Pathways to a CO_2-free mobility system in Germany from a technological point of view

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1 Introduction

Mankind in 21st century is successfully striving for prosperity and better living conditions. In parallel, we recognize unusual climatic phenomena in everyday life. A climate change can be detected by everybody even without special instruments. Due to the high change velocity, the consequences affect mankind within one generation. The population reacts to this change with an increasing energy demand and more migration activities. This leads to a significant unbalance of our living space and fossil energy consumption on our planet.

The CO2 emissions on Earth are negatively influenced by unrestrained combustion and obstruction of photosynthesis as well as climate-damaging emissions by humans. Our Earth reacts with an increase of the mean temperature. Hence, the sea level rises considerably, weather phenomena like heat periods, floods and storms etc. increase dramatically.

The Global Carbon Project /1/ investigated the global relationships between the supply and absorption of CO2. Accordingly, our planets carbon footprint is increasingly out of balance, or rather, out of hand as shown in Figure 1.

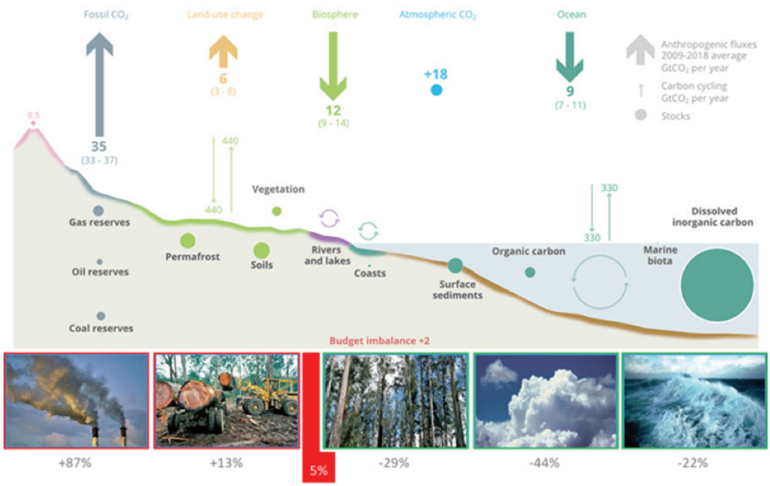

Figure 1: Disruption of the global carbon cycle due to anthropogenic activities (5% annually) /1/

CO2 emissions are released through fossil sources and land use, and on the other hand are stored through the biosphere, the seas and the atmosphere. The atmosphere is overloaded with CO2 and has to absorb an additional 2 Gt of the approx. 40 Gt of CO2 emitted per year. This increased concentration of CO2 on the Globus leads to global warming due to the reduction of infrared radiation into space.

In various scenarios, depicted in Figure 2, relations between the global CO2 emissions and a related global temperature increase was calculated. To comply with the results of the 21st United Nations Framework Convention on Climate Change in Paris from 2015 (COP21), a stabilization of the global warming between 1,5 and 1,8 ° C compared to the preindustrial age has to be reached.

For this purpose, an overall budget of 580 Gt was calculated with medium confidence /2/.The scenarios, marked in violet and blue, will reverse the climate change according to the COP21 target. The other CO2-scenarios create a high level of CO2 concentration in the atmosphere thus rising temperatures with exacerbating climate problems on our planet.

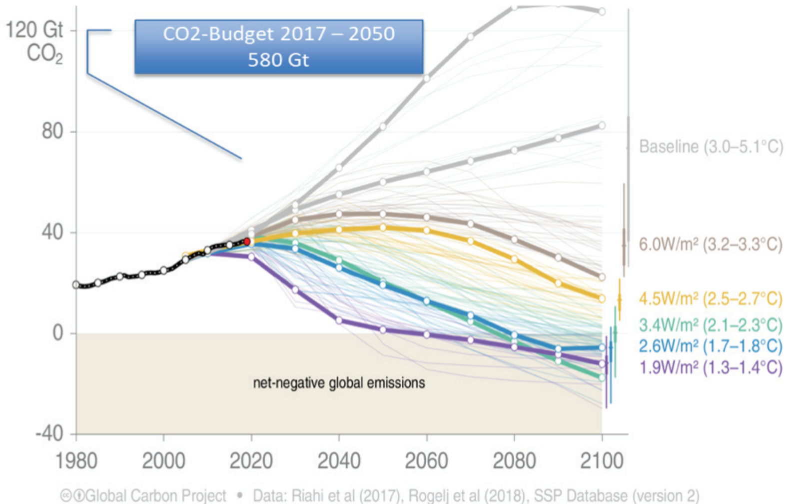

Figure 2: Target corridor for compliance with a global warming limit of 1.5- 2,0 ° C by reducing CO2 /1;2/

