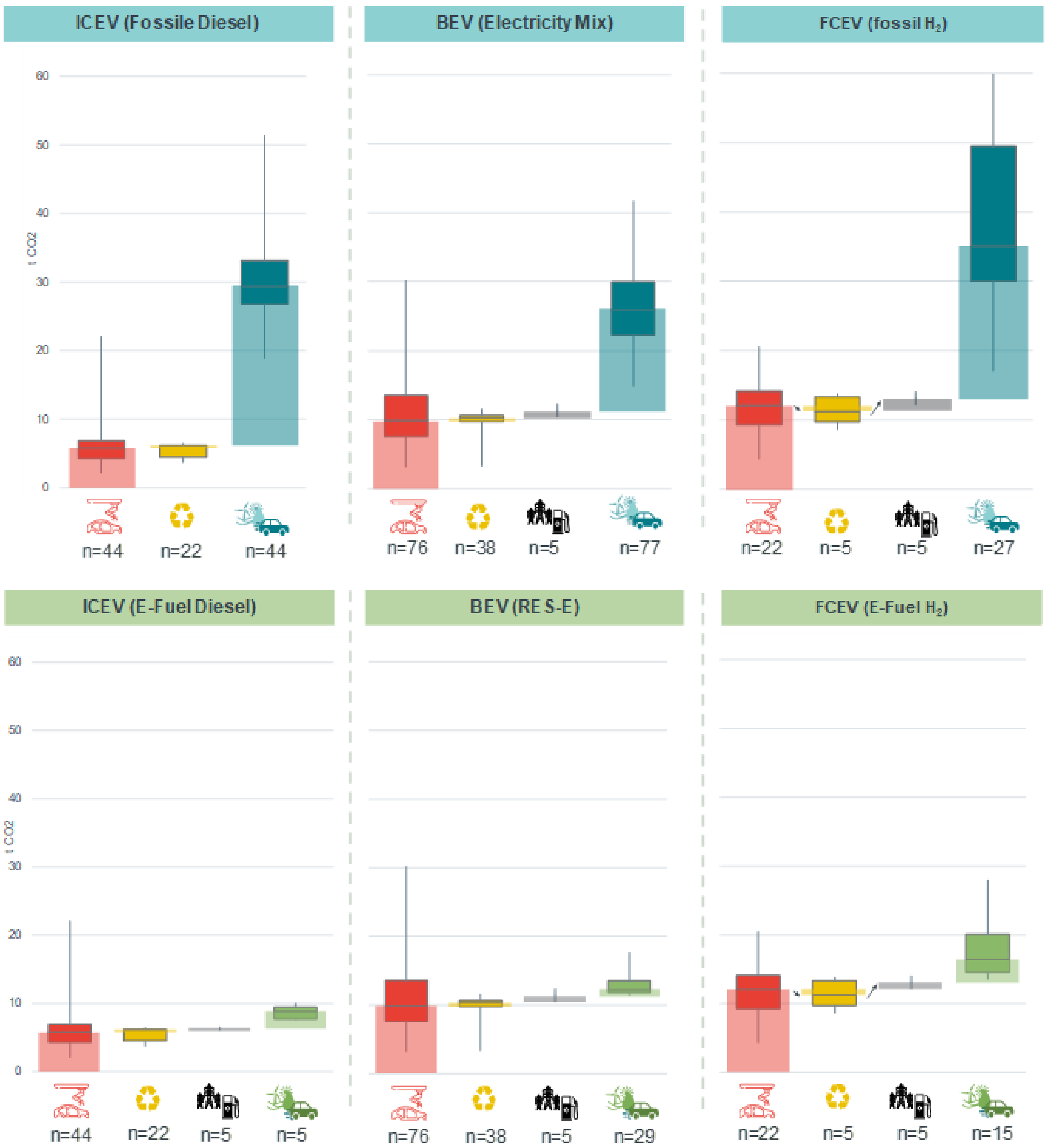
In the FVV meta-study "Cradle-to-Cradle Life-Cycle Assessment in the Mobility Sector"[5] published in June 2020, we show that depending on the intended use and the resulting respective requirements (e.g. with regard to mileage, size or loading), the individual technologies can be advantageous in different ways. **Figure 1** shows the comparison of emissions in the various phases of the life cycle for three different powertrain technologies (diesel-powered vehicle, electric vehicle, hydrogen vehicle), each with conventional and powertrain technologies specifically geared to CO_2 reduction. The comparison of the studies makes clear that the differences between the individual powertrain options are often only marginal, and e.g. based on today's power supply, the life cycle emissions of an electric vehicle are not necessarily lower than those of a diesel vehicle. In fact, when renewable (e.g. synthetic) fuel is considered, the comparison is in favour of the internal combustion engine vehicle. Likewise, the advantageousness of the technologies can change if production locations for vehicle manufacturing or drive energy shift geographically and/or the general conditions there change.

All incentive instruments about GHG abatement must therefore take into account emissions across sectors as well as internationally and intertemporally - otherwise, incentives will only be provided to shift emissions, not to reduce them.

The individual framework conditions are so different that a centralistic political technology control does not allow an efficient achievement of the climate targets! Accordingly, political framework conditions should be formulated in a technology-open manner in order to make sensible solutions for CO_2 reduction possible - with a view to individual mobility needs and uncertain future developments. Openness refers both to technologies that already complement each other and to technologies whose optimal niche is yet to emerge from technology competition.

[5] Frontier Economics (2020).

Figure 1 CO₂ life cycle analyses show that no technology is clearly superior



Source: *Frontier Economics (2020)*

Note: *Results were scaled to 150,000 km lifetime mileage for comparability; ICEV: Internal Combustion Engine Vehicle, BEV: Battery Electric Vehicle; FCEV: Fuel Cell Electric Vehicle, RES-E: Renewable Energy Sources-Electricity; E-Fuel: Electrofuel.*

Production *End-of-life* *Infrastructure* *Vehicle use / energy sources*

1.2 Battery-electric vehicles benefit above all from the shift of CO_2 emissions from the transport sector to the power sector

The current fleet regulation for newly registered vehicles specifies how many grams of CO_2 a vehicle may emit per kilometer driven. With this focus on tailpipe emissions, which is no longer appropriate given the diversity of powertrain systems with more complex emissions effects, the regulation falls short in two key aspects and thus leads to distorted competition between powertrain technologies: On the one hand, a non-negligible proportion of the emissions generated over the life of a vehicle occur not only in the use phase but also in the production phase (**Figure 1).** These emissions are significantly higher for battery electric vehicles ("BEVs") than for alternative powertrain technologies due to the energy-intensive battery production. On the other hand, emissions generated in other sectors are completely disregarded. Through this strict tank-to-wheel approach, fleet regulation creates incentives to shift emissions to other sectors and prevents fair competition that is open to technology.

The exemplary analysis of the life cycle effects of the political goal of introducing 10.5 million battery electric vehicles to the German market by 2030 (**Figure 2**) in the meta-study mentioned above shows that the claimed CO_2 savings of 65 M tCO_2[6] cumulatively by 2030 would predominantly be shifted to other sectors and regions.

In the case of battery electric vehicles, additional power demand is generated as the energy storage device is charged. This incremental demand must be met in the power system by additional generation. Currently - and also in the foreseeable future until the complete defossilisation of the power system - conventional power plants using fossil fuels will meet at least part of the demand. Emissions that are avoided in the use phase of the life cycle in the transport sector are incurred in the power sector. In the meta-study, we show that in the case of 6.5 million additional BEVs by 2030 in Germany, this affects about 51.1 M tCO_2, out of a total of 65 M tCO_2 saved in the transport sector. However, this aggregated presentation abstracted from numerous details such as the feedback mechanisms[7] existing in the European Emissions Trading Scheme (EU ETS), which need to be taken into account in order to estimate the actual savings.

For example, if it were assumed that the GHG emission level in the EU ETS is invariant, no additional emissions would result from the shift in the power sector, but other emissions would be displaced within the EU ETS. However, in other cases, and especially where there are limits to the expansion of renewable generation capacity, there may also be significant additional emissions, as we show in **Chapter 2**.

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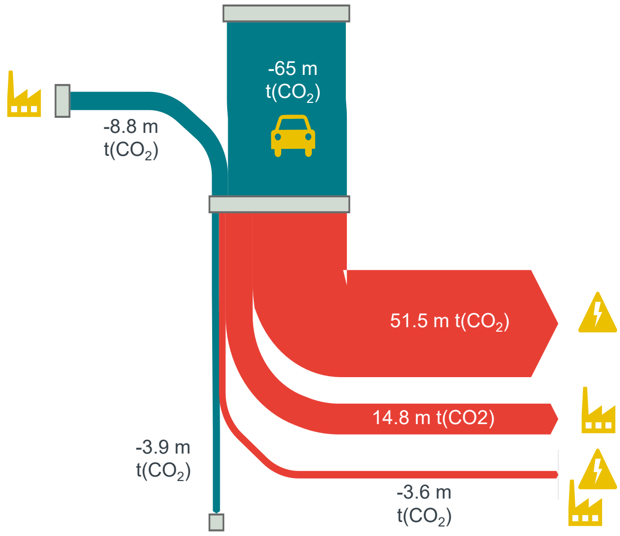
6 CO_2 savings refer to the additional number of 6.5 million BEVs compared to a reference of 4 million BEVs in 2030.

7 The EU ETS primarily covers CO_2 emissions from energy-intensive industry and the power sector. CO_2 emitters in these sectors must submit a certificate for each t of CO_2. The total quantity of certificates is predetermined and the issued certificates can be traded. This creates a certificate (CO_2) price. In total, the EU ETS currently covers c. 45% of all EU greenhouse gas emissions.

Figure 2 Illustration CO_2 budget



Source: Frontier Economics (2020): FVV Meta-Analysis LCA

1.3 The well-to-tank impacts of additional electricity demand from electrification in the mobility sector are often incompletely captured in the process

Much of the political support for a rapid ramp-up of battery electric vehicles is based on the - simplified - argument that renewable energy sources provide CO_2-neutral electricity and therefore electrification would set the course for long-term CO_2-neutral mobility. However, this argument ignores numerous effects:

- **The CO_2 target is a budget target:** The Paris Agreement to limit warming to 1.5 °C ultimately draws on the analyses of the Intergovernmental Panel on Climate Change (IPCC), which shows a remaining residual budget for CO_2 emissions. Against this background, possible additional emissions from an earlier switch to technologies can therefore be counterproductive, depending on the regulatory mechanisms (e.g. if there are early closures and thus one-off emissions accrued during production have to be "written off" in the short term).
- **Fleet regulation is based on the fiction of emissions avoidance:** Through the strict tank-to-wheel approach, fleet regulation creates incentives to shift CO_2 emissions to other sectors. By focusing strongly on battery electric vehicles, tailpipe emissions are thereby replaced by additional power demand.
- **The German and European power generation mix is determined by various political instruments in the short to medium term:** The power generation mix is strongly predetermined by the support programs for the expansion of renewable energies in conjunction with the legal requirements for the phase-out of coal and nuclear energy, so that only limited technical options remain to meet additional demand.
- **The EU ETS provides a complex set of instruments to regulate CO_2 emissions:** The EU ETS initially provides a fixed GHG budget for the

power sector (as well as for the industrial and intra-European aviation sectors, which are also involved) via the "cap and trade" methodology[8], so that changes in final demand would initially not suggest any GHG effects and point 1 would be completely irrelevant. However, there are various additions and consequential effects through which (potentially identifiable) effects may in fact arise after all, including through

- The introduction of the Market Stability Reserve with a rather complex system of "banking" and "deleting" emission allowances, both of which can theoretically be changed in one direction or the other by an expansion of electromobility (less banking and deleting, i.e. emissions increase, or more banking and deleting, i.e. emissions reduction);
- The substitution of other demand, e.g. by
  - A de-electrification of other power demand generators;
  - Carbon leakage effects (in industry); or
  - Elimination of demand with corresponding value creation effects.

In the following, we focus on these complex feedback effects triggered by the shift of emissions from the transport to the power sector. We highlight the mechanisms and cause-effect relationships and elaborate the direct and indirect effects ultimately triggered by an increase in power demand potentially driven by the transport sector. In doing so, we consider the (emissions) impacts that additional power demand from electric vehicles triggers in the power sector.

Schmidt (2020)[9] recently published a discussion paper on this topic, which points out the need to distinguish between average and marginal effects: Often, CO_2 effects of electricity purchases are assessed on the basis of average emissions, which, however, often systematically underestimate the effects, since the "last" kWh is regularly generated by a fossil power plant and the associated emissions may thus be above average. However, these theoretical considerations are not based on a detailed model of electricity production, which is therefore what this study aims to supplement.

1.4 Objective of the study: calculating the impact of incremental electricity demand on the power sector

The aim of this study is to transparently present the overall CO_2 balance of an additional power demand for electromobility in Germany, taking into account the regulatory framework. The focus here is not on the upstream / downstream stages of a life cycle analysis (production and recycling), but in the sense of a "well-to-wheel" consideration on the "ongoing" emissions as they are relevant for the

[8] „Cap and trade" refers to environmental policy instruments that link the emission of an environmentally harmful gas, for example, to the submission of a tradable pollution right (certificate). The total quantity of available allowances is limited (cap) and the obligated actors can trade the allowances among themselves after initial issuance (trade) in order to achieve an efficient combination of abatement options.

[9] Schmidt, U. (2020): Electromobility and Climate Protection: The Big Miscalculation. Kiel Policy Brief.

