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Market prospects of electric passenger vehicles and their effect on CO_2 emissions up to the year 2030 – A model based approach

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Abstract

A method for assessing the potential and costs of various technologies for CO_2 emission reduction of passenger cars, using a newly built computer model, is presented. A variety of vehicle technologies, each with different attributes regarding CO_2 emissions and costs, is simulated for the supply side, as well a variety of different synthetic customer groups for the demand side within the model. An econometric based selection process calculates the number of each type of new vehicle sold in any year of the simulation. Hence, deriving future market shares of vehicle technologies and overall CO_2 emissions is possible.
The detailed technology database used for calculations includes conventional vehicle propulsion technologies as well as innovative vehicle concepts (battery electric vehicles, extended range electric vehicles, fuel cell vehicles). Cost degression effects for new technologies are incorporated using learning curves, with costs depending on the cumulative number of vehicles sold. Different types of fuels and influence of crude oil price on fuel prices are taken into account, as well as different taxation systems.
Using the model, different scenarios for future development of CO_2 emissions of the new vehicle fleet as well as the vehicle stock are evaluated for the time period 2009-2030.

1 Introduction

There exist numerous ideas for technologies, alternative propulsion systems and fuels with the objective of lowering CO_2 emissions from transport. However, prospects of success are difficult to determine as they depend on a complex overall system, including technology costs, energy prices, taxation and customer decision. Tools for modeling this complex system are needed in order to assist with policy decisions, e.g. on investing in new technologies or infrastructure. A computer model, called *VECTOR21*, is newly developed by the authors. It allows incorporating essential influencing parameters and therefore profound analyses of scenarios regarding future market shares of various vehicle technologies and their influence on CO_2 emissions. It is the objective of this article to give an insight into the technology database used in the model, to explain the structure and methodology of the model and to discuss two exemplary results of model calculations. Focus of the examination is on passenger cars in Germany up to the year 2030.

2 Technology Database

Basis for all calculations using *VECTOR21* is an extensive database on vehicle technologies and their effects with regard to energy consumption and costs. A broad range of potential future combinations of vehicle propulsion and energy storage types is covered by the database:

- conventional gasoline and gasoline hybrid electric (HEV) vehicles
- conventional diesel and diesel HEV vehicles
- conventional compressed natural gas (CNG) and CNG HEV vehicles
- extended range electric vehicles (EREV)
- battery electric vehicles (BEV)
- fuel cell hybrid electric vehicles (FCHEV)

Vehicle energy consumption

For each type of vehicle system and size category (small, medium and large), specific energy consumption of a baseline variant is estimated, using data from in-house simulations [1] and literature [2]. Due to reflecting real-world driving conditions, values tend to be higher than in New European Driving Cycle (NEDC).

In addition to baseline energy consumption a number of potential measures for reducing specific energy consumption is identified. These include e.g. direct injection for gasoline vehicles, downsizing and turbo charging, variable valve control and reduction of vehicle curb weight. For each individual technical measure the effect on specific energy consumption of the baseline vehicle is estimated using detailed data from various literature sources (e.g. [3]).

Energy consumption saving potentials of individual measures cannot be added up. Therefore, for each type of vehicle system and size category, several fuel economy packages are defined. These packages are combining a set of individual technical measures and are indicating an overall influence on energy consumption of the baseline vehicle.

Figure 1 illustrates a database excerpt for a medium size gasoline vehicle. Energy consumption of the baseline vehicle is 2.65 million joule per kilometer (MJ/km). A selection of potential individual technical measures to reduce energy consumption of the vehicle is given below, resulting in five fuel economy packages with effects on specific energy consumption ranging from -8 to -40 %. The most advanced vehicle variant, without consideration of hybridization, features an energy consumption of 1.59 MJ/km.

