Electric vehicles – A model based assessment of future market prospects and environmental impacts

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Abstract

Assessing future market prospects and environmental impacts of electric vehicles requires taking into account the competitive situation with regard to established conventional vehicle propulsion technologies. The Modelica library *AlternativeVehicles* is used to analyse energy consumption of battery (BEV), extended range electric (EREV) as well as fuel cell hybrid electric vehicles (FCHEV). Costs of technical measures for enhancing conventional vehicles, as well as cost curves for batteries and fuel cells are assessed. Using a newly developed model, *VECTOR21*, customer purchase decision is modeled to derive future market shares of propulsion technologies and fuels, taking into account energy consumption, energy prices and taxation as relevant influencing factors. Two different scenarios demonstrate the dependency of future market prospects on a set of general conditions. With electricity and hydrogen being produced from renewable energy sources, as well as implementation of strict regulations regarding CO_2, BEV and FCHEV could achieve a market share of up to approx. 65 % on the German new passenger car market by 2030. CO_2 emissions of the vehicle stock could be reduced by approx. 65 % in this scenario. In a less ambitious scenario a market share of approx. 20 % is seen for BEV, with no application of FCHEV in the long run. CO_2 emissions of the vehicle stock could be reduced by approx. 40 % in this scenario.

Keywords: modeling, passenger car, energy consumption, cost, market, environment

1 Introduction

In order to assess future market prospects and environmental impacts of electric vehicles, it is necessary to not only focus on an analysis of individual concepts, but to furthermore compare different technologies and to analyze in detail the competitive situation with regard to established conventional vehicle propulsion technologies.

For determining energy consumption of electric power-train concepts and for comparing the results with energy consumption and efficiency of conventional vehicle technologies, the Modelica library *AlternativeVehicles* is applied in chapter 2. Production costs and retail prices for a variety of vehicle technologies and individual assembly parts, in particular batteries and fuel cells, are assessed in chapter 3.

Taking into account relevant influencing parameters, like energy consumption, energy prices, taxation and customer decision, concurrency of vehicle concepts is simulated using the *VECTOR21* scenario model in chapter 3 and 4. The results include future market shares of electric vehicles as well as their influence on CO_2 emissions of the fleet. Focus of the examination is on passenger cars in Germany up to the year 2030.

2 Vehicle energy consumption

Energy consumption and efficiency depend on many different factors like driving resistance, power train concept, dimensioning, driving style and use of auxiliaries. To analyze different power train concepts the Modelica library *AlternativeVehicles* has been developed (s. section 2.1). In section 2.2 three reference vehicle sizes, in accordance to the *VECTOR21* model, are defined. Furthermore, assumptions for technological development (e.g. driving resistances) are made and driving cycles as well as auxiliary loads are chosen. In section 2.3 the simulation results for different segments, years and power train concepts are shown.

2.1 *AlternativeVehicles* library

The Modelica library *AlternativeVehicles* (AV) has been developed by the DLR Institutes of Vehicles Concepts and Robotic / Mechatronics [1] and is based on the freely available *VehicleInterfaces* library (VI) which defines all major components of power trains including interfaces and basic models. The AV library is an addition to the commercial *PowerTrain* library which has also been developed by DLR [2]. It contains parameterized component models, like batteries, supercaps, fuel cell systems, electrical drives and thermal systems for modeling alternative power trains. Furthermore, ready to use vehicle models as hybrids, fuel cell hybrid, range extender and battery are included.

Modelica is a free object oriented description language for modeling and simulation of dynamic multidisciplinary systems (electrical engineering, thermodynamics, mechanics and control). In Modelica different component models are linked by undirected physical connectors. E.g. an electric pin consists of a potential and flow variable which represent the electrical potential and current. Further information about Modelica can be found in [3], [4]. Figure 1 shows the graphical view of a fuel cell hybrid electric vehicle (FCHEV) model.