German CO_2 emissions target. We distinguish between two dimensions of CO_2 emissions:

- **How do the physical emissions that are shifted to the power sector develop?** In a first step, we evaluate which power plants are used to meet the additional power demand of electromobility in Germany and Europe and which physical additional CO_2 emissions are generated in the power sector as a result. These are the emissions that are attributed to battery electric vehicles in many studies such as the aforementioned study by Schmidt (2020) but also in the context of the FVV meta-study[10]. To quantify the physical emissions, we employ a simulation model that depicts the development of the Central-West European electricity market. The modelling of the electricity system takes into account essential regulatory guidelines, such as the German coal phase-out by 2035 or compliance with the quota of renewable power generation stipulated in the EEG. [11]
- **What de facto CO_2 emissions remain after feedback with the EU ETS?** The physical emissions of electromobility generate additional demand for CO_2 allowances in the EU ETS. Emissions in the power sector are absolutely limited by the cap of the EU ETS. However, with the last reform of emissions trading, the Market Stability Reserve ("MSR") was introduced as an instrument that partially flexibilizes the supply quantity: In the event of oversupply, allowances are removed from the market and partially cancelled. In the event of excess demand, previously stored allowances from the MSR can be returned to the market. Using the EU ETS models from Frontier Economics and the IfW, we investigate how the additional demand for allowances from electromobility affects the mechanisms of the MSR and how this changes the total supply of allowances in the EU ETS. We refer to the change in the total supply due to more or less cancellation of allowances as de facto additional emissions.

This is a partial consideration of the "well-to-wheel" CO_2 emissions. Other life cycle effects and GHG-independent effects of electromobility (local pollutant emissions or possible resource shortages in battery production) are not taken into account. A statement on whether electromobility makes macroeconomic sense or not is thus not possible on the basis of the study results alone; however, the results can contribute to a more comprehensive and meaningful life cycle analysis.

In addition to the emissions effects, we consider further regulatory challenges outside the power sector and substitution effects due to the increased demand for allowances in other sectors of the EU ETS. Finally, we draw a comparison between the regulatory requirements and actual emissions of different powertrain technologies.

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[10] Frontier Economics (2020).

[11] In addition to the 65% target in 2030, the latest draft of the EEG2021 provides for additional annual capacity targets as well as quantity targets for renewable energy sources (§4 EEG2021 and §4a EEG2021, respectively). These annual targets are not yet included in our analysis but, as expected, do not fundamentally change any of the results shown here.

2 QUANTIFICATION OF INDIRECT (PHYSICAL) EMISSIONS FROM ELECTROMOBILITY

In this section, we quantify the indirect physical emissions of electromobility, before accounting for possible feedbacks in the EU ETS. We

- estimate the additional power demand from an expected increase in electromobility in Germany;
- determine which power plants and energy sources will be used to meet additional demand using Frontier's European Electricity Market Model; and
- assess what CO_2 emissions are thus associated with the additional demand for electricity.

2.1 Electromobility leads to a significant increase in power demand

For the analysis in this study, we assume that the number of electric vehicles will increase from about 100,000 vehicles today to 8 million electric vehicles by 2030.[12] We estimate the electricity consumption of electric vehicles using a bottom-up calculation based on four different vehicle classes: Small cars, mid-range cars, executive cars, and SUVs (**Table 1**).[13] From today to new vehicle registrations in 2030, we assume a 22% increase in battery efficiency. With an average lifetime of 15 years, this results in a fleet average of 19.3 kWh per 100 km in 2030 and, with an average mileage of 15,000 km**, an additional consumption of electricity from German production of 23 TWh.**

Table 1 Assumptions on electricity consumption BEV

BEV	Share of new registrations*	Status Quo [kWh/100km]	Registration 2030 [kWh/100km]
Small car	38%	16.9	14.1
Mid-range	26%	20.1	16.0
Executive	11%	23.7	17.8
SUV	25%	30.6	22.1
Mix	**100%**	**21.9**	**17.0**

Source: Frontier Economics

Note: Estimate based on WLTP all-seasons approach incl. additional consumers such as heating or air conditioning.
** New registrations in the period 2010 to 2018 based on European Automobile Manufacturers Association (2020): https://www.acea.be/statistics/article/segment-breakdown-body-country*

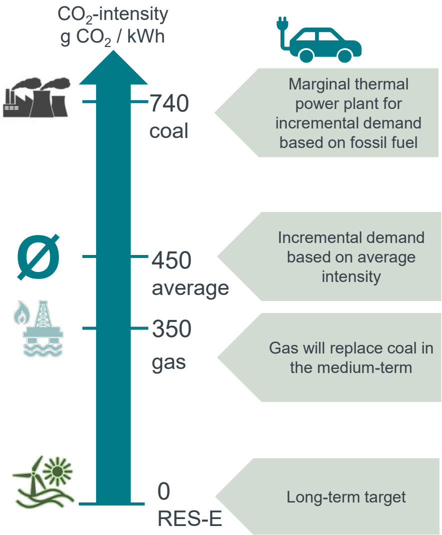
[12] We are guided by the mean value of scenarios B and C of the German Electricity Transmission System Operators' Network Development Plan 2030, see Scenario Framework for the Grid Development Plan 2030 (version 2019).

[13] Own research and calculations, taking into account onboard charging losses.

2.2 The additional demand leads to an increase in fossil power generation

The indirect physical CO_2 emissions caused by this additional demand in the power sector depend on which power plant and which energy sources are used. If primarily renewable energies sources (RES) cover the demand, low additional emission of CO_2 can be expected.[14] In fact, however, the RE potentials are limited and also the charging of electric vehicles does not always follow variable feed-in of RE to the grid. Therefore, it can be assumed that at least parts of the additional power generation needed will be provided by conventional thermal power plants.

Figure 3 Emissions per kWh of charging energy



Source: Frontier Economics

In the scientific discourse, it is sometimes argued that the charging of electric vehicles should be evaluated with the average CO_2 intensity of the electricity mix.[15] Schmidt (2020) argues that due to limited RE potentials, especially in the short term, the CO_2 intensity of the last thermal power plant (so-called marginal power plant) used to meet demand is decisive for the CO_2 intensity of the charging power.

To answer the question of which power plants provide the required charging energy, we examine how the power plant dispatch in Frontier's electricity market model[16] adjusts with and without additional power demand from electromobility. For this purpose, we use a typical charging profile, as it is also used by the European Transmission System Operators in the analyses for the grid development plans.[17] **Figure 4** uses the charging profile of the European Network Transmission System Operators for Electricity (ENTSOE[18]) and an exemplary energy mix in Germany[19] to illustrate the hours at which electric vehicles charge and which power plants provide the majority of the energy at these times. On the day shown, the average CO_2 intensity was around 450 gCO_2/kWh, weighted with the charging profile of an electric vehicle then at 470 gCO_2/kWh and thus slightly above the daily average.

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[14] Primarily caused by the manufacture and construction of RE plants, e.g. concrete foundations for wind onshore or offshore plants. However, we neglect these emissions in the further course of the study and value RES-E with zero emissions.

[15] Joanneum Research (2019): Estimated greenhouse gas emissions and primary energy consumption in the life cycle analysis of passenger car-based transport systems. Study commissioned by ADAC.

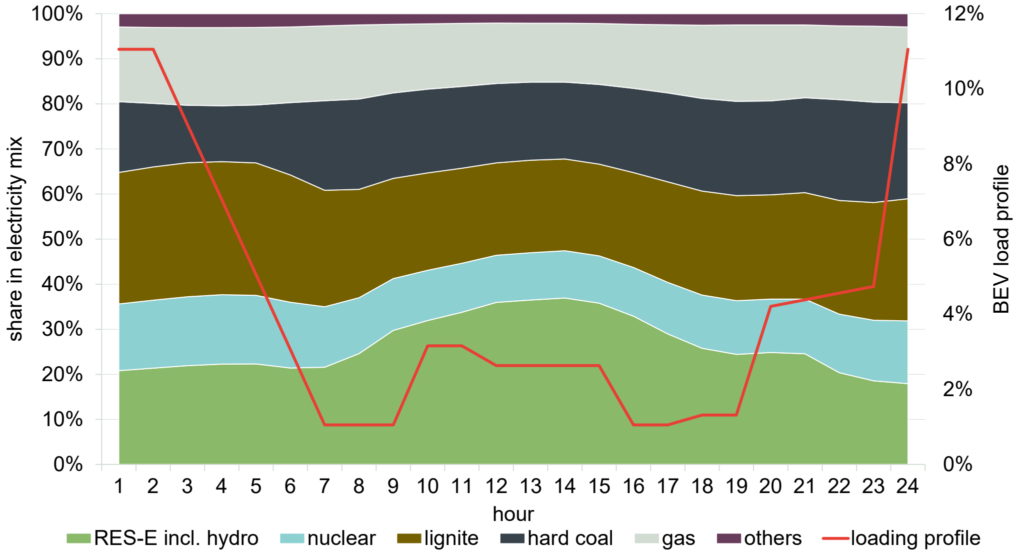
[16] Model description in Annex B.

[17] We acknowledge that as fleet size and workplace charging opportunities increase, there is a steepening of charging. This effect is not accounted for in our analysis.

[18] European Network of Transmission System Operators Electricity (ENTSOE) (2019).

[19] Source: SMARD, 29.09.2020

Figure 4 Schematic representation of energy mix and charging curve



Source: *Frontier Economics based on SMARD; ENTSO-E TYNDP 2020.*

Note: *Figure shows energy mix in Germany on 29.09.2020*

The reform of the EEG 2021 is expected to make charging a private electric vehicle with self-produced solar power more attractive. However, a complete decarbonisation of the charging power cannot be expected even then, as generation is always supply-dependent and there may not be enough solar energy available when the vehicle needs to be charged.

2.3 In the medium term, the CO_2 intensity of the charging energy set by gas-fired power plants

In our modelling of the European electricity market, we take into the current legal framework such as an increase in the RE quota in Germany to 65% and the coal phase-out by 2038. The development of the market within these political framework results from a system-wide optimisation of power plant expansion and deployment. We derive the CO_2 intensity of charging energy by comparing two scenarios, one with and one without incremental power demand from electromobility.

Since the European electricity market is integrated and Germany in particular is very closely linked to its neighbouring countries, we not only take into account an increase in electromobility in Germany, but also model a rise in Europe that corresponds to the assumptions of the European transmission system operators.[20] **Figure 5** shows the energy mix resulting from the electricity market model in Germany (without taking into account trade flows) as well as in the model region EU:

- **Energy mix of incremental charging energy in Germany dominated by coal in the short term** - Our analysis shows that the increase in demand in the short term particularly increases the utilisation of the still existing coal-fired

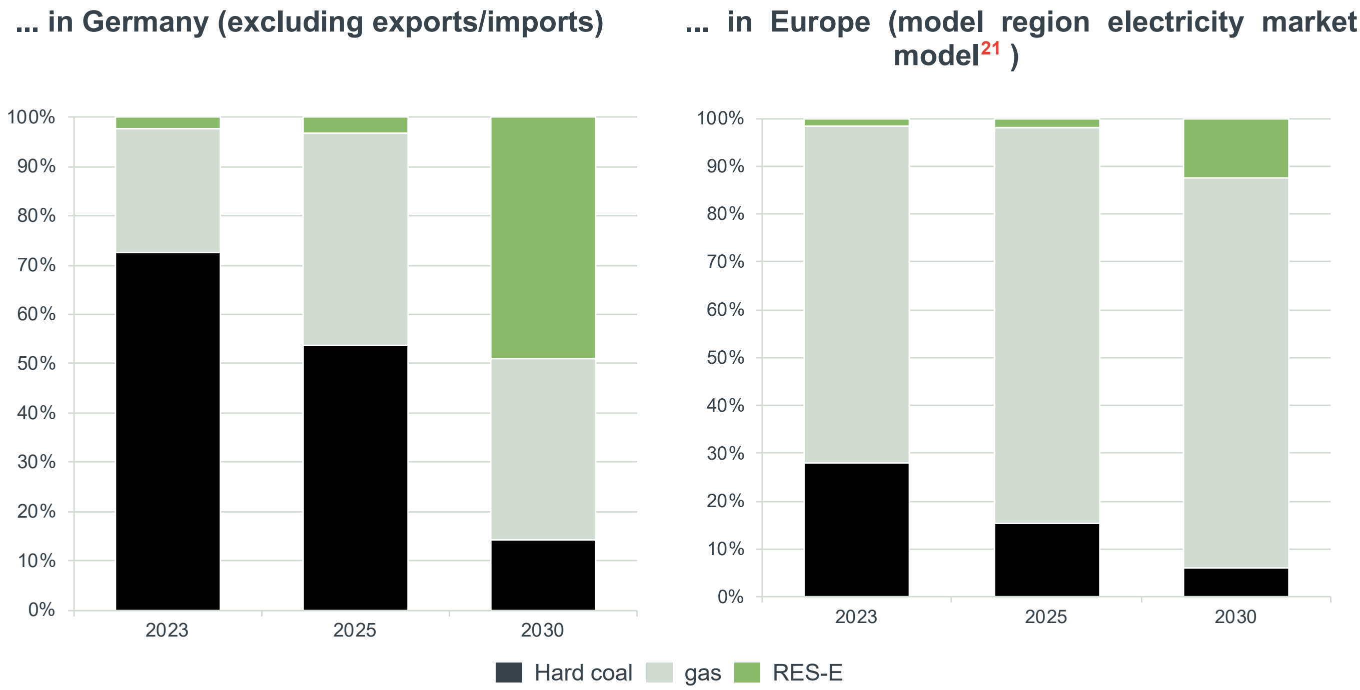
[20] Increase to approximately 100 million electric vehicles in 2030, "Global Ambitions" scenario TYNDP 2020.

power plants. In the medium term until 2030, the share of renewable electricity increases, also due to compliance with the 65% RES quota in Germany.