	Fuel Econ. Packages					Energy Cons.	Production Cost	Retail Price
Baseline Vehicle						**2,65 MJ/km**	**9.337 €**	**15.000 €**
Individual Measures								
Reduced engine friction losses	X	X	X	X	X	-3,0%	70 €	112 €
Direct injection: homogeneous charge		X	X	X		-2,0%	150 €	241 €
Direct injection: stratified charge					X	-8,0%	700 €	1.125 €
Medium Downsizing with turbocharging		X	X			-5,0%	200 €	321 €
[...]								
Improved transmission (e.g. Dual-Clutch)			X	X	X	-4,0%	350 €	562 €
Weight reduction: package 1 (mild) = 1,5% veh. weight (20 kg)		X	X			-1,0%	120 €	193 €
Weight reduction: package 2 (medium) = 3,5% veh. weight (50 kg)				X		-2,0%	300 €	482 €
Weight reduction: package 3 (strong) = 9,0% veh. weight (120 kg)					X	-5,0%	720 €	1.157 €
Fuel-Economy Packages								
G_FE#01	X					-8,0%	300 €	482 €
G_FE#02		X				-17,0%	870 €	1.398 €
G_FE#03			X			-24,0%	1.490 €	2.394 €
G_FE#04				X		-34,0%	2.645 €	4.249 €
G_FE#05					X	-40,0%	3.615 €	5.807 €
Best available vehicle (medium size gasoline, no hybrid)					X	**1,59 MJ/km**	**12.952 €**	**20.807 €**

Figure 1: Individual technical measures and fuel economy packages (medium size gasoline vehicle)

All fuel economy packages are treated as optional add-ons to a baseline vehicle in the model. Therefore, the model automatically generates a range of vehicle variants, each equipped with a different set of fuel economy packages, representing the supply side of a virtual new vehicle market.

Vehicle production costs and retail price

Manufacturing costs for gasoline, diesel and CNG vehicles are estimated based on sales prices of currently available passenger car variants. In order to derive overall production costs for other vehicle types, individual costs for non-necessary technical parts are deducted and costs for supplementary necessary parts, according to literature data (e.g. [2],[3]), are added. For example, for HEV vehicles costs for a standard ICE alternator and starter are credited, while costs for a battery, an electric motor and several other system components are added.

Furthermore, for each technical measure to reduce energy consumption previously identified, production costs are estimated and summarized in order to define overall costs of available fuel economy packages. Figure 1 illustrates the process of costs definition for the example of a medium sized gasoline vehicle. It becomes obvious that ambitious fuel economy packages come at high investment costs, e.g. more than 3.500 € for package #05 with an energy consumption reduction potential of -40 %.

For conversion of production costs in retail prices a factor 1.35 is applied, as discussed in literature [3]. This mark-up includes profit of the vehicle manufacturer as well as costs and profit of dealership. Furthermore, value-added tax (VAT) is added on top.

Costs for batteries and fuel cells

For new technologies, like batteries and fuel cells, production costs strongly depend on experience gained from manufacturing processes at increasing numbers of units produced. In order to incorporate this effect, technology database production costs for batteries, fuel cell system components, electric motors and other similar parts are defined using learning curves. For each component a learning rate is given, indicating the relative reduction of production costs for each doubling of the cumulative number of units produced [4].

Current production costs for high-energy Lithium-ion batteries for use in vehicles are at approx. 500 to 1,000 €/kWh [5]. A detailed bottom-up cost estimate, taking into account materials needed and their chemical as well as physical properties, assesses manufacturing costs of approx. 200 to 300 $/kWh as being realistic for mass production volumes [6]. Potential for cost reduction mainly comes from application of improved materials for electrodes and conducting salts (learning-by-searching), optimization of production processes (learning-by-doing) and higher quantities ordered of raw materials (economies of scale). Summarizing publicly available recent cost estimates for Lithium-ion batteries leads to the conclusion that future cost reduction would follow a learning curve with a rate of approx. 88 % (figure 2), i.e. manufacturing costs would be reduced by 100 - 88 = 12 % for each doubling of cumulative number of units produced.