2 Transfer of the guidelines by the climate targets to the transport sector

In the further course we want to concentrate on the contribution of traffic and in particular on the share of car traffic in CO2 emissions as well as possible and necessary measures.

The transport sector in Germany is responsible for approx. 162 million tons of CO2 out of a total of 866 million tons in 2018 which is 19% of the total share. The biggest part of this is caused by car traffic with 61%. Commercial vehicle traffic accounts for 35% and all other modes of transport for the remaining 4% of CO2 emissions.

National air transport plays a subordinate role. In contrast to international aviation, which was deliberately excluded from the transport sector, but is limited in the EU by CO2 certificates. The CO2 emissions contributions calculated internally on the basis of the UBA and the Federal Statistical Office are significantly higher in international aviation /3; 4/.

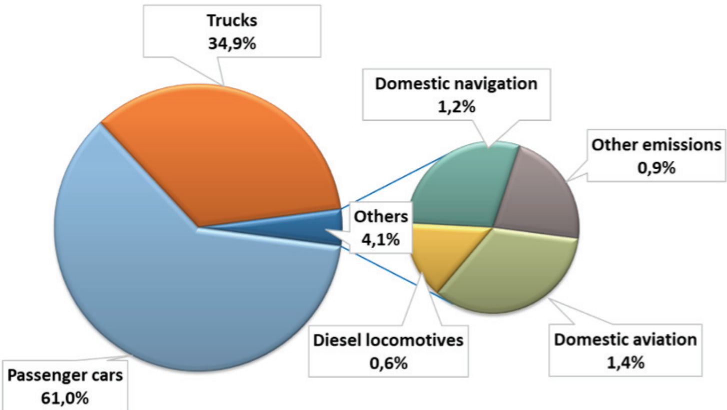

Figure 3: Share of the individual modes of transport in the CO2 emissions of the transport sector /3; 4/

This paper encompasses the simulation results of the CO2-emission of the German car traffic. In addition, the modeling enables the calculation of other modes of transport.

As stated at the beginning, the limitation of global warming to 1.5-2 ° C requires a restriction of the total global CO2 emissions to 580 gigantic tons in the period from 2017 to 2050.

The percentage CO2 reduction required for this was transferred to the CO2 emissions generated by German car traffic starting from 2017, hence, a CO2 emission budget for car traffic of 1,76 megatons in the period 2017-2050 could be calculated.

Figure 4 describes the percentage of reduction and the resulting CO2 emission budget for the car traffic in Germany. This shows that the annual passenger car CO2 emissions must be reduced to below 50% by 2030, based on the starting value in 2017.

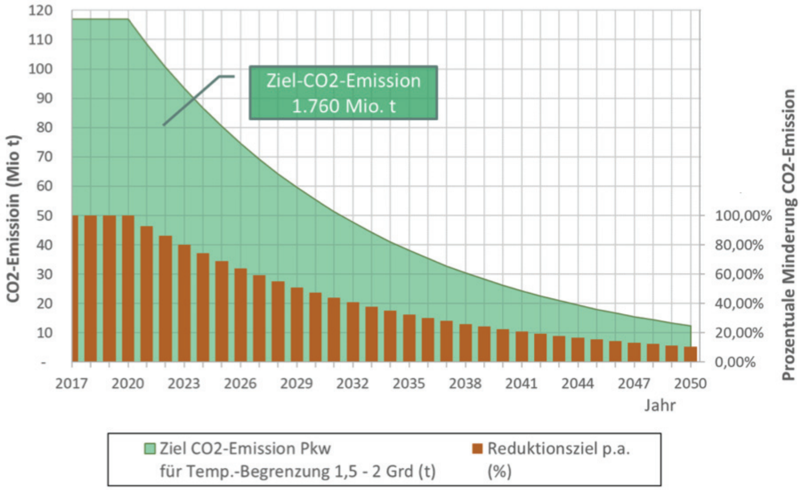

Figure 4: CO2 target emissions for passenger car traffic to limit global warming to 1.5-2.0 °C

3 Measures to reduce CO2 emissions in the car traffic sector in Germany

3.1 Examined scenarios and premises for the simulation

The EU emissions legislation for passenger cars currently requires a maximum fleet consumption of 95 g CO2 / km from 2020 /5/. This motivates the vehicle manufacturers to introduce electric vehicles and plug-in hybrids, as otherwise no series-compatible technology is available for a target-oriented reduction in CO2 emissions.