- **At the European level, the incremental demand is met in particular by gas-fired power plants** – Taking into account the effects in the other member states, as well as the cross-border electricity flows between countries, predominantly gas-fired power plants are used to meet the incremental demand. Coal-fired power plants, on the other hand, are only used to a lesser extent in the short term.

Since part of the incremental charging energy generated in Germany is also covered by imports from abroad, and vice versa, we use the modelled CO_2 intensity of charging energy in Europe in the following analyses to assess the indirect emissions of German electromobility.

Figure 5 Energy mix incremental charging power

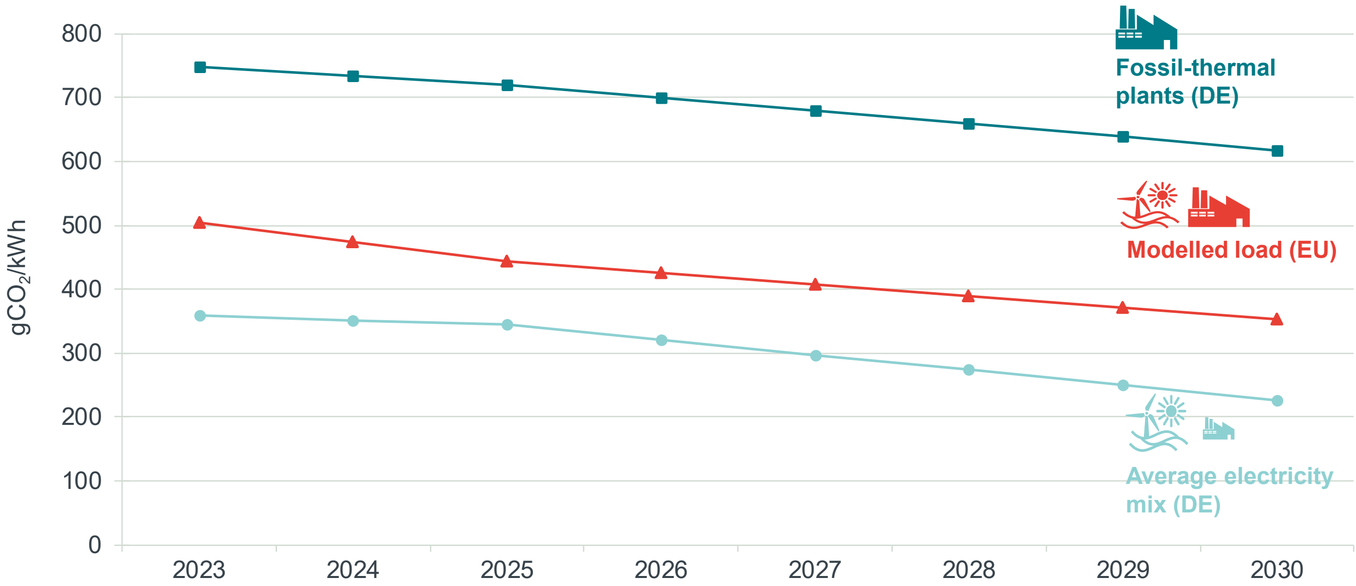


Source: Frontier Economics

Figure 6 shows the modelled charging power (red line) based on the change in the European electricity mix compared to the CO_2 emission intensity of the average power mix (light blue) and the intensity of fossil-thermal power plants in Germany (dark blue). The CO_2 intensity decreases over time from about 500 gCO_2/kWh in 2023 to about 350 gCO_2/kWh due to the progressive decarbonisation of the electricity system and is thus between the average and marginal (fossil-thermal) CO_2 intensity of the German power mix.

[21] Includes: Germany, Netherlands, Belgium, France, Switzerland, Austria, Italy, Czech Republic, Poland, Denmark and United Kingdom.

Figure 6 **CO_2 intensity of electricity**



Source: Frontier Economics, based on electricity market model

2.4 Conclusion: Per km, electric vehicles are currently as CO_2-intensive as vehicles powered by combustion engines

Our quantification of the emissions intensity of charging energy shows that for the foreseeable future, demand for charging energy will shift CO_2 emissions to the power sector. The modelled CO_2 intensity of charging energy forms the best estimator of these shifted physical CO_2 emissions. In the following, we show we show the resulting indirect physical emissions per kilometre driven.

For illustration purposes, we focus on the year 2030, vary the energy consumption by +/- 10% for further sensitivity analyses, and combine this with the three previously defined CO_2 intensities of the charging current:

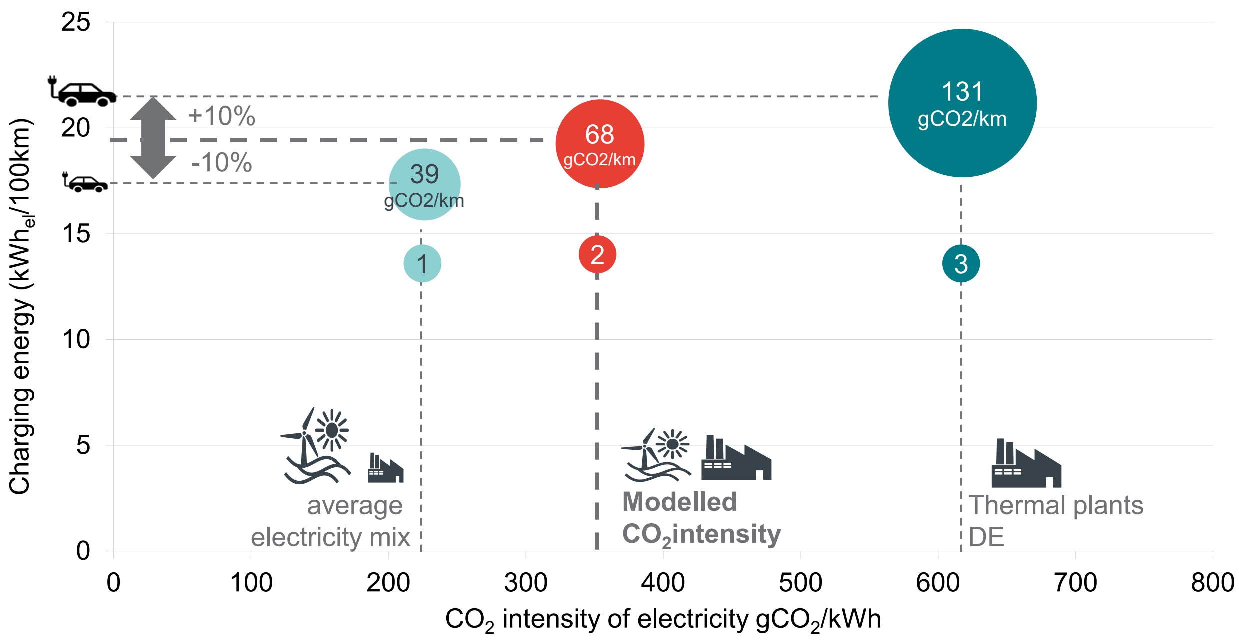
- In the *best case,* an above-average efficient vehicle (17 kWh/100 km) is charged with the average electricity mix and thus emits about **40 gCO_2/km** in 2030.
- In our *central scenario* based on about 19 kWh/100 km and the modelled CO_2 intensity, the indirect CO_2 emissions in 2030 are about **70 gCO_2/km.**
- In the *worst case,* a below-average-efficiency vehicle is charged primarily with fossil-thermal electricity and thus emits about **130 gCO_2/km.**

Thus, in 2030, electric vehicles achieve an emission value per kilometre driven that is slightly below the range of current internal combustion engines, which is between 117 and 170 gCO_2/km[22], without taking into account possible

[22] Fleet average of vehicles sold in the EU, new registrations 2019, see **Figure 12.**

dampening effects of the EU ETS. The results from these three scenarios are summarised again in **Figure 7.**

Figure 7 Indirect emissions per km driven (2030)



Source: Frontier Economics

3 EU ETS PARTIALLY DAMPENS CO_2 EFFECTS, BUT LEADS TO SUBSTITUTION EFFECTS

In this section, we show, based on modelling of the European Emissions Trading System, that while the EU ETS has a dampening effect on indirect physical emissions, the argument of CO_2-neutral charging energy does not hold up in its current design. Rather, our analysis shows that the complex feedbacks between different instruments and sectors must be taken into account when designing effective climate policy. We show below

- how the mechanisms in the EU ETS create supply flexibility;
- that this flexibility in supply will result in additional demand not only displacing other emissions in the ETS but also be leading to de facto additional emissions; and
- that the additional demand will also lead to substitution and price effects in other sectors.

3.1 Various extensions flexibilise the emissions limit under the EU ETS

The EU ETS is an effective and efficient climate protection instrument

The European Emissions Trading System (EU ETS) is the central climate protection instrument at European level. Players operating in sectors covered by the ETS must submit a certificate (European Union Emission Allowance, EUA for each ton of CO_2 emitted. The obliged parties either procure the necessary allowances in centrally conducted auctions, receive allocated allowances for free or can buy them from other market participants. Importantly, the total quantity of allowances available to market participants is limited and decreases by a defined amount from year to year. Currently, the Linear Reduction Factor ("LRF") is 2.2%, which corresponds to an annual reduction in the cap of approximately 48 M tCO_2.

If a market participant fails to submit allowances in the amount of its measured emissions, it must pay a penalty (100 €/tCO_2) and additionally deliver the missing allowances. Allowances issued in one year do not lose their validity at the end of the year; they can be stored (so-called „banking“) and used at a later date.

With the high-emission sectors "public electricity & heat supply" and energy-intensive industry, the EU ETS covers slightly less than half of all European CO_2 emissions.

The annually decreasing supply of allowances guarantees that a politically determined emissions reduction target is achieved in a given year. The EU ETS is thus a very effective instrument. Trading between actors and the possibility to save allowances further ensures that the most efficient emission abatement option is used. It is therefore also an efficient climate protection instrument.

External shocks unbalanced the EU ETS and created significant oversupply of allowances

However, no provision was made in the original regulations for external shocks. As a result, a number of factors outside the EU ETS have thrown the system out of balance and caused demand for allowances to develop differently than expected when CO_2 trading was launched in 2005: The economic and financial crisis of 2008/2009 and the subsequent recession depressed economic performance. The expansion of renewable energies in Europe pushed more and more conventional power plant operators out of the market. In addition, the high allowance of international CO_2 credits[23] further inflated the already existing supply in the EU ETS.

This demand shock, in combination with an inflexible supply quantity, has led to CO_2 prices falling sharply and remaining at low levels for several years. This would not be a problem if the EU ETS targets had already been oriented towards the complete decarbonisation of the economy, which is necessary in the medium term. However, as long as the necessary structural change has only been partially initiated, it is appropriate to maintain a certain incentive level.

[23] Clean Development Mechanism (CDM), Joint Implementation Credits (JI)

Introduction of the Market Stability Reserve and deletion of certificates to make the supply quantity more flexible and reduce the surplus

In response to the lack of price and investment signals and the resulting dwindling political confidence in the instrument of the EU ETS, the EU Commission implemented a structural reform of CO_2 trading in 2018. In addition to an increase in the linear reduction factor, which instead of a reduction of approximately 38 $MtCO_2$ per year now implied a reduction of 48 $MtCO_2$ per year, the introduction of the Market Stability Reserve ("MSR") represents the most important reform in the EU ETS.

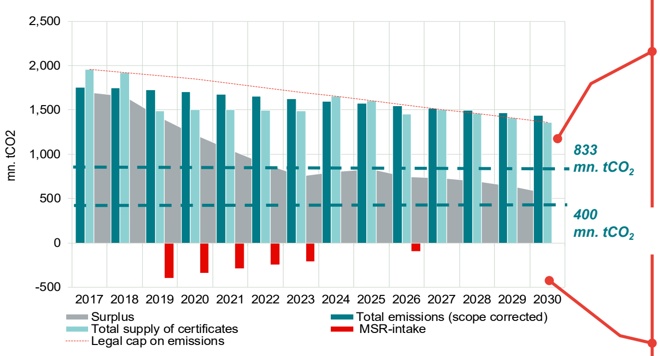
The basic operation of the MSR is relatively simple: If the number of allowances in circulation exceeds a certain threshold, fewer allowances are auctioned the next year. The certificates that are not auctioned are stored in the MSR. If, at a later date, the quantity of allowances falls below a critical value, the following year's auction volume is increased again from the MSR's inventory.

TECHNICAL FUNCTIONING OF THE MARKET STABILITY RESERVE

Current legal framework

- If the number of allowances in circulation (TNAC) exceeds 833 mn. tCO_2 in a given year, the auction volume of the following year will be reduced by 24% of TNAC (2019-2023) and by 12% after 2023
- If the TNAC falls below 400 mn. tCO_2, 100 mn. allowances will be fed back into the market from the stock of the MSR
- The number of certificates that exceed the previous year's auction volumes will automatically be cancelled from the MSR (starting in 2023)

Functioning of the MSR (example)



- Reduction of auction volumes by a fixed %share of surplus if TNAC >833 mn. tCO_2 and
- Increase in auction volumes by 100 mn. tCO_2 if TNAC <400 Mio.

TNAC = total of allowances available to the market (incl. banked allowances) – submitted allowances

- Automatic cancellation of allowances if stock of MSR exceeds previous year's auction volumes

Source: Frontier Economics

Thus, the MSR shifts quantities from periods with a surplus to scarcer years. This shift in time does not in itself lead to a change in the total number of emission allowances available. However, in order to reduce the surplus of over 1 billion tCO_2 that has built up, allowances will be deleted from the Market Stability Reserve from 2023 onwards if their holdings exceed a certain level.[24] With this allowance cancellation, the Commission creates a unilateral option to tighten supply if demand for allowances falls faster than supply due to external shocks or other influences. The way this works is illustrated again in the diagram above and calculated for an example.