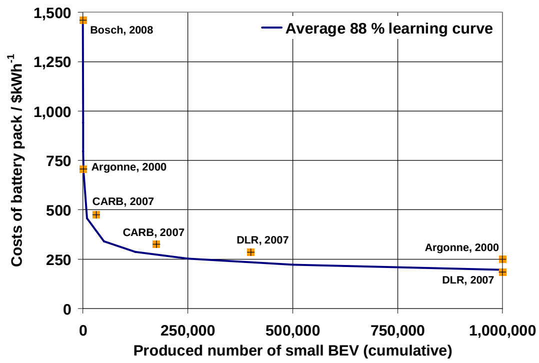

Figure 2: Production cost estimates for high-energy Lithium-ion battery packs [5, 6, 7, 8]

For fuel cell stacks, platinum loading of the catalyst, necessary for a fast running fuel cell reaction, has been reduced remarkably in the past. Recent analysis indicates only 10 to 20 % of the catalytic material being active during reaction, a further reduction of platinum loading therefore appears realistic. Meanwhile, power density of the fuel cell stack has been improved significantly to approx. 600 mW/cm² today. Continuing improvements of materials and production processes lead to the expectation of considerably decreasing manufacturing costs of fuel cell systems for high production volumes in the future. As shown in figure 3, for PEM fuel cell stacks future manufacturing costs of approx. 12-40 $/kW could be achieved for a cumulative number of 1 million fuel cell vehicles produced, compared to approx. 1,000 $/kW today [9].

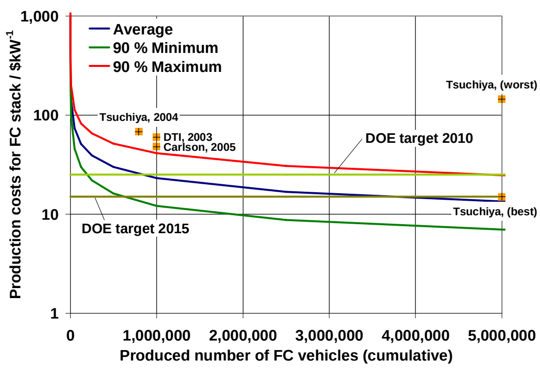

Figure 3: Production cost estimate for fuel cell stacks for platinum market price 20,000 $/kg [9, 10, 11, 12]

3 Scenario model

Using *VECTOR21*, data on vehicle energy consumption as well as costs is combined with relevant boundary conditions, including energy prices and taxation, in order to model customer purchase decision and to determine profound scenarios on future market shares of vehicle technologies and their effect on CO_2. The model is divided into two major parts: vehicle manufacturer behaviour (supply side) and customer behaviour (demand side).

3.1 Supply side

Similar to reality, a broad range of vehicle variants with individual energy consumption and retail price is offered to customers in each year of the analysis by combining baseline vehicles with previously identified fuel economy packages and incorporating the results on vehicle energy consumption from chapter 2.

For innovative vehicle technologies with a learning curve rate used to describe future development of production costs, the cumulative number of units sold in previous years is used by the model to derive manufacturing costs in the current year. In the beginning of production of a new technology, it is necessary for the manufacturer to subsidy these vehicle variants (see e.g. first generations of Toyota Prius) in order to attract potential customers and to build up an increasing number of sales for lowering production costs according to learning curve theory. With increasing units produced, manufacturer subsidies are automatically reduced by the model, finally leading to the standard mark-up rate applied to all conventional technologies.

For modeling the supply side for fuel and electricity, sales prices may be directly predefined by the user or alternatively are calculated according to crude oil price development, using calculation factors previously derived from an analysis of historical correlations of crude oil and fuel prices. For each fuel type, as well as for hydrogen and electricity, it is possible to define a separate fuel tax and VAT. Similarly, raw material price developments may also be taken into account. E.g. it is possible to connect platinum price with the overall price for a fuel cell stack in order to achieve a more dynamic and realistic modeling.