Against this background, several states, vehicle OEMs and political parties have communicated a replacement scenario for the internal combustion engine cars currently used. The table below shows the current decision situation. Only a few OEMs have published a clear position regarding an exit of the internal combustion engine (ICE) as a car powertrain. In summary, the automotive industry hopes to sell combustion engines by around 2040, followed by the market exit around 2050.

Table 1: Decision status for the exit of passenger cars with combustion engines /6; 7/

	New development		Sales until					Market exit	
Vehicle manufacturers									
Daimler	2020				2039				
VW, Audi		2026				2040			2050
Volvo						2040			
Political parties									
B.90/Grüne				2030					
Countries									
Norway			2025						
China				2030				2040	
Denmark				2030					
India				2030					
Iceland				2030					
Israel				2030					
California				2030					
Netherlands				2030					
Sweden				2030					
France						2040			
Great Brit.						2040			2050
Canada						2040			
Ireland							2045		
Taiwan							2045		
Germany									2050

A summary of the announcements from the political environment of the countries listed in Table 2 regarding the exit of the internal combustion engine (ICE) will lead to an end of sales by 2030 and a market exit by 2040.

Against this background, the following scenarios were chosen.They are encompassing the following criteria: Political and industrial announcements, the possibility of the visualization of important core parameters of the transition to electric powertrains.

Table 2: Key data for simulation scenarios

Scenario	Sales of ICE-PCs until	Market exit of ICE-PCs
1 Industry	2036	2048
2 Politics	2030	2042
3 Extreme	2029	2038

The actual course of future market development depends on many social and market-specific parameters at the beginning of a disruptive change process /8/ and can therefore only be simulated with restrictions. However, to demonstrate and investigate the core parameters of this transformation, the following premises and constants were used for all simulation calculations.

Table 3: Premises for simulation scenarios

Criteria	Definition
Replacement of ICE vehicles with electric vehicles	only
The number of passenger cars remains constant at	47.1 million
Average and constant vehicle service life	14 years
Average and constant electricity demand of the electric cars	20.4 kWh/100km
Average and constant CO2 emissions from ICE cars	181 g/km
Average and constant mileage per car and per annum	13.400 km/a

The emission of CO2 by electric cars essentially depends on the proportion of electricity generated from renewable sources. Based on the forecasts of the network operators /9/ with a regenerative share of 56% in 2030, 62% in 2035 and 71% in 2040, a maximum value of 80% in 2050 was extrapolated for the calculation of the scenarios. (See also figure 8)

3.2 Analysis of the simulation results

To calculate the scenarios, the period defined by the Global Carbon Project from 2017-2050 was considered. Figure 5 shows a comparison of the stocks of cars with ICE and electric drivetrains for the scenarios described using the assumptions made above.

The different introduction speeds of electric cars and the respective market exits of ICE cars are clearly visible.

The necessary new registrations of electric cars in Figure 6 show strong to considerable fluctuations, especially in the scenarios Extreme and Politics.

The reason for this undesirable behavior from a production perspective is shown as an example for the Scenario Extreme in Figure 7. As a result of the rapid market launch, high numbers of new car registrations are achieved in the area of market growth, which will be driven by a pull effect from a funding program and the fascination for the new drivetrain technology. If the car stock approaches saturation, the new registration drops sharply.