The vehicle model is a forward oriented model. Acceleration and brake pedal position are controlled depending on the desired driving cycle and actual velocity. Inside the control module the acceleration pedal position is converted into a signal for controlling the electrical drive. The electrical drive is mainly modeled by a map which describes the relation between angular speed, torque and efficiency. Models for driving

resistances like aerodynamic drag, rolling-, climbing resistance and acceleration drag are placed within the chassis model. Main task of the battery is to supply and buffer energy during acceleration and deceleration phases.
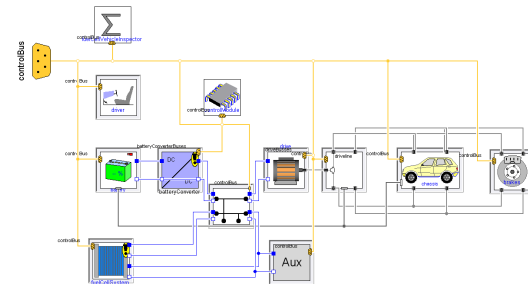

Figure 1: Graphical layer of the FCHEV model

Battery and fuel cell systems have a key role regarding electrical power trains. E.g. a powerful battery is required because the fuel cell system needs a high response time to provide full power. Thus in the following sections these component models are explained more in detail.

2.1.1 Battery model

Easiest way of modeling an electro-chemical cell is a serial connection of an ideal voltage source and ohmic resistor. Real electrical characteristics are much more comprehensive. To cover electro-chemical processes like double layer capacitance, charge transfer resistance, solid electrolyte interface and diffusion, a complex impedance based model has been implemented [5]. Figure 2 shows the electric equivalent circuit model of a Li-ion cell as an example. Beside electrical pins the equivalent circuit elements also have a thermic interface to model the thermal losses of the cell (s. red lines/squares in Figure 2).
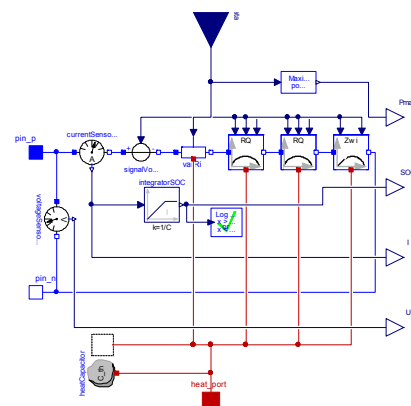

Figure 2: Electric equivalent circuit model of Li-ion cell

Main influencing parameters of Li-ion cells are state of charge (SOC), current and temperature.

E.g. the impedance magnitude has its maximum values at high and low state of charge. Therefore, impedance spectroscopy measurements have been carried out for different state of charges, dc currents and temperatures. On the basis of different impedance spectra, the model parameters were fitted by a complex nonlinear least square fitting (CNLS) algorithm. The CNLS algorithm fits the parameter of the equivalent circuit model as long as the differences between measured and simulated impedance values are minimal. All identified model parameters were stored in multidimensional maps which generate the model parameter to the corresponding SOC, current and temperature.

Another contribution factor of battery technologies is their specific energy density. High or low energy densities correspond to high or low battery weight and volume. Prototypes of high power Li-ion battery systems reach energy densities of around 80 Wh/kg [6]. For the following vehicle simulations energy density of Li-Ion battery systems as in Table 1 is assumed.

Table 1: Assumed technical attributes Li-ion batteries

		Year		
Parameter	Unit	2010	2020	2030
Battery energy density	Wh/kg	80	115	150
Usable capacity	-	50 %	60 %	70 %