For vehicle technologies which require installation of a novel infrastructure for vehicle refuelling and maintenance services, the investment and time necessary is reflected by restricting the technology to more innovative and therefore less demanding customer types at first. Following a time delay of approx. 5 years, the respectively next adopter group is allowed to purchase the affected vehicle variants, assuming that infrastructure density would be sufficient by then [13].

3.2 Demand side

Research indicates that vehicle purchase decision involves a high cognitive effort with vehicle size, safety and price ranking at top priority of most important criteria to customers. Environmental issues are also often considered important, however at almost no willingness to pay an additional charge [14].

Therefore, for modeling customer purchase decision, a three-step approach is implemented:

- Step 1: Reduce the number of available vehicle variants by choosing a size category and filtering for general compulsory requirements.
- Step 2: Within remaining variants choose the ones with lowest total cost of ownership (TCO).
- Step 3: Finally, choose the vehicle variant with lowest WTW CO_2 emissions.

Step 1 is based on the assumption that customers generally select an appropriate vehicle size category based on their everyday needs, as well as a vehicle variant which satisfies basic requirements, e.g. regarding a certain minimum driving range. Nevertheless, it is evident that this decision often is made on a non-rational basis, e.g. when buying a vehicle excessively large due to prestige reasons. Therefore, for step one market shares of vehicle size categories, as well as general compulsory requirements to be satisfied by the vehicles considered, are to be predefined by the user and are not modeled implicitly.

Following the pre-selection step 1, customers are supposed to react rational on the basis of TCO when choosing a vehicle variant within a certain size category. TCO here include all relevant costs, such as vehicle purchase price, annual ownership tax and costs for fuel, calculated over a time period of 4 years to reflect the average time horizon for return of investment of new vehicle's purchasers.
Depending on the type of customer examined an additional willingness-to-pay for technically more advanced vehicles is found. In order to reflect this behaviour adequately, 5 different types of adopters are defined in the model: a small group of "innovators", a somewhat larger group of "early adopters", two major groups "early majority" and "late majority", as well as the group of "laggards" (s. [15] for a detailed description of the adopter groups). Willingness-to-pay, and more generally the grade of innovativeness, is highest for the group of "innovators" and decreases gradually towards the group of "laggards".
Each adopter group within a vehicle size category furthermore is differentiated into 60 subgroups with annual mileages from 1,000 km to 60,000 km. In total, there are 900 different types of customers in the model, which allows a precise calculation of TCO based on annual mileage (s. figure 4).

In step 3, among the remaining vehicle variants with lowest TCO, the one with lowest WTW CO_2 emissions is selected, in order to reflect customer's awareness for environmental topics within their individual price ranges. Limited pollutants (e.g. NO_x) are not taken into account at this point but may be included in the analysis in the future.

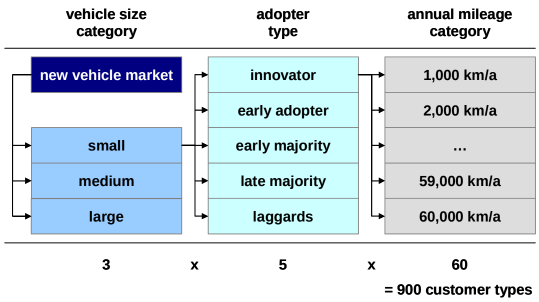

Figure 4: Schematic illustration of customer subgroups within the model *VECTOR21*

3.3 Verification

The functionality of the model *VECTOR21* is verified using a historical case study. The increasing proportion of diesel passenger cars in Germany between 1995 and 2008 is a suitable example with detailed information available for relevant input and output parameters.

All relevant input data, e.g. fuel prices, vehicle prices and taxation, are aligned to historical data and model calculation is carried out. Figure 5 demonstrates the result, the development of proportion of diesel passenger cars for three individual vehicle size categories as well as for the sum of all vehicles.