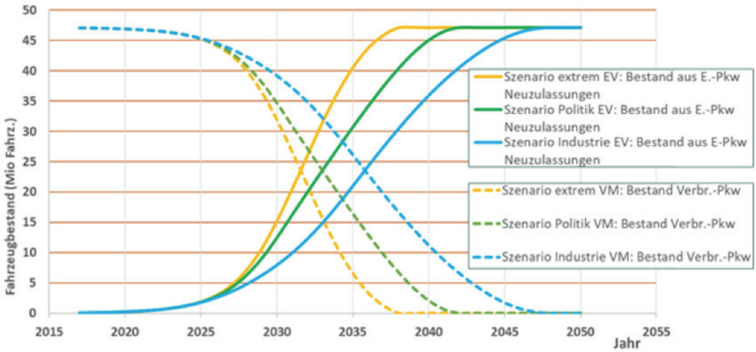

Figure 5: Comparison of car stocks in the extreme, politics and industry scenarios

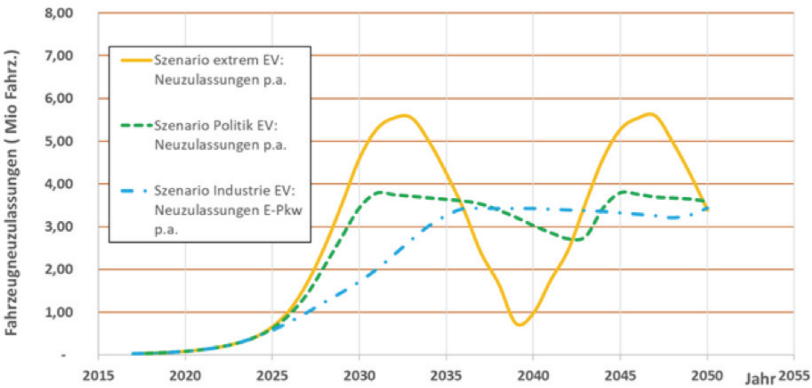

Figure 6: Comparison of new vehicle registrations (industrial, political and extreme scenarios)

After 2038, the car stock only consists of E.-cars with low replacements needs. This is due to the high introductions speed and cars live span of 14 years. The high introduction numbers at around 2032 are then causing a strong demand growth of car replacements in 2047. This analysis demonstrates the problems which will occur with an accelerated introduction of electric cars. The concerns of the car manufacturers to provide a feasible fluctuation of the vehicle production can therefore be understood. A mitigation of this problem is expected by linking several vehicle markets.

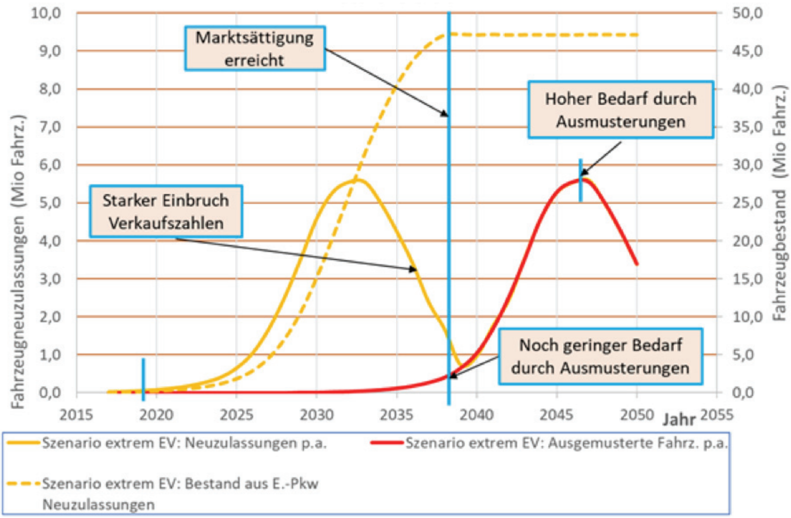

Figure 7: Comparison of the E.car registrations, vehicle stock and retirement (extreme scenario)

More effects of the introduction of electric cars, especially on CO2 emissions and electricity requirements are presented and analyzed for the scenario Politics. Figure 8 shows the course of the electricity demand for the electric cars together with the amount of