With the introduction of the MSR, it was expected that over 2 billion tCO_2 would be cancelled in the period 2023 to 2030[25]; this is more than the annual allocation with

[24] Certificates from the MSR that exceed the previous year's auction share are deleted.

[25] BMU (2018): The reform of EU Emissions Trading for the 4th trading period (2021-2030), p. 4.

EUA (2019: 1.9 billion tCO_2). However, how many allowances are actually finally removed from the market depends on the future development of CO_2 emissions, i.e. demand, and future reforms of the ETS supply. Therefore, we examine below the future development of the EU ETS in a scenario that takes into account both expected changes in demand, e.g. decarbonisation of the power sector through RES-E subsidies and coal phase-out, and in supply in the form of reforms currently under discussion as part of the EU Green Deal.

SCENARIO ANALYSIS FOR VOLUME MODELLING IN THE EU ETS WITH THE MSR MODEL FROM FRONTIER ECONOMICS

To examine the impact of incremental power demand from electromobility, we use Frontier Economics' MSR model and, for sensitivity analyses, we also use IfW's MSR model, which is discussed in more detail below. The assumptions in Frontier Economics' MSR model are as follows:

Demand for certificates in the Frontier ETS model

In a first step, we define an EU ETS demand scenario that represents the most likely development of emissions in the power sector and energy-intensive industries from today's perspective. In doing so, we take into account

- a short-term **demand shock as a result of the COVID-19 pandemic** with reduced economic output in 2020 to 2022[26] ;
- an **increase in electricity demand to** 3,200 TWh and an EU-wide **RE quota of** 62% in 2030 [27]; and
- **economic growth of** 1.5% annually from 2022 and a 30% **reduction in the emissions intensity** (tCO_2/EUR GDP) of the economy.

Compared to 2018, emissions from the power sector thus fall by 65% and those from the ETS industrial sectors by 21%. In total, emissions in the EU ETS fall by 61% by 2030 in this scenario compared to 2005.

Supply of certificates in the Frontier ETS model

With the Green Deal, the EU has defined clear ambitions for higher GHG reduction targets. In order to contribute to the higher targets, the EU Commission is currently consulting on possible reforms of the EU ETS. From today's perspective, it is likely that a tightening of the reduction targets in the EU ETS will be adopted in 2021. For our modelling, we assume that a tightening will occur in 2024. We define two supply scenarios

- **Scenario 1: Steep LRF, moderate MSR** - Increase the Linear Reduction Factor from 2.2% today to 4.6% for the period 2024 to 2030 while maintaining the MSR rules known today.
- **Scenario 2: Moderate LRF, Flexible MSR** - Increase the Linear Reduction Factor from 2.2% today to 3% for the period 2024 to 2030 while increasing the MSR uptake rate from 12% after 2023 to 24%.

[26] 8% GDP decline in 2020 and reaching pre-crisis levels in 2023 (see ECB 2020).

[27] Based on ENTSO-E TYNDP 2020, "Global Ambitions" Scenario

3.2 Additional emissions in the power sector are only partially offset by MSR

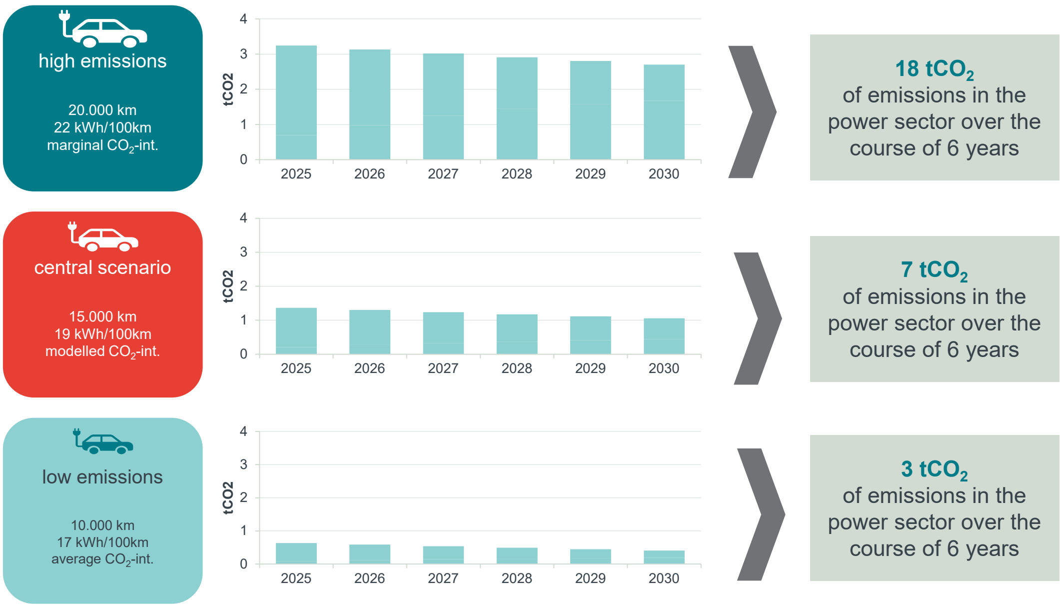
In **section 2** we show that the rise of electromobility leads to a shift of physical CO_2 emissions from the transport sector to the power sector. We also explain that the power sector, as part of the EU ETS, is subject to a general cap on emissions. However, this cap is not binding due to the current situation of a supply surplus in the EU ETS as well as the cancellation of allowances by the MSR.

The additional demand reduces the surplus of allowances

The additional emissions from incremental electricity demand from electromobility increase the demand for certificates. This leads to the current surplus of certificates being reduced more quickly and fewer certificates being transferred to the MSR. Compared to a scenario without electromobility, the stock of allowances in the MSR is then smaller and accordingly fewer allowances are eliminated by the mechanism of automatic cancellation: In total, more certificates are available to the market than without incremental demand from electromobility.

In the Frontier's EU ETS model, we consider the three variants of additional emissions in the EU ETS described above (**Figure 8)**. Combined with the German ramp-up curve of electromobility, our central scenario results in physical emissions and thus additional demand for allowances of 42 $MtCO_2$ in the period 2025 to 2030. A vehicle registered in 2025 leads to an increase in emissions in the power sector of 1 tCO_2 per year.[28]

Figure 8 Physical emissions shifted into EU ETS (per vehicle)



Source: Frontier Economics

[28] When considering the entire European BEV fleet, demand increases by approximately 100 $MtCO_2$ per year in the central scenario.

Lower surplus implies less cancellation of allowances

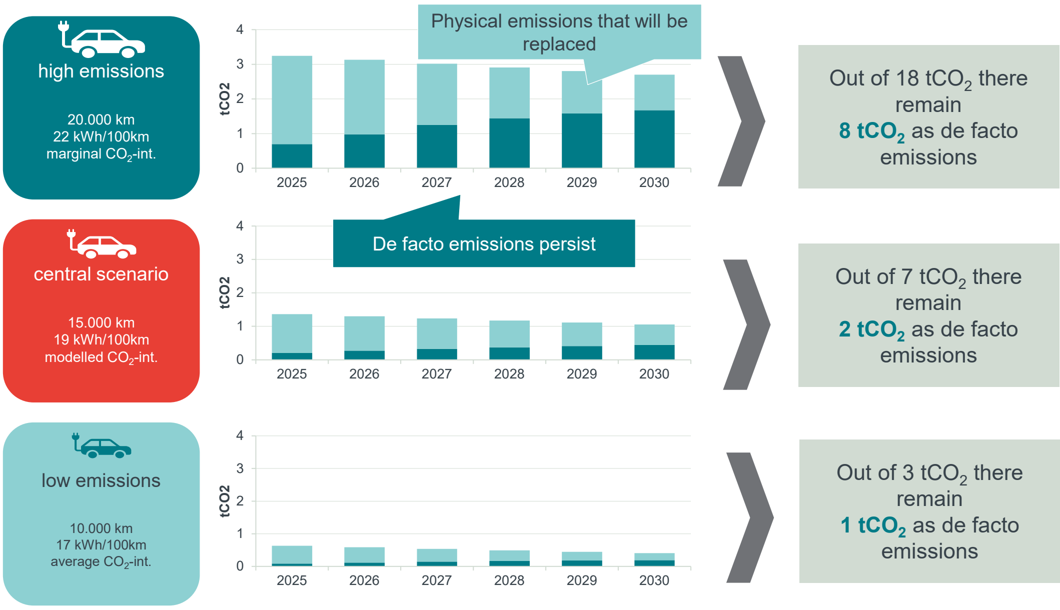
In the period 2025 to 2030, the demand for certificates increases by about 42 $MtCO_2$ in our central scenario due to the increase in German electromobility.

This additional demand leads to a decrease in the cancellation of surplus allowances by approx. 13 $MtCO_2$. Due to this overall increase in supply, circa 30% of the physical emissions remain in the EU ETS as de facto additional emissions in the central scenario.

Using the example of an electric vehicle registered in 2025 (**Figure 9**), this is roughly equivalent to 2 tCO_2 out of a total of 7 tCO_2 generated in the power sector by 2030.

If we assume a less steep increase in the Linear Reduction Factor ("LRF") but a more flexible MSR, even more allowances would be invalidated without electromobility. In this scenario, the share of allowances remaining in the system increases to almost 50% ("High Emissions" scenario).

Figure 9 Remaining de facto emissions vary per scenario and year



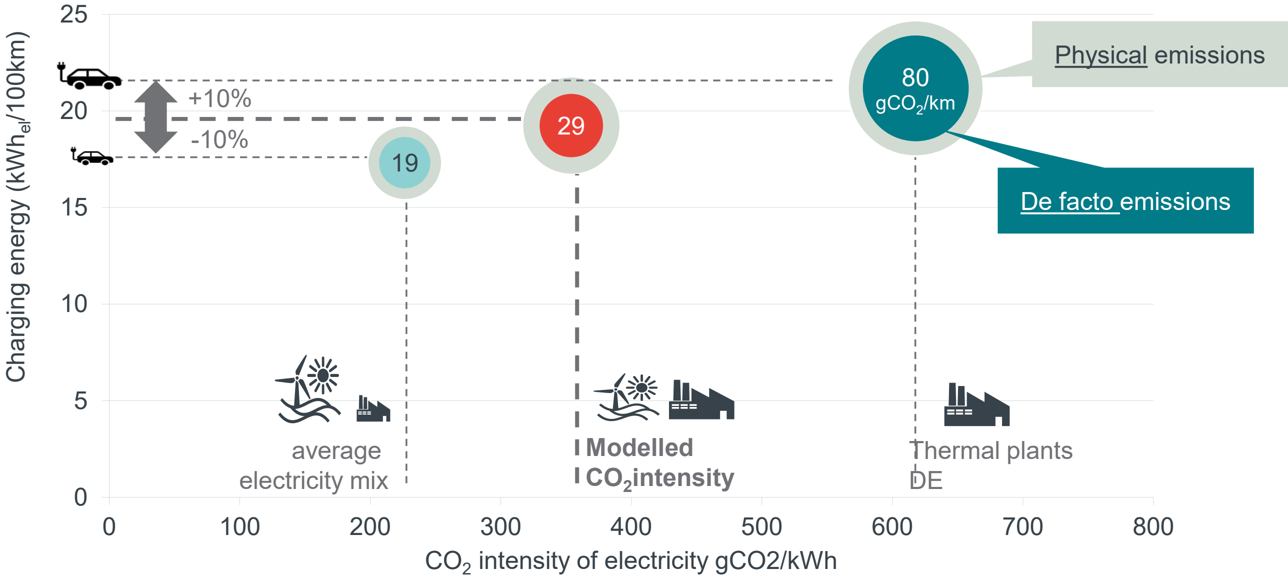
Source: Frontier Economics

Per kilometre driven, approx. 30 gCO_2/km will remain in 2030

Broken down to the assumed mileage, our Central Scenario results in remaining de facto emissions of 30 gCO_2/km in 2030 compared to 68 gCO_2/km of physical emissions. If the expected reform of the EU ETS results in a more flexible Market Stability Reserve than assumed in the Central Scenario, the share of de facto emissions would increase further. This is illustrated in our "High Emissions" scenario, in which approximately 80 gCO_2/km of de facto emissions remain out of 131 gCO_2/km of physical emissions. In contrast, in the „Low Emissions" scenario, approximately 19 gCO_2/km of physical remain out of 39 gCO_2/km. This scenario is summarized in **Figure 10)**. Shown are the results for ETS supply scenario 1

(Stricter Cap, MSR unchanged) in conjunction with the "Low Emissions" and "Central Scenario" consumption scenarios, and ETS supply scenario 2 (Less Strict Cap, Strong MSR) with the "High Emissions" consumption scenario. Due to the stronger MSR intervention in the second supply scenario, the leverage of the additional charging-related emissions on allowance cancellation is larger. Therefore, of the 131 gCO2/km of physical emissions, a larger share (80 gCO2/km) remains as de facto emissions in the electricity system, at about 60%. In ETS supply scenario 1, which reflects the current MSR framework, the proportion of remaining emissions is between 40% and 50%.

Figure 10 Actual emissions per km driven (2030)



Source: Frontier Economics

3.3 Considering expectations in the ETS also influences de facto emissions

In many models of MSR, such as Perino (2018), but also in the model used so far, it is assumed that limiting the overall scope of MSR means that an increase/decrease in allowance demand triggered by environmental legislation automatically leads to fewer /more allowances cancelled. However, these models do not take into account the expectations of market participants[29]: if market participants anticipated stricter environmental regulations in the future, they would also expect higher allowance prices in the future. In this case, they would buy more allowances today than they need in order to be able to use them later instead of the more expensive newly issued allowances. They would therefore make greater use of the option of banking certificates.