As shown, calculated evolution for medium and large vehicles is close to historical developments, whereas calculated diesel proportion is higher than historical values for small size vehicles. This is due to an unavailability of a sufficient selection of small diesel passenger vehicles during the 1990s, as well as to investment budget restrictions for many small vehicle size customers preventing them to buy diesel vehicles with higher investment costs but later on possibly lower TCO. Overall, the calculated evolution for average diesel passenger car share corresponds very well to historical values.

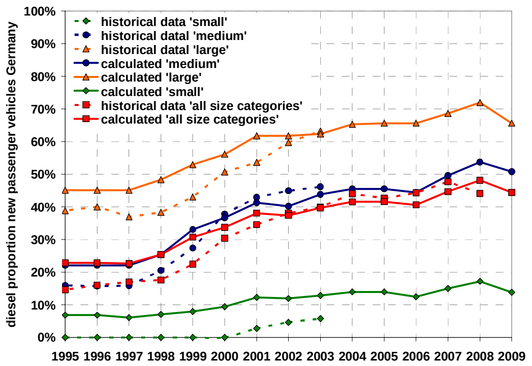

Figure 5: Model results vs. real historical developments for the proportion of diesel passenger cars in Germany

4 Modeling market prospects and environmental impacts

For assessing future market prospects and environmental impacts of electric vehicles in consideration of concurrency with conventional propulsion technologies, two scenarios for the German passenger car market are analyzed using *VECTOR21*.

4.1 Key assumptions

Scenario 1 is defined as a business-as-usual scenario with only minor changes compared to nowadays situation. Crude oil price, and therefore prices for conventional fuels, increases moderately. The proportion of bio-fuels increases to 15 % in 2030. Electricity is generated according to the German national power station mix, with a moderately increasing share of renewable sources by 2030. Hydrogen is produced from natural gas at first, and from electricity later on. A new tax for electricity and hydrogen in transport is stepwise introduced beginning in 2018 to compensate for fuel tax deficits due to an increasing share of electric vehicles.

Starting in 2015 a target value for average CO_2 emissions of the new vehicle fleet is introduced, with a penalty to be paid for every gram of CO_2 exceeding the target level.

The maximum willingness to pay more for a low-CO_2 vehicle is set at 20 % for the adopter group of the "innovators" and consequently lower for the following adopter groups (0 % for laggards).

The number of new vehicles is kept constant at today's level of approx. 3.1 million passenger cars, with an increasing share of small and large vehicles at the expense of a decreasing share of medium size vehicles (see table 6 for a summary of assumptions).

Scenario 2 is set up to reflect stronger governmental intervention in view of impending climate change. Electricity for transportation now is generated solely on the basis of renewable sources, at higher prices than in scenario 1. Hydrogen is produced using electricity, accounting for efficiency loss due to electrolysis process and distribution. The price for hydrogen is assumed to be similar to electricity, due to non-applicable grid utilization charges. The proportion of bio-fuels is higher then in scenario 1 and the new vehicle CO_2 emission target values and penalty levels are stricter. (s. table 1).

4.2 Results – new vehicle fleet

Figure 6 shows the results of the two scenarios for the new vehicle market in Germany between 2010 and 2030.

Table 1: Summary of scenario assumptions

	scenario 1		scenario 2	
	2009	2030	2009	2030
crude oil price	54 [€/bbl]	65 [€/bbl]	54 [€/bbl]	65 [€/bbl]
proportion of bio-fuels	0-8 %	15 %	0-8 %	25 %
electricity – CO_2 emission	600 [g/kWh]	550 [g/kWh]	21 [g/kWh]	20 [g/kWh]
electricity – consumer price	0.18 [€/kWh]	0.35 [€/kWh]	0.21 [€/kWh]	0.37 [€/kWh]
hydrogen – source	natural gas	electrolysis	electrolysis	
hydrogen – CO_2 emission	350 [g/kWh]	650 [g/kWh]	25 [g/kWh]	24 [g/kWh]
hydrogen – consumer price	0.13 [€/kWh]	0.35 [€/kWh]	0.21 [€/kWh]	0.37 [€/kWh]
CO_2 – new vehicle fleet target	---	113 [g/km]	---	76 [g/km]
CO_2 – penalty for exceeding	---	95 [€/(g/km)]	---	120 [€/(g/km)]
market share small / medium / large	25 / 55 / 20 %	30 / 45 / 25 %	25 / 55 / 20 %	30 / 45 / 25 %