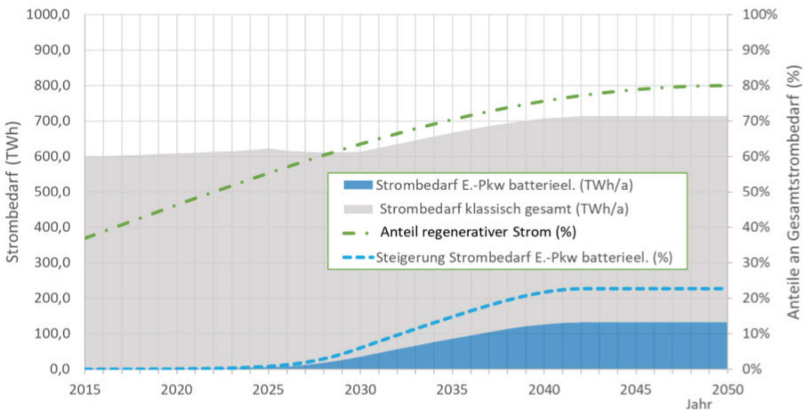

Figure 8: Gross electricity demand for electric vehicles scenario Politics

electricity required for all other consumers in Germany. The total requirement increases due to the transition to E.-cars from approx. 600 to 710 TWh annually. This is less than 25% of the total electricity demand in 2050. Furthermore, the previously mentioned introduction scenario of regenerative energy sources is depicted in Figure 8. The simulation result for the CO2 emissions to cover the electricity demand is shown in Figure 9. The steady reduction in CO2 emissions mainly results from the increase in electricity generated from renewable sources. It can also be seen that the increase in CO2 emissions from the operation of electric cars contributes by 20% to the CO2 emissions calculated for 2050 to cover the electricity demand.

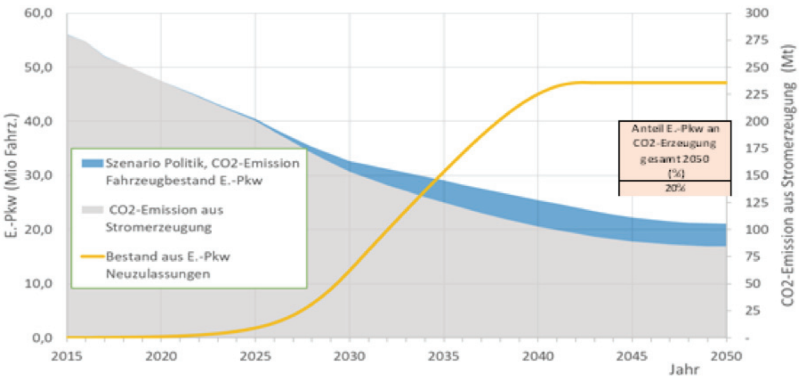

Figure 9: Overall CO2 emissions to generate the gross electricity demand (political scenario)

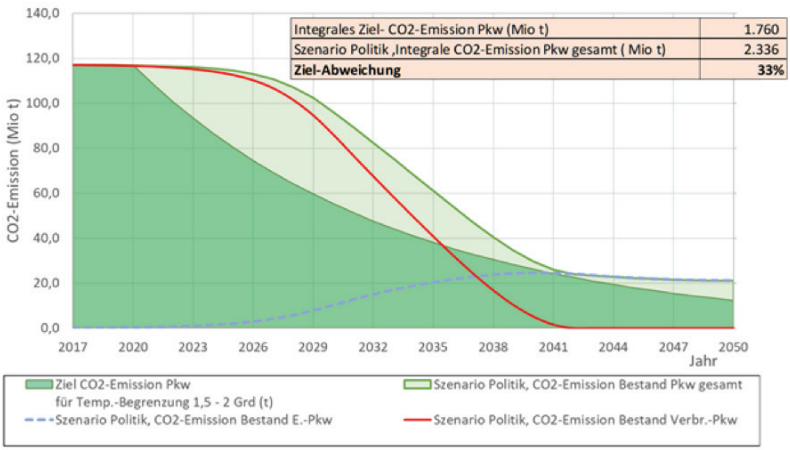

Figure 10: Comparison of CO2 emissions scenario Politics with the CO2 target value

Figure 10 shows the CO2 emissions of the scenario Politics for the entire car fleet, consisting of E.cars and ICE cars, compared to the CO2 target budget determined in Chapter 1. The evaluation of the integral under the envelope of both, ICE & E.cars, shows a significant deviation compared to the integral under the target curve. With the solitary introduction of electric cars and the defined increase in the share of renewable electricity, the goal of limiting global warming of <2 degrees will be exceeded by 33%.