We adapted Rosendahl's stylised ETS model (Rosendahl 2019) to our current scenario (see Appendix D for the more detailed approach). A simulation of the

[29] The existence of such expectations has led to the introduction of the Market Stability Reserve.

three scenarios described above shows that accounting for such market participant expectations reduces the excess emissions of a BEV-induced demand shock. Under certain assumptions, the extreme case could occur in which an increase in allowance demand triggered by electromobility results in net lower emissions. This phenomenon is due to the fact that market participants in the IfW-Rosendahl ETS model act without uncertainty and under perfect foresight. Under these assumptions, the market participants increase their stock of allowances („banking“), which in turn leads to a stronger deletion of certificates through the MSR; i.e. the market participants contribute to a scarcity of allowances through individually rational behaviour.

The assumptions made by Rosendahl (2019) are certainly only realistic to a limited extent, as companies generally only have a medium-term planning horizon and are therefore unable to adjust their expectations and correspondingly their behaviour perfectly. Conversely, however, it is just as unrealistic for companies not to react at all to future market developments and accordingly leave their behaviour unchanged. The reality will lie between the assumption of unchanged banking behaviour (as shown above), as well as the perfect adjustment of banking behaviour.

Moreover, since the IfW-Rosendahl ETS model is a stylised model, the results presented are only rough estimates and should not be misunderstood as numerical forecasts. Nevertheless, it can be seen from these simulations that the inclusion of market participants' expectations can have a dampening effect on the demand-driven additional emissions, since such a demand shock would lead to a reduction in the emissions of the other sectors. This is shown in the following Table 2[30]. In addition, the total amount of additional emissions from BEVs is relevant for the formation of expectations, which is why we also calculate a scenario with increased BEV demand in the EU, the results of which are shown in the appendix.

The "Low Emissions" scenario for Germany actually shows the case where more allowances are cancelled, i.e. the vehicles have negative emissions. As described above, market participants - because they expect higher allowance prices in the future - engage in more banking today, so that initially more allowances are cancelled. Although there is later increased demand for allowances and thus again fewer deletions, the first effect dominates in this scenario, in which low increased demand is assumed. Appendix D.1 describes this mechanism in more detail.

In all other scenarios, even taking expectations into account and disregarding time preference, there are positive de facto additional emissions in the ETS, but these are lower for the German scenario than without taking expectations into account.[31]

[30] Note that by considering expectations, the "Low Emissions" scenario is now the one with an LRF of 4.6% and adjusted MSR, while "High Emissions" is the scenario with LRF 3%.

[31] In contrast, they are even higher in the „Central“ scenario for an increased certificate demand taking into account the complete European electric vehicles fleet (see Annex).

Table 2 Physical and de facto emissions in the different scenarios (2030, g CO_2/km)

Scenario	Physical emissions	De facto emissions (Frontier ETS)	De facto emissions (Rosendahl ETS)
Low Emissions	39.2	18.8	-97.0*
Central Scenario	68.1	28.6	18.0
High Emissions*	130.8	79.6	45.4

Source: IfW / Frontier Economics "High Emissions" scenario assumes an LRF of 3% and a more flexible MSR, the other scenarios assume an LRF of 4.6% and the current configuration of the MSR
** Special case in which a small increase in emissions leaves actual less de facto emissions.*

3.4 Additional emissions also lead to substitution and price effects

The additional demand for electricity from electromobility and the associated demand for certificates in the EU ETS result in corresponding market reactions in the EU ETS:

- Certificate prices are rising;
- the other buyers reduce their demand for allowances or their emissions; and
- part of the additional emissions is shifted (e.g. to abroad).

In order to estimate the increase in allowance prices and the reduction in demand, on the one hand, the IfW-Rosendahl ETS model is used. On the other hand we use marginal abatement cost curves for 2030 derived from the IfW-DART model (a general equilibrium model used for climate policy analyses) for the EU and the German electricity and industrial sectors in the EU ETS, respectively (for details, see Appendix D).

Price effects from German electromobility are low

The effects in scenarios in which BEV use increases only in Germany are relatively small under most assumptions: The price effect reaches only 1.5 €/tCO_2 in most scenarios; this is within the weekly variation range. Only the IfW- Rosendahl model shows a price increase of around 3.6 - 4.1 €/tCO_2 for the scenario with strong MSR deletion, as here the expectation formation has a stronger effect.

The price effects when taking into account pan-European electromobility are much more significant. The size depends strongly on the extent to which the EU ETS already enters the range where each additional reduction becomes increasingly expensive and also on how large the additional certificate demand by BEVs is. In the „Central" scenario, the increase of the CO_2 price reaches almost 6 €/tCO_2, in the "High Emissions" scenario even more than 18 €/tCO_2. Furthermore, the change depends very much on MSR assumptions.[32]

With additional BEV demand in Europe, significant CO_2 price increases in the EU ETS can therefore be expected. It can therefore be assumed that demand in the other EU ETS sectors will be reduced.

Substitution effects in the EU ETS primarily affect the power sector, less so the industrial sectors

The DART marginal abatement cost curve model can show how the reductions resulting from the higher prices are distributed across sectors - however, there is in this case a 1-to-1 emission reduction in the other sectors[33]. Across all scenarios, nearly 95% of the reductions occur in the EU power sector (through fuel switching, i.e., the shift from coal-fired power generation to gas and, in part, more renewable power). Only about 5% of the reductions stem from the industrial sector (through energy efficiency, fuel switching, relocation abroad). A significant part of the substitution occurs within Germany, with Germany accounting for about 30% of the total EU reductions in the power sector and about 22% of the EU reductions in the industrial sector. However, the power sector is very aggregated in DART and no detailed policies such as EEG targets or coal phase-out are mapped, so this can only be a rough estimate. If expectations are taken into account, this buffers these substitution effects.

Importance of international carbon leakage here rather low

Regarding the offshoring of production and emissions, existing studies show that the carbon leakage rate of climate policies is typically between 5% and 30%.[34] This means that for every 100 tCO_2 saved in the EU, 5-30 additional tons more CO_2 are emitted outside the EU. An additional demand for allowances by BEVs means in principle an additional emission saving in the other EU ETS sectors to reach the given targets. Translated, this means that of the 3-330 MtCO_2 allowance demand by electromobility, depending on the scenario and excluding the MSR, a corresponding share is shifted abroad in each case. However, since the analyses with DART show that the pressure is primarily in the power sector, which is little exposed to international competition, the lower end of the range is more likely.

3.5 Conclusion: CO_2 emissions physically associated with charging energy are only partially reduced and substitute other CO_2 emissions

In this chapter, we have shown that the additional demand for allowances in the EU ETS due to the increase in electromobility is generally not CO_2-neutral.

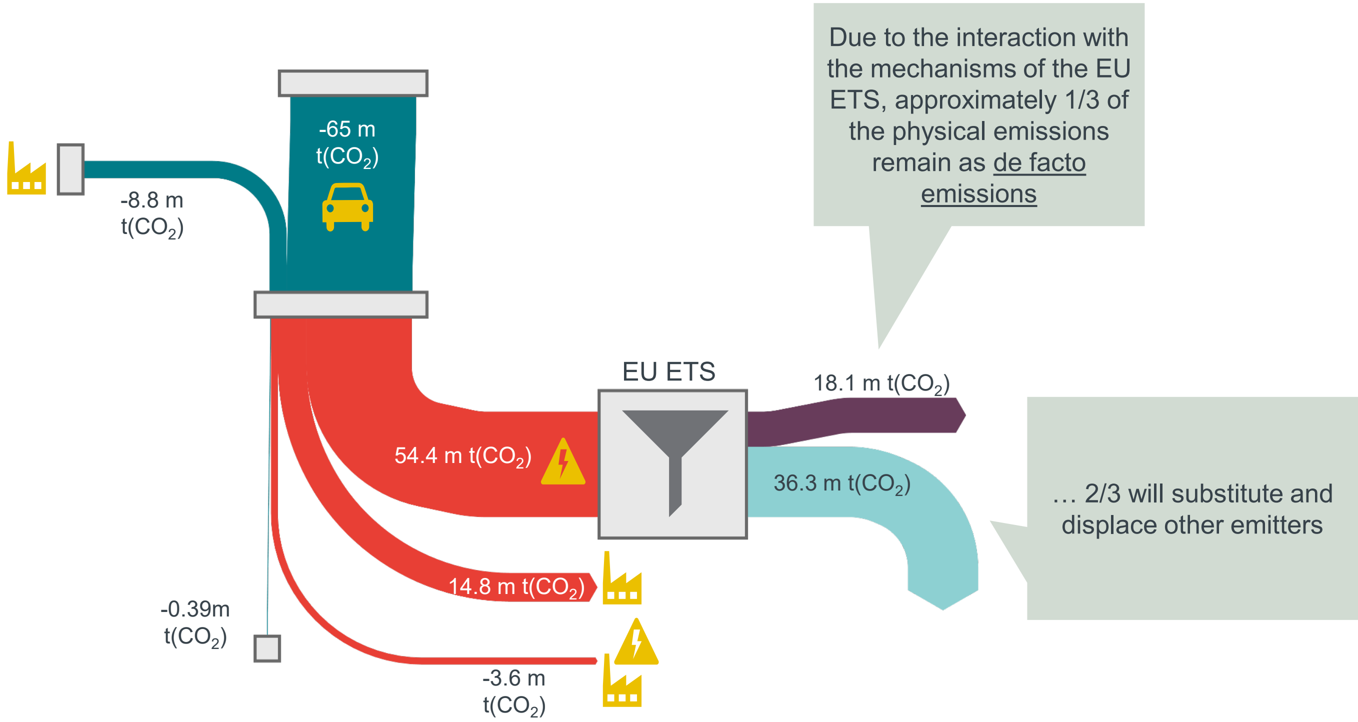
[32] In the IfW-Rosendahl model, less MSR deletion (=additional demand) dampens the price effects for all scenarios, but they can still reach 10 €/tCO_2.

[33] The MSR is not included in the marginal abatement cost curve model. For more detailed analyses, it would be necessary to integrate the MSR into a sector-differentiated model. Such a model does not yet exist.

[34] Branger and Quirion (2013), Böhringer et al. (2018).

Although some of the emissions shifted to the power sector lead to a substitution of other emitters – especially in the power sector – there remains in fact an increase in emissions. In our „Central“ scenario, the share of emissions remaining in the ETS is about 1/3. These core results are illustrated again in **Figure 11.** Here, we also take into account the CO_2 intensity of charging energy derived in **section 2.3** increases the shift of emissions to the power sector from 51 to 54.4 MtCO2 compared to the average consideration in **Figure 2.**

Figure 11 Emission shifting instead of emission avoidance



Source: Frontier Economics

Note: Calculation based on AG1 of the National Platform Future of Mobility (NPM); based on data from the Climate Protection Plan (8.10.2019) and NPM AG1's Report (29.03.2019): 7-10.5 million vehicles with approx. 6-13 MtCO2 TtW savings (2030). Vehicle assumptions: mileage: 10,000km; consumption (compact car, WLTP plus): 22.4 kWh/100km (BEV), 5.6 l/100km (ICEV); CO^2 electricity mix 2023-2030: 463h/kWh (incl. 42g/kWh RES-E); charging loss 10%; production 9.9 t CO_2 (BEV); 5.8 t CO_2 (ICEV).

4 REGULATORY FRAMEWORK BEYOND THE POWER SECTOR FURTHER EQUALISES BENEFITS OF ELECTRIFICATION

The preceding analyses show the complex interactions that result from the various regulatory requirements in the electricity market alone. In addition, there are further repercussions from regulatory requirements outside the power sector, which potentially further dampen the possible relative advantages of electrification over alternative powertrain technologies. In the following sections, we address two effects.

4.1 Fleet targets neutralise benefits of additional electromobility

In addition to the interaction with the EU ETS, the interaction with the fleet limits is also relevant for assessing the demand for BEVs. The fleet limits set upper limits for the average CO_2 emissions of a manufacturer's passenger cars sold in Europe within a year (BMU 2020). Specifically, a fleet limit of 95 grams per km will apply from 2021 and this limit will decline to approximately 59 grams by 2030, which corresponds to approximately 2.2 litres of diesel per 100 km. It is important to bear in mind that this is an average for newly registered vehicles. This means that while vehicles with CO_2 emissions above the limit value can be sold, at the same time vehicles with CO_2 emissions below the limit value must be sold accordingly so that the limit value is met across the entire fleet.

As with the other instruments, a distinction has to be made between actual physical emissions and those that are relevant for regulatory purposes. Within the calculation of fleet limits, BEV emissions are assumed to be zero[35], even though - as already discussed - this does not necessarily apply with regard to physical emissions. It follows that the calculated fleet limit for BEVs within the fleet is lower than the actual physical fleet emissions. At the same time, however, this also means that the CO_2 emissions of the remaining vehicles of a manufacturer must fall to a lesser extent in order to achieve the fleet limit value than would be the case without the share of BEVs (see Waterbed Effect of Fleet Regulation).

In other words, regulatory requirements on average fleet emissions neutralise any potential positive effects of additional BEVs ("waterbed effect").

[35] By 2022, they will even be weighted by a factor greater than 1 for fleet consumption ("supercredits"), but this is no longer relevant for the 2030 observation year of this study.