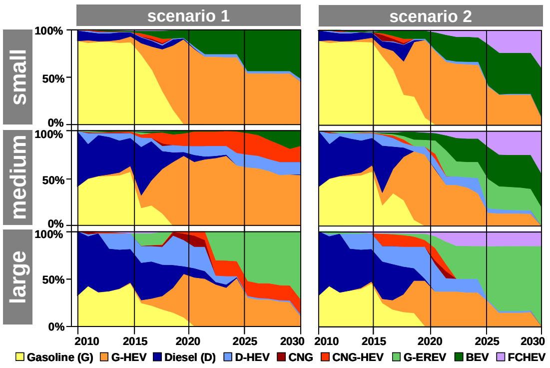

Figure 6: Market shares new vehicle market – differentiated by size categories

For the small vehicle size category gasoline cars (G) dominate the market nowadays. According to calculations, in both scenarios gasoline hybrid (G-HEV) variants would enter the market in large numbers between 2015 and 2020, as CO_2 target values are tightening and production costs for HEV are decreasing. Especially in scenario 2 diesel (D) and CNG vehicles would be successful during a short period of time between 2015 and 2020, as CO_2 target values are tightening and alternatives are not yet competitive. Starting in 2015 BEV would enter the market in significant numbers, consequently further decreasing production costs due to learning curve effects and therefore increasingly displacing conventional technologies. A maximum market share of 50 % was set for BEV to reflect existing customer concerns regarding the driving range of the vehicles. FCHEV would enter the market for a short period of time in scenario 1, only as long as these vehicles are subsidized by governmental funds.

In contrast, in scenario 2, FCHEV would penetrate the market in the long run and achieve market shares as high as 40 % by 2030. The remarkable success of BEV and FCHEV in scenario 2 is due to strict CO_2 regulations which enforce vehicle technologies with low TTW emissions, and furthermore due to electricity and hydrogen being produced from renewable sources, making BEV and FCHEV attractive from a customer point of view during vehicle purchase decision process. A EREV was not included in the analysis for the small vehicle size category, a fact which supports the selection of FCHEV for customers with high annual driving ranges who are not willing to buy BEV.

For the medium size vehicle category today's market is divided almost equally into gasoline and diesel vehicles. According to calculations, by 2015 G-HEV would enter the market significantly, as CO_2 target values are introduced. Additionally, D-HEV would penetrate the market. Nevertheless, by 2030 in total the proportion of diesel vehicles would reduce in both scenarios to approx. 15 % in scenario 1 and almost 0 % in scenario 2. A reason for the decreasing diesel proportion is seen primarily in higher technical potential for improvement for gasoline vehicles at similar costs. CNG vehicles would achieve a significant market share of approx. 20 % in scenario 1, but entering only temporarily in scenario 2 until being displaced by electric vehicles. In scenario 1, electric vehicles are penalized due to their relatively high WTW CO_2 emissions, as electricity and hydrogen would be produced using fossil energy sources. BEV would achieve market shares of approx. 15 % by 2030, EREV would enter only temporarily until a tax for electricity in transport would be introduced starting in 2018, and FCHEV would leave the market as soon as subsidies would be stopped. In contrast, in scenario 2, electric vehicles would achieve significantly higher market shares by 2030 (BEV 35 %, EREV 20 %, FCHEV 45 %). Crucial for this development are low CO_2 emissions due to the usage of renewable energy sources for production of electricity and hydrogen as well as strict CO_2 target values, increasing the price of conventional technologies with higher TTW emissions due to penalty payments.