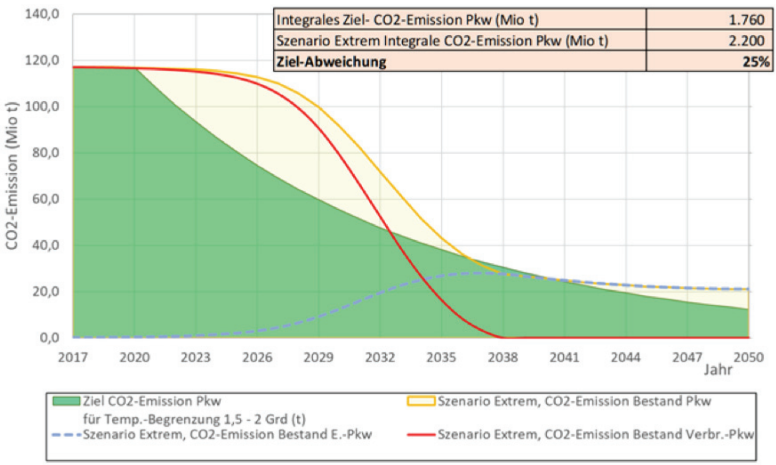

Figure 11: Comparison of CO2 emissions of scenario Extreme with the CO2 target value

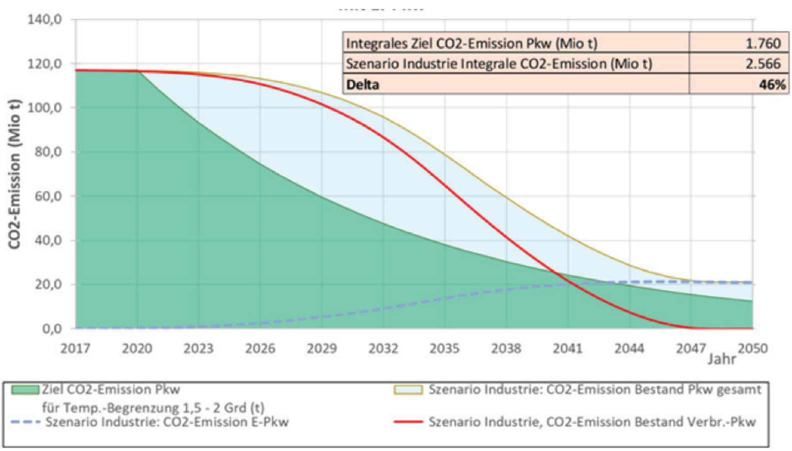

Figure 12: Comparison of CO2 emissions of scenario Industry with the CO2 target value

Figure 11 and 12 show the CO2 simulation results for the scenario Industry and Extreme. Even in the scenario Extreme (Figure 12) the CO2 target value will be overshoot by 25% The scenario Industry (Figure 11) leads to a CO2 target exceed by 46%. With the next simulation, the replacement of electric cars by fuel cell cars (FC cars) was calculated to demonstrate the effect on the CO2 emissions within the scenario Industry. The current state of development of FC cars, which does not allow a short-term entry into mass production, was disregarded. The efficiency of a FC drivetrain with 22% from the mains power supply to the wheel torque was used to calculate the electricity requirement and the resulting CO2 emissions. /10/ The same source calculates an efficiency for the E. drivetrains of 73%. This results in a significant advantage or E. cars, when using electricity as an energy source.

The operation of a FC car at the same driving conditions, requires approximately three times as much electricity as an E. car. Figure 13 shows the CO2 result for the FC car analogous to the other scenarios. The scenario Industry, operated with FC cars leads to