WATERBED EFFECT OF FLEET REGULATION

Let FE_t the fleet emission values in year t and $\overline{FE}_t$ be the limit value in the corresponding year. We assume that lowering the fleet emissions is associated with costs $C(.)$, for which holds correspondingly: $C'(FE) > 0$. Thus, by minimization cost, manufacturers have the incentive to set fleet emissions equal to the fleet limit. If the share of BEVs within the annual vehicles sold is α (and correspondingly $1 - \alpha$ is the share of conventional internal combustion vehicles), then the average fleet emissions are:

$$FE_t = \overline{FE}_t = (1 - \alpha)FE_t^V + \alpha FE_t^{BEV}$$

It follows that, due to $FE_t^{BEV} \coloneqq 0$, the fleet emissions of the internal combustion engine vehicles sold are above the fleet limit when $\alpha > 0$, i.e. when BEVs are sold:

$$FE_t^V = \frac{\overline{FE}_t}{(1-\alpha)} > \overline{FE}_t$$

In other words, the regulatory specification of BEVs as zero-emission vehicles leads to vehicles with higher emissions being added to the fleet elsewhere than without BEV vehicles ("waterbed effect") due to the fleet targets. The overall (imputed) effect on fleet targets is therefore neutral, i.e., imputed fleet emissions do not improve as a result of additional BEV vehicles. However, since BEVs do in fact lead to additional emissions (see the results in the previous sections), it could even be argued that additional market penetration of BEVs ultimately even leads to increasing overall emissions.

To illustrate this effect, **Figure 12** uses manufacturers' current fleet emissions to show how the share of BEVs may affect the indirect fleet limits in 2025.[36] Based on today's average weight distribution and an extrapolated mass dependence in 2025 (of 0.0285 based on Regulation (EU) 2019/631), we derive the manufacturer-specific limits. The two bars on the right show the indirect limits that result when manufacturers reach the benchmark of 15% BEV and 20% BEV[37], respectively. If the benchmark of 15% is exceeded, the fleet limit is increased (but by a maximum of 5%).[38] It should be noted that Figure 12 is for illustrative purposes only, as different pooling models result in different limits for manufacturers and there are other regulations that affect the calculated fleet limits (e.g. eco-innovations in vehicle construction).

When discussing the fleet limits, it must also be taken into account that this is only an upper limit for the average CO_2 emissions of the vehicles sold, but not for the average emissions of the entire vehicle fleet, let alone the emissions from real-world consumption. For the average emissions of the entire vehicle fleet, the extent to which BEVs substitute conventional vehicles or vehicle purchases must be taken into account. Depending on the extent to which the BEVs sold are "additional“, i.e., do not displace internal combustion engine vehicles within new purchases, or at the same time substitute BEVs within the existing vehicle fleet, primarily small

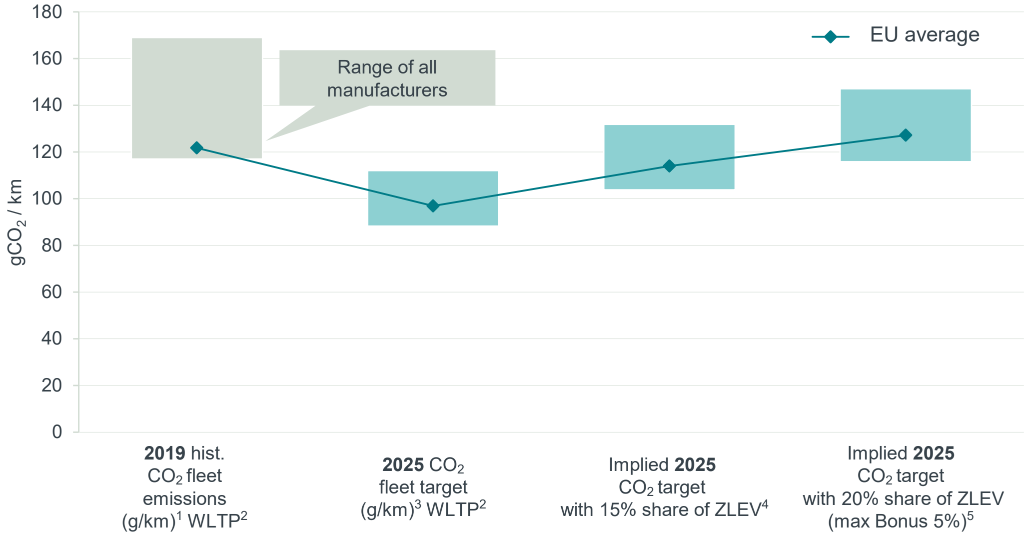
36 We convert approximately from NEDC (New European Driving Cycle) limits to WLTP (Worldwide Harmonized Light-Duty Vehicles Test Procedure) limits.

37 The regulation talks about ZLEV (= Zero and Low Emission Vehicles).

38 This does not take into account that there are additional incentives for BEVs in small markets (including Poland or the Czech Republic), because BEVs then have a share of 1.85 here (BMU 2020).

vehicles with low emissions, the average emissions of the fleet will decrease much more slowly than anticipated by the reduction in the fleet limit. This effect is further amplified when taking into account possible different utility profiles of ICEVs and BEVs.

Figure 12 Indirect fleet limits in 2025 by taking ZLEVs into account



Source: IfW

1 Values taken from JATO press release (March 2020).

2 From 2021, there will be a switch from the NEDC to the WLTP procedure, which will increase the actual values by around 20% and the fleet limit values will also be adjusted accordingly. However, the final value will not be announced until 2021, based on the ratio of the old to the new test procedure in 2020 (BMU 2020).

3 The specific CO_2 fleet limits have been calculated according to the above formula under Annex I. Part A of REGULATION (EU) 2019/631 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 17 April 2019.

4 Here, a share of zero and low emission vehicles (ZLEV) of 15% of vehicles sold is assumed. ZLEVs include pure battery or fuel cell vehicles with 0 g CO_2/km or externally chargeable plug-in hybrid vehicles (provided they have CO_2 emissions of less than 50 g CO_2/km) (BMU 2020).

5 Here, it is assumed that manufacturers achieve the maximum bonus for lowering the fleet limit by achieving a 20% share of ZLEVs.

In the extreme case, in which additional BEVs do not substitute internal combustion vehicles due to the existing fleet limits, but more vehicles are sold, or those with higher emissions are sold, a situation can occur in which emissions in the transport sector increase (ignoring additional instruments). If, in addition, the internal combustion vehicles made possible by a higher proportion of electromobility are also used with a higher mileage, this effect is even stronger. In addition, these considerations do not take into account the physical emissions of BEVs, which, unlike in the calculation of fleet limits, are not zero. This further amplifies the effect. Basically, with each additional vehicle, even if average fleet emissions remain unchanged, emissions from new vehicles increase. Taking into account physical rather than de facto emissions, this effect is disproportionate for BEVs.

However, it must be clearly stated that this is not a "disadvantage" of BEVs in the proper sense, but that this effect results from the instrument of fleet limits and the consideration of BEVs as zero-emission vehicles. From these considerations it follows once again that overlapping instruments can have unintended consequences.

4.2 Actual GHG reduction impact of synthetic fuels higher than electrification due to strict regulatory requirements of RED II

The requirements of the European Renewable Energies Directive ("RED II"), which came into force at the end of 2018, must be implemented in national law by 30 June 2021. At present, many details are still unclear, but RED II already contains important information and requirements with regard to synthetic fuels, which will then also be reflected in the German Federal Immission Control Act (BImschV).

Draft bill for the implementation of RED II with important changes and more ambitious targets for Germany

With regard to the greenhouse gas impact of synthetic fuels compared to electromobility, the following specifications are particularly relevant:

- **RES quota of 28% in the transport sector** - Each member state is obliged to achieve a quota of at least 14% (of final energy consumption) of renewable fuels in the transport sector (road and rail transport) by 2030. To this end, member states are developing a quota target for fuel distributors in their member state. In Germany, this was designed as a greenhouse gas reduction quota for the fuel distributors as obligated parties. Currently, the target value is minus 6% compared to a reference emission value for a reference fuel (currently e.g. reference value 95.1 gCO_2-eq/MJ diesel fuel). According to initial drafts by the BMU, this value is to be tightened from -10% in 2026 to -22% by 2030. According to BMU calculations, this would then correspond to a RES share in the transport sector of 28% in 2030.[39]
- **Unequal multi-fuel crediting for charging energy and synthetic fuels** - "Authorised" fuels for reaching the 14% renewable fuel quota in the member states, or 28% in Germany, are charging energy (electromobility), various biofuels as well as synthetic fuels (so-called "renewable fuels of non-biogenic origin" RFNBO). In addition to the 14% requirement, there are multipliers and minimum or maximum limits for certain biofuels. In Germany, for example, a multiplier of "4" was initially planned for charging energy in road transport[40]; however, this multiplier was lowered to "3" in the last consultations. For hydrogen or RFNBO, the current draft provides for a "double" crediting for refineries and road transport.
- **In 2021, 1 kWh of grid charging energy enters the quota like 1.26 kWh of green fuel** - Charging energy taken from the public electricity grid is assessed using the RES quota of the public electricity supply from the period of two years before the reference year.[41] For Germany, for example, this would mean:

[39] German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (2020): Implementation of RED II in transport - key points for the transposition of Directive (EU) 2018/2001 into national law; presentation 18.12.2020.

[40] Information by the Federal Government: Integrated National Energy and Climate Plan http://dipbt.bundestag.de/dip21/btd/19/203/1920364.pdf , p.50.

[41] See RED II, Article 27, Sentence 3ff: "For the calculation of the share of renewable electricity in the electricity supplied to road and rail vehicles [for the minimum RES quota of 14% in 2030], Member States shall refer to the two-year period before the year in which the electricity is supplied in their territory. Furthermore, electricity

Charging energy consumed in 2021 is valued using a RE share from 2019 (42%) (possibly increased percentages if RES direct connections are counted). So, in combination with the multiplier "3" for 1 kWh of RES charging energy in road transport can be included in the quota calculation as 3 x 42% x 1 kWh = 1.26 kWh of green fuel, provided that the Member State applies these multipliers in this way for the calculation of its RES quota target achievement.

- **Currently, charging energy sourced from the grid pays 550 gCO_2/kWh towards GHG reduction** - In view of GHG reduction rate (currently minus 6%, increasing to minus 22%) applicable to fuel in-transit providers in Germany, the CO_2 reduction contribution of charging energy sourced from the grid (i.e. electricity mix, no direct connection of a RE plant to a charging pole) is calculated according to the following logic (regulations in detail are currently still in coordination at European and national level):
  - The starting value for the calculation of the GHG reduction is the physical CO_2 emission intensity of the electricity mix of the member state two years before the charging process (i.e. for 2021 then the year 2019). Let's assume approx. 400 $gCO_{2eq}/kWh_{electricity}$.
  - For charging current for e-cars, the adjustment factor for drive efficiency of 0.4 is applied - i.e. the CO_2 intensity of the charging current would then be 400 $gCO_{2eq}/kWh_{electricity}$ x 0.4 = 160 $gCO_{2eq}/kWh_{electricity}$.
  - The GHG reduction compared to the reference value (diesel in this case) would then be around 180 $gCO_{2eq}/kWh_{electricity}$ (reference value of 342 gCO_{2eq}/kWh_{diesel} (corresponding to 95 gCO_{2eq}/MJ) – 160 $gCO_{2eq}/kWh_{electricity.}$)
  - Last but not least, the multiplier "3" for charging energy is applied to the target achievement in relation to the RES quota for the member state as well as to the national GHG quota for the fuel distributors in Germany. In total, a kWh of (gray) charging energy from the grid in 2021 achieves a GHG reduction of approx. 550 $gCO_{2eq}/kWh_{electricity}$ compared to the reference value.

"Additionality requirement" of green fuels vs sustainability of grid-sourced charging energy

To qualify as an eligible fuel under RED II, a fuel must achieve a minimum level of GHG reduction compared to a conventional reference fuel ("sustainability check").

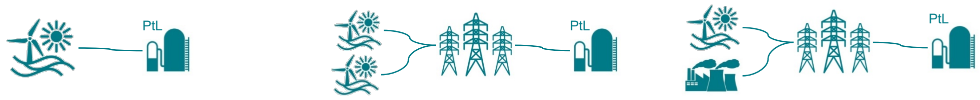
- **Charging energy obtained from the grid is also "sustainable" by definition** - charging energy meets this sustainability check - even if it would de facto come from coal-fired electricity and - as shown above - would still entail considerable emissions in the medium term.
- **RFNBO with strict target of 70% lower CO_2 intensity** - RFNBO in the transport sector is subject to a minimum 70% improvement over a fossil reference CO_2 intensity of 94 gCO_{2eq}/MJ gasoline fuel (or 95.1 gCO_{2eq}/MJ for diesel fuels).

obtained from direct connection to an installation generating renewable electricity may be fully counted as renewable electricity and is provided to road vehicles for the purpose of determining the share of electricity.“

- **Strict requirements of RED II ensure actual CO_2 reduction contribution of RFNBO -** Unlike charging energy for BEVs, additionality requirements also apply to the electricity used to produce RFNBO:
  - Additionality (additionality of RES-E generation);
  - Temporal correlation (between RES feed-in and electrolysis operation);
  - Geographic correlation (between RES feed-in and electrolysis operation).

  The exact implementation of these requirements in Germany is currently not yet known, but with regard to the additionality of RE, there are already three possible paths outlined in RED II, which are briefly illustrated in Figure 13 and behind which the national transposition cannot fall behind.