In the large vehicle size category the proportion of diesel vehicles would remain at approx. 30 % until 2020, but would decrease significantly afterwards. CNG vehicles would enter the market only temporarily in scenario 2 until being displaced by electric vehicles, but penetrate the market (approx. 15 %) in the long run in scenario 1. EREV would be successful in both scenarios starting in 2020, with market shares of approx. 70 % / 85 % by 2030. Similar to the small and medium vehicle size categories, FCHEV would enter the market only temporarily in scenario 1, while in scenario 2 achieving a market share of approx. 15 % by 2030.

Figure 7 summarizes the results for the individual vehicle size categories. Scenario 2 is more dominated by electric vehicles and especially FCHEV, whereas the focus in scenario 1 is more on G-HEV, D-HEV and CNG-HEV.

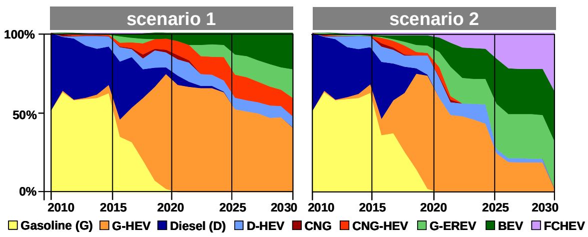

Figure 7: Market shares new vehicle market – sum of all size categories

Figure 8 shows the development of the average CO_2 emissions of the new vehicle fleet for both scenarios. In scenario 1 it would be possible to reduce average TTW emissions from approx. 162 g/km today to as low as 75 g/km by 2030. Due to an increasing share of electric vehicles and the use of electricity and hydrogen from fossil sources, well-to-tank (WTT) emissions would increase from approx. 22 g/km in 2010 to approx. 31 g/km by 2030. In scenario 2, with a higher proportion of electric vehicles and at the same time renewable sources for electricity and hydrogen production, CO_2 emissions would reduce from approx. 162 g/km to approx. 17 g/km (TTW) and from approx. 22 g/km to approx. 3 g/km (WTT).

Costs from a customer point of view would increase in both scenarios. TCO would increase from approx. 25,000 € in 2010 to approx. 29,000 € in 2025 and then decrease to approx. 28,000 € by 2030. This is due to increasing prices for fuels as well as higher average sales prices for vehicles, as CO_2 penalties have to be paid or costly innovative technologies have to be applied. With increasing production volumes for new vehicle technologies, and therefore cost degression effects, TCO tend to decrease again.

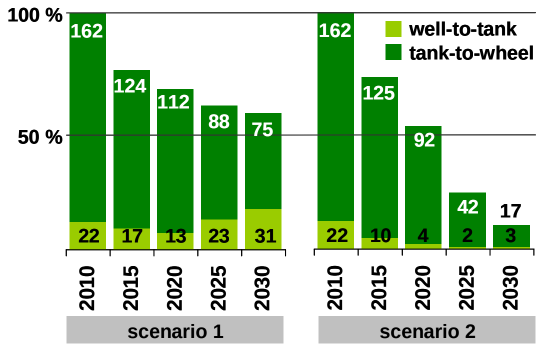

Figure 8: CO_2 emissions new vehicle fleet [g/km]

From a manufacturer's point of view extra costs would apply temporarily, as new technologies, e.g. BEV and FCHEV, would have to be subsidized at the beginning. Manufacturer's profit would be reduced by approx. 5 % in 2012 (the first year of introduction of FCHEV) compared to 2009 in scenario 1 and approx. 8 % in scenario 2. However, in the long run profits would tend to be higher in scenario 2, as it is assumed for the analysis that with increasing production volumes mark-ups for new technologies would adjust to the values for conventional technologies, while at the same time turnover would be higher for a high proportion of electric vehicles as these would be more expensive, even by 2030. Turnover in scenario 1 would be approx. 77 billion € by 2030, compared to 83 billion € in scenario 2 (60 billion € in 2009).