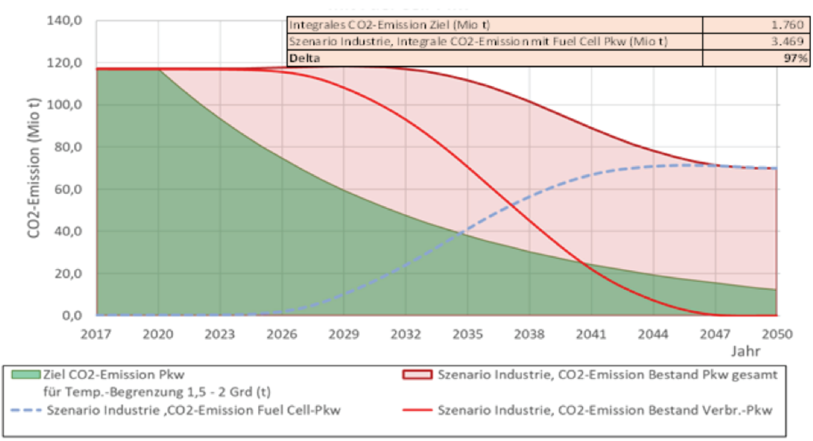

Figure 13: Comparison of the CO2 emissions in the industrial fuel cell scenario with the CO2 target value

the very sobering result with a target exceed by 97%. This is due to the poor efficiency in converting electricity into hydrogen and its subsequent conversion back into electrical current.

Conclusion from the CO2 calculation results:

None of the scenarios reach the target CO2 emissions. In particular, too much CO2 is emitted by the ICE cars in the period from 2020-2030. Measures that lead to a reduction in CO2 emissions in this time window must therefore be considered in order to achieve the defined CO2 budget. In the period from 2040 to 2050, a significant amount of CO2 will be emitted when generating the electrical power required for electric cars. Therefore measures to reduce the CO2 emission from the electric energy production are necessary.

3.3 Approach to limit global warming in accordance with the Paris climate protection agreement

Even in the scenario Extreme, the CO2 target will not be reached. Therefore, further CO2 reduction measures are required, which encompass an efficiency increase of the cars stock in combination with a reduction of the fleet mileage. In order to be able to evaluate their impact, a CO2 reduction field was introduced in the scenario Politics, which reduces the CO2 excess from 33% to the target level. (See Figure 14). This field fulfills the requirement for an immediate CO2 reduction with the ICE cars and the requirement for further measures in the electro mobile phase from 2040.

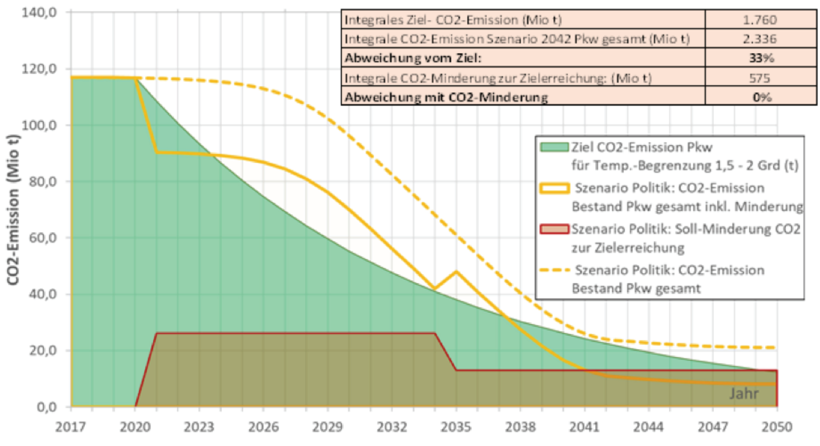

Figure 14: CO2 emissions in the scenario politics with CO2 reduction to achieve the target

In the following, the mentioned reduction field is used as the CO2 target to meet the car traffic CO2 budget. Table 5 describes measures that have been evaluated to achieve the goal together with an examination of their CO2 reduction type. In addition, the percentage of the CO2 reduction was estimated, and the earliest possible introduction date was defined.

Table 4: CO2 reductions to achieve the target value in the scenario

E cars	ICE cars	CO2 Reduction Type	Mitigation measures for CO2 reduction in car traffic	CO2 reduction	Introduction
X	X	Efficiency	Speed limit BAB 120 km/h, Bundesstrasse 90 km/h	3%	2022
X		Efficiency	Increase in the regenerative share of electricity mix to 87% in 2050	24%	2042
X	X	Mileage	Public ride app	5%	2025
	X	Efficiency	Bio share in fuel doubled to E20 & D14 (for all ICE cars)	3%	2025
X	X	Mileage	Public transport free in metropolitan areas, increase usage by 50%	6%	2025
X	X	Mileage	Attracting rail, increasing usage by 30%	3%	2025
X	X	Mileage	Avoidance of trips through by regulations (price, restrictions, ..)	6%	2025
X	X	Efficiency	Traffic control (congestion avoidance, avoidance of accelertion,..)	1%	2022

The reduction potential of these measures is summarized in Figure 15 and compared to the CO2 target field for ICE and electric cars.