Figure 13 Additionality of renewable electricity for RFNBO production



Scenario 1: Direct connection of RE plant

- PtL plant is directly connected to a RE plant
  - **RE-share 100%** (RED II, Art. 27 (3))
  - **Additionality** necessary: RE-plant may only go into operation after the PtL plant
  - Proof of no additional grid purchase

In line with RED III, but
- Possible utilisation limited
- Realisation holds additional barrier (additional building of new RE plants on the same site)

Scenario 2: Grid supply RE-electricity

- RE – electricity supply from the public electricity grid
  - Proof of **100% RE-share**
  - Proof of **additionality**
  - Proof of correlation between generation & supply in terms of time and geography
- There is uncertainty:
  - Role of RE-excessive electricity & existing plants at end of generation
  - How strict will requirements be expressed (e.g. transition phase)

Specification of requirements only expected by 31st December 2021 in the form of an EC legal act (RED II, Art. 37 (3))

Scenario 3: Grid supply „grey electricity“

- PtL plant is connected to the public grid supplying it with „grey electricity“
  - **RE-share** based on the **average share** in the electricity mix 2 years before (RED II, Art. 27 (3))
  - **GHG-savings** need to amount to **> 70%** lin order to be accepted as RFNBO in accordance with RED II (RED II, Art. 25 (2))

In DE not realistic within the foreseeable future (RE-target 2030: 65%, §1 (2) EEG 2017)

Source: *Frontier Economics based on RED II*

Notice: *Details of the "Delegated Act" are currently still being discussed in Europe.*

- **For synthetic fuel produced in Germany, only 100% RES share is possible –** Case 3 "Grid procurement with (partial) grey electricity" is presumably not applicable for RFNBO production in Germany, since the 70% criterion would not be met for grid procurement from the German electricity mix. This means that approved RFNBOs in Germany can only be produced with 100% additional renewable electricity. In member states with "cleaner" electricity systems, such as Austria or in Scandinavia, there could also be a mix of RES-E and little grey electricity. But even in these combinations, which are rather less favourable from an environmental point of view compared to the additional new plant, an eligible RFNBO fuel will always end up being at least 70% cleaner than the fossil reference: i.e., a maximum of 30% of 94 gCO_{2eq}/MJ. This then corresponds to about 27 CO_{2eq}/MJ or about 100 gCO_{2eq}/kWh of fuel. With a consumption of a diesel vehicle powered by an RFNBO of 5l/100 km, this corresponds to a "well-to-wheel" emission of approx. 50 gCO_{2eq}/km. In Germany, 100% EE-RFNBO production (i.e. either case 1 or case 2 in the above figure) is the only viable option given the current electricity mix with domestic generation in view of the sustainability criterion. In this case, the "well-to-wheel" emissions of the RFNBO-powered vehicle would actually be zero.

- **Ensure sustainability of carbon source for RFNBO** - It is also important to note that in addition to electricity, a carbon source is usually required for the production of RFNBO - here too, care must be taken to ensure that the production of RFNBO does not result in additional CO_2 emissions, i.e. either CO_2 capture from the air or biogenic CO_2 is used, or emissions from processes e.g. within the EU ETS are used, but these must also not be double-counted. This means that an RFNBO in connection with industrial processes can only be considered sustainable if the CO_2 emission used there has also been "paid for" in the EU ETS (i.e. an EUA has been deleted).

Charging current from the grid with a higher CO_2 content as just barely permitted RFNBO

In this section, based on the results of our analyses in section 3 and the RFNBO permitting requirements described above, we show that the climate change mitigation contribution of alternative green fuels in 2030 is greater than that of a grid-sourced BEV.

- **Despite the dampening effect of the EU ETS, a BEV produces about 29 gCO_2/km in 2030** - Without taking into account the dampening effect of the EU ETS, the *physical emissions of* a BEV charged with German or European electricity are about 40 – 130 gCO_2/km - in our „Central“ scenario about 68 gCO_2/km (see **section 2**). Taking into account the dampening effect from the EU ETS, the *de* facto emissions of grid-related charging energy are around 19 – 80 gCO_2/km - in our „Central“ scenario around 29 gCO_2/km.

- **Climate protection impact of RFNBO larger than of electromobility** - 1 kWh charging current in road transport counts with factor 3 and approx. 65% RE share in the German electricity mix in 2030 as 1.95 kWh green fuel in the quota calculation for the RE quota of the member states. If the environmental disadvantages from the multipliers are still included in the consideration of the charging current, the comparison of the environmental impact would even be 68 gCO_2/km x 1.95 = 132 gCO_2/km, or **57 gCO_2/km** when applying the de facto emissions after taking into account the dampening effect of the EU ETS.

  A combustion engine with a consumption of 5l/100 km and a RFNBO that just meets the 70% GHG reduction, on the other hand, only comes to **50 gCO_2eq/km.** If the RFNBO is produced by additional RE generation (as in Germany), the RFNBO emissions decrease accordingly.

The application of the rules planned according to our understanding in the 38th BImschV for the GHG reduction quota in Germany can become critical if "multiplier" and "adjustment factor for drive efficiency" in interaction certify a GHG reduction of about 550 gCO_2/kWh to the grey charging current with a de facto CO_2 intensity of 29 gCO_2/km (physically 68 gCO_2/km). With an electricity consumption of an electric vehicle of 20 kWh/100km, this would therefore correspond to a credited reduction by the charging current of about 110 gCO_2/km - for comparison: the target value from the fleet regulation for new registrations is currently 95 gCO_2/km. Such a generous crediting of charging current significantly lowers the incentives for fuel-distributors within the framework of the GHG quota in Germany, so that other avoidance options are not drawn and the actual CO_2 reduction in reality will be significantly below the value of the GHG quota (perspective -22% in 2030) on paper.

Conclusion: Climate protection impact of synthetic fuels greater than that of BEVs charged from the grid for the foreseeable future

Due to the fact that the so-called "Sustainability Criteria" of RED II applies to domestically produced synthetic fuels, but this criterion is not mandatory for domestic (German or European) charging energy, the physical emissions of an eligible synthetic fuel (incidentally also those of an eligible biofuel) are currently and in the medium term significantly below the physical emissions from European electricity production for BEV charging energy.

This does not take into account any distortions from multipliers - if these are designed in favour of the charging energy of BEVs, as seems to be the case, this environmental disadvantage will increase significantly.

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ANNEX B MODELLING OF THE POWER MARKET

In this study, we use Frontier Economics' power market model to assess the CO_2 intensity of charging energy. In the following, we describe the characteristics of the electricity market model and the key scenario assumptions used in this analysis.

Model properties

Our European power market model, which we use to answer the questions raised here, can be described as follows:

- **Objective function** - The "minimisation of the total cost of power generation in Europe ("present value today)" is formulated as the objective function. Included as the most important constraints of the optimization are among others
  - the coverage of the hourly energy balance in each region (with the possibility of supply restriction);
  - Transmission system capacity between regions; and
  - the technical and economic constraints of power plants, storage, renewables and demand side management (DSM).
- **Integrated investment and dispatch model** - The model is an integrated investment and power plant dispatch model. Thus, the optimization period is oriented to the lifetime of power plants (model optimized using sample years up to the year 2040), the temporal resolution is 4032 hours per sample year. In this stage, additions and removals in the European power plant fleet are modelled on the basis of aggregated power plant units, also taking capacity markets into account. In addition, the model is suitable for determining scarcity rents on the generation side for those model periods (sample years) in which the capacity supply is scarce in hours with high residual demand. This information is taken into account in the model when determining hourly electricity prices.

  The model is formulated as a **linear optimisation problem in GAMS.** Inputs and outputs are read in via Microsoft Access and Excel. The optimization problem is solved using the commercial solver CPLEX.
- **Model results** are, for example, hourly electricity prices based on short-term marginal costs for 4,032 hours per sample year. In addition, the detailed operating modes of the power plants, calls for load flexibility, power exchanges between model regions and other results can be generated from the model. In this project, this information is used to check the plausibility and explain the electricity price curves. In addition, in this step we generate the electricity prices (with corresponding electricity price volatility) by interpolation for the years that do not represent sample years ("intermediate years").

Scenario framework for the electricity market analysis

For a consistent and comprehensive market and environment scenario that is fully defined and self-contained, assumptions must be made about future development with regard to a number of parameters. In this study, we take the approach that

- the assumptions should come from **publicly available and known sources, if** possible;
- assumptions should **reflect recent developments**, such as those related to sector coupling, CHP targets, RE expansion, or technology developments; and
- should meet with the **greatest possible** public **acceptance.**

We use for this

- Relevant **available forecasts and assessments from** recognized sources (IEA, EIA, EU Commission, ENTSO-E, etc.) such as.
  - Ten-Year-Network-Development Plan und Scenario Outlook and Adequacy Forecast des ENTSO-E; oder
  - International Energy Agency: World Energy Outlook;
- **Data from relevant databases** (BNetzA power plant list, Platts database for power plants, ENTSO-E data for cross-border capacities, national statistics, etc.);
- **legislative texts and political programs** (in Germany, goals and resolutions of the German government on the energy transition, EU energy and climate packages, etc.).

In the following we describe the assumptions of the core parameters

Scenario assumptions - fuel prices

- **Short-term (until 2024) futures prices:** Prices for natural gas and hard coal in the period from 2021 to 2024 are based on futures for the respective year traded on the EEX[42].
- **Medium-term interpolation to IEA World Energy Outlook:** Medium-term fuel prices for coal and gas for 2025 to 2032 are based on an interpolation of futures prices (to 2024) and the forecast of the Stated Policies Scenario of the IEA World Energy Outlook (2019).[43]
- **Long-term orientation to WEO (Stated Policies Scenario):** In the further course to 2040, we also use the forecast of the Stated Policies Scenario of the IEA World Energy Outlook (2019) and interpolate the intermediate years.

The following price assumptions are made for the energy sources gas and hard coal:

- **Natural gas**: In the near term, based on prices of traded futures, the price of natural gas decreases slightly to €15(real 2017)/MWh by 2024. In the medium

[42] Trade Date 09/15/2019..

[43] The translation is based on an assumed exchange rate of 1.18 USD/EUR.

and long term, the price of natural gas is expected to recover to €25(real 2017)//MWh.

- **Hard coal:** For hard coal, we expect the low fuel prices (2020: < €6(real 2017)//MWh) to recover to around €9(real 2017)/MWh in the medium and long term.

Consistent with other fuel and commodity prices, we assume increase in CO_2 prices following the World-Energy Outlook 2019 from €25(real 2017)/tCO_2 in 2019 to about €30(real 2017)/tCO_2 in 2030.

Scenario assumptions - Regulatory framework

The market environment assumptions reflect what we consider to be the probable development of the main factors influencing the electricity market and, in addition to the political objectives in Germany, also take into account the current status of legislation in neighbouring countries:[44]

- **Long-term increase in electricity demand due to sector coupling** - We assume that power demand in Germany will remain almost constant in the years up to 2030. However, with increasing supply of electricity to the transport and buildings (heat) sectors, demand (net) increases significantly in the long term from 538 TWh in 2018 to 775 TWh in 2040. In the other modelled regions, there is also an increase in demand (+17% from 2018 to 2040). However, this is less pronounced than the increase in Germany.

- **Moderate increase in fuel prices** - The fuels coal and natural gas are currently characterized by a low price level on the relevant markets. We assume that this low price level (corresponding to currently traded future prices) will continue into the 2020s and that an increase will only take place in the medium term. However, fuel prices will remain below historically observed levels even in the long term (in 2040 natural gas: approx. €27/MWhth; hard coal approx. €9/MWhth). [45]

- **Long-term increase in CO_2 prices** - The price for CO_2 emissions is formed in European emissions trading (EU Emission Trading System, EU ETS). The price that arises in the market on the basis of current regulations is taken into account in the electricity market model using a predefined price path. For the years up to 2025, we use the prices of currently traded futures. In the long term, CO_2 prices increase in real terms to about 35 €/tCO_2 in 2040.[46]

- **Existing power plant park in Germany based on BNetzA power plant list** - The development of the power plant park in the core region results from the model-endogenous as well as the additions and reductions already known for certain today (for example, security readiness, nuclear phase-out).[47] For the

[44] When interpreting the results as well as the assumptions, it should be noted that the modelling is carried out in a simplified manner in the form of selected sample years, i.e. a "power plant decommissioning by 2025" is carried out in the interval 2020 up to and including 2024.

[45] IEA 2020, Stated Policies Scenario. Prices real, 2017.

[46] Ibid.

[47] The power plant operating times take into account the operating times and permits of the opencast mines assigned to the power plants in each case. An example of this is, for example, the Inden open pit mine and the connected Weisweiler power plant, which will cease operation around 2030 with the expected decarburization of the connected Inden open pit mine.

derivation of the initial value in Germany, we used the BNetzA power plant list; the initial values of the other countries are based on the Platts PowerVision database or national capacity balances of the transmission system operators as well as on our own research.

In addition to the model-endogenous addition and decommissioning decisions, we also specify key political cornerstones, such as the phase-out of coal-fired power generation or nuclear power generation, in the model.

- **Expansion of renewable energies** - The expansion of renewable energies in the core region is also model-based. In addition, we assume for Germany that the targets set today by the EEG (target corridor) will at least be met. We assume that the target of a 65% share of renewable energies in electricity consumption will be achieved in 2030.

ANNEX C MODELLING OF THE EU ETS (FRONTIER ECONOMICS)

The EU ETS is the central instrument at EU level for regulating emissions of CO_2 in the "public electricity & heat supply" sectors and certain energy-intensive industries. The amount of CO_2 that can be emitted annually is controlled by means of a fixed supply quantity. The EU climate targets are to be achieved in the long term via a declining path of the emissions cap.

In our EU ETS model (Frontier), we derive the annual supply and demand balance, the interventions of the Market Stability Reserve, and the cancellation of allowances from it. In the following we describe

- the parameterisation of the EU ETS supply volumes;
- the assumptions on the demand for allowances; and
- The analysis of charging energy.