4.3 Results – vehicle stock

Using information on today's vehicle stock and data on average surviving rates of new vehicles, market shares for the future vehicle stock are calculated (Figure 9). According to calculations, approx. 650,000 / 1 million (scenario 1 / 2) BEV would be on the roads in Germany by 2020 and 4.5 million / 8 million by 2030, additionally approx. 5 million FCHEV scenario 2.

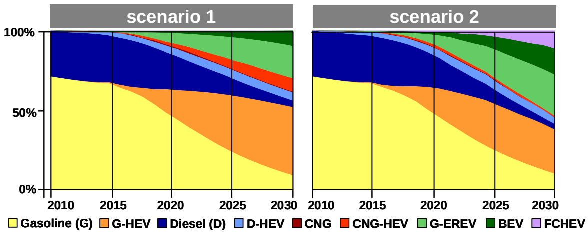

Figure 9: Market shares vehicle stock

TTW CO_2 emissions of the passenger vehicle stock would decrease from approx. 109 million tons today to approx. 61 / 40 million tons by 2030 (Figure 10). WTT emissions would decrease from approx. 19 to approx. 12 / 2 million tons.

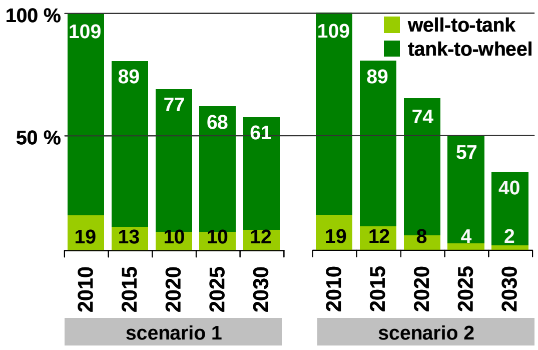

Figure 10: CO_2 emissions veh. stock [million tons]

Demand for conventional fuels in the passenger car sector would decrease for both scenarios. For gasoline from approx. 900 PJ today to approx. 550 / 400 PJ by 2030, for diesel from approx. 600 PJ today to approx. 150 / 100 PJ by 2030. Demand for CNG would increase from today 0.2 PJ to 120 PJ / 10 PJ by 2030, which equals approx. 4 % / 0.3 % of today's total demand of CNG in Germany. Demand for hydrogen would increase to approx. 0.5 / 85 PJ in 2030, which equals approx. 0 % / 39 % of today's total hydrogen demand in Germany. Demand for electricity for passenger vehicles would increase to approx. 65 PJ / 95 PJ in 2030. The total production of electricity from renewable sources in Germany in 2006 was at approx. 190 PJ.

5 Conclusion

Calculation of two scenarios, each with a different set of input variables, using the *VECTOR21* model, led to the conclusion that remarkable changes of the passenger vehicle fleet appear feasible for the time horizon up to the year 2030. Assuming a moderately increasing crude oil price, electricity and hydrogen from fossil energy sources as well as an average CO_2 target value of 113 g/km for the German new vehicle fleet in 2030, electric vehicles (BEV and EREV) could achieve market shares of approx. 40 % by 2030 in scenario 1. Under different constraints, with a stricter CO_2 target value of 75 g/km and higher penalty fines as well as electricity and hydrogen being produced from renewable sources, electric vehicles could achieve market shares as high as 95 %, including a 35 % proportion of FCHEV in scenario 2.
Regarding CO_2 emissions both scenarios indicate significant potential for reduction. WTW emissions of the vehicle stock could decrease by approx. 40 % in scenario 1 by 2030 and even by approx. 65 % in scenario 2. For permanently limiting CO_2 emissions from transport at low values in the future, a combination of electric vehicles as well as electricity and hydrogen from renewable energy sources therefore appears promising.

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