For the following 2 years from 2020, no CO2 reduction is visible due to their ramp up. Furthermore, it can be deduced from this that politicians have not yet decided and implemented any significant CO2 reduction measures in the transport sector. This necessitates a consequent CO2 reduction following this dead time, especially for ICE vehicles in the time window 2025-2035.

From 2040, for the existing electric car fleet, the increase in the share of renewable electricity will lead to the desired reduction in CO2 emissions.

Figure 16 shows the comparison of the CO2 reduction in percentage of the defined measures for ICE- and electric powered passenger cars. For the ICE powered cars, the whole bundle of defined measures create the desired reduction. No measure can be avoided for the target fulfillment. For electric powered cars, the increase of the amount of regenerative electric energy is the crucial measure for the target fulfillment.

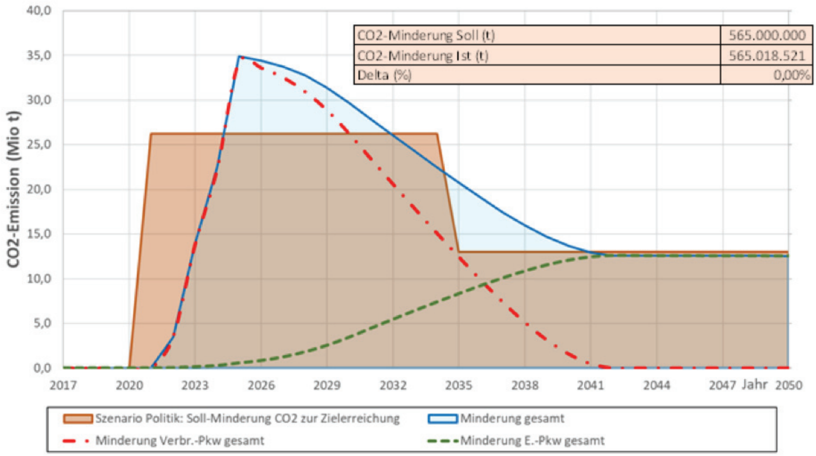

Figure 15: CO2 reduction from the reduction measures for the car fleet to achieve the goals with the Political Scenario

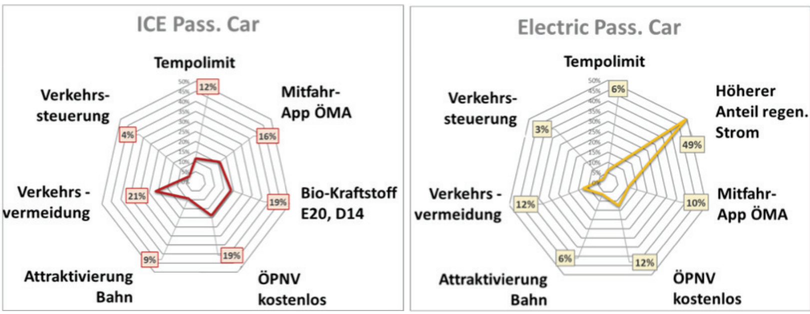

Figure 16:Comparison of CO2 reduction in percentage of the defined measures for ICE- and electric powered passenger cars

4 Summary

The present study shows that an introduction of electric passenger cars is not sufficient to reach the CO2-reduction targets according to the 21st United Nations Framework Convention on Climate Change in Paris from 2015. Additional measures have to implemented as soon as possible to preserve a chance of a target fulfillment.

The introduction of these measures which also consist several restrictions, will create a significant impact of our mobility habits. Scientists and politicians are confronted with the task to explain the society the urgent status and the need of this change.

The upcoming crisis of the current ICE orientated mobility industry will increase the social and economic challenges of this transition. However, the measures listed in this study are manageable for our society and will influence our quality of life in a mid term rather positively. In the long term anyway through the sustainable climate effects.

Unfortunately, the currently decided “climate package” and the results of the climate conference in Madrid in December 2019 suggest that our politicians and the global community does still not work serious enough to solve our climate problems. It is five past twelve. There is nothing good unless to do it!

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