Modelling of the EU ETS quantity structure under consideration of the climate targets of the EU Green Deal

For our modelling of the EU ETS, we assume that the stricter climate targets proposed by the European Commission as part of the EU Green Deal will lead to a tightening of the cap in 2030. The current regulatory framework provides for a -43% reduction in emissions by 2030 compared to 2005. With the implementation of the Green Deal and the raising of the EU-wide 2030 CO_2 reduction target from -40% to -55% compared to 1990, we assume a -62% reduction in supply in the EU ETS. This target value can be derived from the current sharing of mitigation efforts between ETS and non-ETS sectors (Effort Sharing Regulation). For the implementation of the EU Green Deal in the EU ETS, we use two scenarios in our modelling:

- **Scenario 1**: Raise LRF to from 2.2% to 4.6% starting in 2024; no changes to MSR rules (i.e., take-up rate drops from current 24% to 12% starting in 2023, as previously envisioned).
- **Scenario 2:** Raise LRF from 2.2% to 3.6%; maintain current MSR uptake rate (24%) beyond 2023.

Both scenarios lead to comparable net supply quantities in the sum of the measures LRF / MSR. In scenario 2, however, the cancellation of allowances by the MSR is more important than in scenario 1.

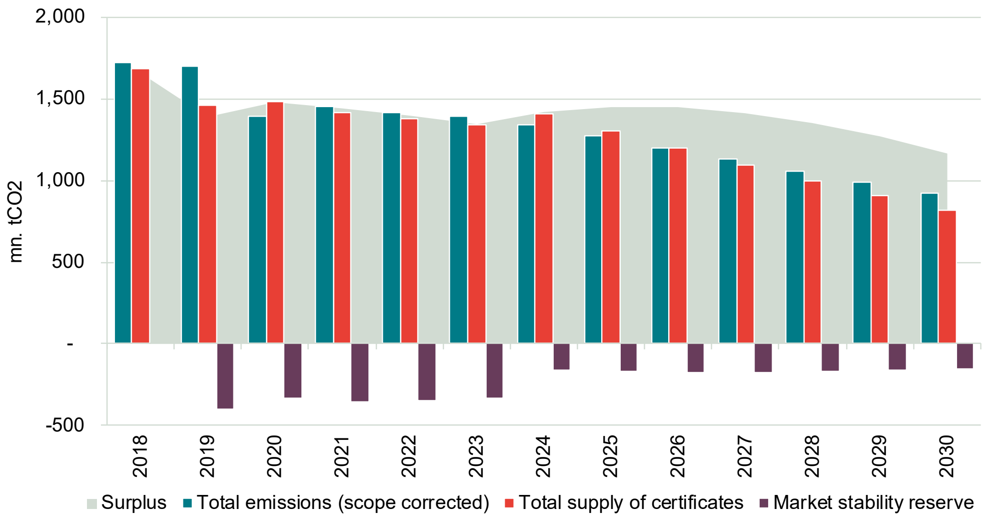
Demand for certificates assumed to fall due to decarbonisation of the economy

In our model, the supply in the EU ETS is matched by an exogenously determined demand. The demand for allowances takes into account major trends in decarbonisation of the sectors in the EU ETS, whereby we are guided by studies of the European Commission[48] or the European Network of Electricity Transmission System Operators.[49] In the short term, we also model a temporary drop in demand as a result of the COVID-19 pandemic.

- **Power sector:** Increase in power generation (EU-28) to > 3,400 TWh; of which approx. 62% from renewables and approx. 18% from nuclear in 2030; based on ENTSOE "Global Ambitions" scenario. Decarbonisation of the remaining power generation, among other things, through increases in CO_2 prices or national decisions such as the German phase-out of coal-fired power generation. In total, emissions from the EU power sector are assumed to decrease by approx. 65% compared to 2018.
- **Industrial sectors:** Our scenario for the decarbonisation of industry is based on the European Commission's "COMBO" scenario[50] and envisages a 30% drop in emissions intensity (tCO_2 / EUR value added). At the same time, we assume an approx. 15% increase in output, so that the emissions of the industrial sectors are assumed to fall by approx. 20% by 2030.

We then use the ratio of supply to demand in each year to derive the number of allowances that will be transferred to the MSR and then partially cancelled from it if the inventory in the MSR exceeds the previous year's auction share.

Figure 14 Development of supply-demand balance EU ETS (LRF: 4.6% after 2024).



Source: Frontier Economics

Evaluation of the charging energy

With the help of our electricity market model, we analyse which CO_2 intensity can be assigned to the charging energy. In doing so, we take into account the

[48] European Commission (2018): In-Depth Analysis in Support of the Commission Communication COM(2018)773 "A CLEAN PLANET FOR ALL - A EUROPEAN LONG-TERM STRATEGIC VISION FOR A PROSPEROUS, MODERN, COMPETITIVE AND CLIMATE-NEUTRAL ECONOMY", Brussels, 28 November 2018.

[49] European Network of Transmission System Operators Electricity (ENSTOE) (2020).

[50] European Commission (2018).

decarbonisation trends in the electricity industry described above and show a decreasing CO_2 intensity over time, which in 2030 is roughly equivalent to the emissions per kWh from a gas-fired power plant.

We then use the EU ETS quantity model to assess the impact of the additional emissions on the cancellation of allowances from the MSR. In doing so, we combine the "Central scenario" and "Low emissions" consumption scenarios with ETS scenario 1 and the "High emissions" consumption scenario with ETS scenario 2.

Table 3 ETS results: Low emissions

Low emissions	2022	2023	2024	2025	2026	2027	2028	2029	2030
Number of vehicles Fleet (million BEV)	1.68	2.47	3.26	4.05	4.84	5.63	6.42	7.21	8.00
Additional demand due to charging energy ($MtCO_2$)	1.11	1.67	2.14	2.57	2.83	3.01	3.12	3.16	3.14
Physical emissions per vehicle and year (10,000 km /a) (gCO_2/km)	**65.9**	**67.8**	**65.6**	**63.4**	**58.4**	**53.4**	**48.6**	**43.8**	**39.2**
Deletion of certificates from the MSR without ...	0	1,348	364	219	228	232	232	228	221
... and with consideration of additional charging current ($MtCO_2$)	0	1,348	363	219	228	231	231	227	220
Difference Deletion = De facto emissions ($MtCO_2$)	0.00	0.16	0.38	0.34	0.56	0.80	1.04	1.28	1.50
De facto emissions per vehicle and year (10,000 km /a) gCO_2/km	**0.0**	**6.6**	**11.6**	**8.5**	**11.6**	**14.2**	**16.3**	**17.7**	**18.8**

Source: Frontier Economics

Table 4 ETS results: Central scenario

Low emissions	2022	2023	2024	2025	2026	2027	2028	2029	2030
Number of vehicles Fleet (million BEV)	1.68	2.47	3.26	4.05	4.84	5.63	6.42	7.21	8.00
Additional demand due to charging energy ($MtCO_2$)	2.69	3.91	4.80	5.52	6.25	6.88	7.41	7.84	8.18
Physical emissions per vehicle and year (15,000 km /a) (gCO_2/km)	**106.9**	**105.7**	**98.2**	**90.9**	**86.2**	**81.5**	**77.0**	**72.5**	**68.1**
Deletion of certificates from the MSR without ...	0	1,348	364	220	229	233	233	230	223
... and with consideration of additional charging current ($MtCO_2$)	0	1,348	363	219	228	231	231	227	220
Difference Deletion = De facto emissions ($MtCO_2$)	0.00	0.42	0.93	0.82	1.30	1.81	2.34	2.89	3.43
De facto emissions per vehicle and year (15,000 km /a) gCO_2/km	**0.0**	**11.2**	**19.1**	**13.6**	**17.9**	**21.4**	**24.3**	**26.7**	**28.6**

Source: Frontier Economics

Table 5 ETS results: High emissions

Low emissions	2022	2023	2024	2025	2026	2027	2028	2029	2030
Number of vehicles Fleet (million BEV)	1.68	2.47	3.26	4.05	4.84	5.63	6.42	7.21	8.00
Additional demand due to charging energy ($MtCO_2$)	5.88	8.53	10.91	13.14	15.08	16.82	18.37	19.74	20.93
Physical emissions per vehicle and year (20,000 km /a) (gCO_2/km)	**174.9**	**172.6**	**167.4**	**162.3**	**155.7**	**149.3**	**143.1**	**136.9**	**130.8**
Deletion of certificates from the MSR without ...	0	1,349	365	364	353	345	341	340	340
... and with consideration of additional charging current ($MtCO_2$)	0	1,348	363	361	348	338	332	329	327
Difference Deletion = De facto emissions ($MtCO_2$)	0.00	0.91	2.04	3.59	5.35	7.22	9.11	10.96	12.74
De facto emissions per vehicle and year (20,000 km /a) gCO_2/km	**0.0**	**18.4**	**31.2**	**44.4**	**55.3**	**64.1**	**70.9**	**76.0**	**79.6**

Source: Frontier Economics

ANNEX D MODELLING OF EXPECTATIONS AND SUBSTITUTION EFFECTS

D.1 Consideration of expectations in the ETS model according to Rosendahl (2019)

Rosendahl (2019) argues that demand shocks resulting from environmental measures announced for the future influence market participants' actions today. This reduces the size of the substitution effect described in **section 3.4** and may even reverse the effect in certain cases.

Rosendahl presents this effect for the case of a policy-induced lower certificate demand due to the German coal phase-out. However, the arguments can be directly transferred to the case of higher certificate demand due to more electromobility. The logic is then that market participants already take into account a later demand shock at time X and the associated increased certificate prices in their behaviour today and therefore buy more certificates today to use them later at time X of the demand shock. This increased banking then leads to higher allowance prices and increased MSR. In the case where this increase in MSR is above the cap, this will also lead to increased cancellation of allowances before time X. From time X onwards, there is an increased demand and thus fewer deletions again. However, if time X is far in the future, it can happen that there are even more net deletions. This would then mean that the additional demand for certificates due to electromobility would actually lead to more emission savings. There would therefore be negative emissions. This is certainly a special case, but taking into account the expectations of the market participants in any case increases the amount of deleted allowances. Thus, the emissions attributed to a vehicle are lower than without taking this effect into account. In this sense, the previous estimates are an upper bound.

To simulate these effects, Rosendahl has designed a stylized model of the EU ETS that incorporates market participants' expectations. This model is used for this study to estimate the extent to which market participants' expectations might influence the effect of an EV increase on the EU ETS and MSR. Rosendahl has calibrated the demand function so that the model results in the real allowance price for 2019. However, he used the current LRF and MSR rates.

In order to be able to use the model also for the scenarios with changed ETS parameters (Higher LRF, current MSR parameters and Moderate LRF, stronger MSR), we recalibrate the emission reduction parameters from Rosendahl's demand function so that the resulting certificate prices correspond again to the real certificate prices. This is due to the fact that with a higher LRF or a stronger MSR, it can be assumed that market participants will adapt their production processes to the stricter EU ETS in order to have to demand fewer allowances.

For the simulations, this then results in additional demand for allowances to the extent of the physical emissions in each of the scenarios defined above until 2030. This implies that we assume a limited expectation horizon until 2030.

The following table shows the results for Germany already shown in the text compared to the results of a scenario in which the number of BEVs increases throughout the EU.

D.2 Price and substitution effects

In order to estimate the increase in certificate prices and the reduction in demand, the IfW-Rosendahl model is used on the one hand, and on the other hand, marginal abatement cost curves derived from the IfW-DART model (a general equilibrium model used for climate policy analyses) for 2030 for the EU and the German electricity and industrial sectors in the EU ETS respectively. The IfW-Rosendahl model takes into account the changes in the MSR, but contains only a rather aggregated function for the allowance demand. The marginal abatement cost curves in DART map the abatement costs in the respective sectors, but cannot capture the effects of the MSR. They can be used to estimate what the price and substitution effects would be without MSR. Together, this provides an estimate of the magnitudes to be expected. All values refer to the year 2030.

As in the core calculations, values are calculated for three scenarios, in this case also for the assumption of an EU-BEV scenario, since non-linear effects are to be expected here.

For the DART marginal abatement cost curve model, the already derived emissions of the additional BEVs are assumed as additional demand in the EU ETS for the respective scenarios. Since the three scenarios for the EU ETS cannot all be transferred, the current reduction factor of 2.2% per year is assumed here for the "Low Emissions" scenario, a reduction factor of 3% for the Central scenario, and a reduction factor of 4.6% for the "High Emissions" scenario. This factor determines the overall reduction in the EU ETS and the greater it is, the steeper the marginal abatement cost curves and the more expensive it becomes for each additional BEV electricity demand to meet the same targets.

For the IfW-Rosendahl model, all three EU ETS /MSR scenarios are calculated for the physical emission scenarios and the lowest/highest value is given in each case. This does not necessarily originate from the same scenario of the other MSR model used, as the consideration of expectations can lead to other orders as already explained in section 3.3.

Table 6 summarizes the results of the calculations discussed in **sections 3.3**. and **3.4.**

Table 6 Price and substitution effects in the EU ETS

	Low-DEU	Med-DEU	High-DEU	Low-EU	Med-EU	High-EU
ETS price increase per tCO_2						
DART	0,15 €	0,43 €	1,49€	1,35€	5,96€	18,11€
Rosendahl		0,11€ – 4,08€		4,52€ – 10,95€		
Emission reduction other sectors in Mt CO_2						
DART: EU power sector	2,94	7,63	19,39	25,82	97,99	210,06
DART: EU industry	0,19	0,53	1,54	1,73	7,09	17,23
DART: DE power sector	0,88	2,29	5,87	7,71	29,45	63,72
DART: DE industry	0,04	0,12	0,35	0,38	1,56	3,90
Rosendahl (% Red EU rel. to additional demand	13% – 345%			3% – 52%		
Additional demand for BEV certificates in Mt CO_2	3,14	8,18	20,93	27,61	105,26	227,14

Source: IfW

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