2.1.2   Fuel cell system model

For vehicle propulsion systems of passenger cars primarily the PEFC (Proton Exchange Fuel Cell) is utilized. The PEFC is driven with gaseous hydrogen at the anode and oxygen or air at the cathode supply. In vehicle applications almost exclusively ambient air at the cathode is used. The separation of anode and cathode gas is achieved through a thin membrane, which is permeable only for protons. Since the proton conductivity of the membrane strongly depends on water content, the working fluids are humidified in most cases. Therefore, to supply the PEFC an air compressor and a humidifier at cathode side are necessary. As hydrogen from the vehicle tank is supplied with sufficient high pressure regardless of tank technology, only a recirculation pump and a humidifier are necessary at anode side. Since the reaction water is needed to moisten the supply media, at least one water separator in the waste gas stream is necessary. However, gas humidifier and separator might be combined in a single apparatus (e.g. Nafion gas humidifiers). Figure 3 shows the graphical layer of a PEFC system model with the mentioned periphery. Calculation

of the dynamic behaviour of a PEFC system and calculation of the auxiliary energy consumption is possible using this model. E.g. control strategies for the air compressor and the recirculation pump may be developed. The auxiliary energy primarily is needed by the air compressor and to a lower degree by the hydrogen recirculation pump. Energy consumption of cooling pump, valves, sensors etc. is considered by a constant power demand.
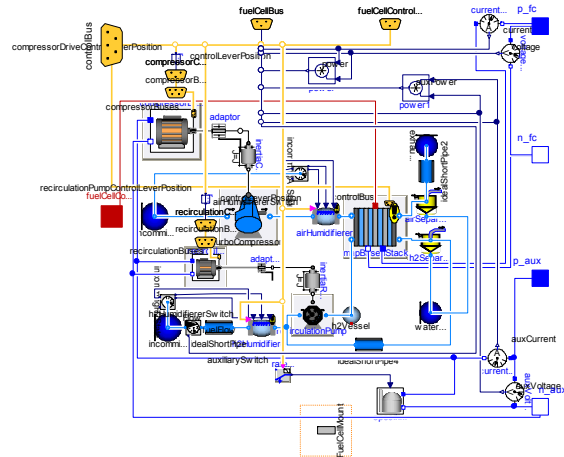

Figure 3: Top layer of a PEFC system model

For the simulation of complete driving cycles which last several minutes, this model is not suitable due to the high computation effort. A simplified model, assuming a well controlled fuel cell system is necessary, which is shown in figure 4. This quasi-stationary model is based on tables for stack voltage and auxiliary power demand. The calibration of this model was done using the more complex model of Figure 3 and checked against performance data of existing automotive PEFC-systems.
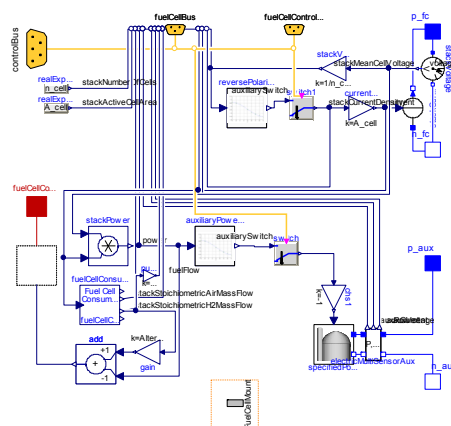

Figure 4: Table-based fuel cell system model

For the vehicle simulation a specific power weight of the fuel cell system of approx. 3.2 kg/kW is

assumed [7]. For hydrogen storage a high pressure-tank with a specific energy density approx. 21 kg/(kg H_2) is used [8].

2.2 Definition of scenario vehicles

Vehicle size today is defined by the means of vehicle dimension and installed traction power. To cover a wide range, three vehicle size categories are defined for the analysis (table 2).

Table 2: Definition of scenario vehicle categories

| Parameter | Unit | Vehicle class | | |
		Small	Medium	Large
Maximum velocity	km/h	150	170	190
Acceleration (0-100 km/h)	s	14	12	10
Power ICE-vehicle	kW	53	91	120
Kerb weight ICE-vehicle	kg	1,050	1,340	1,650
Aerodynamic coefficient c_w	1	0.31	0.28	0.32
Frontal area A	m²	2	2.2	2.7
Rolling resistance k_{r0}	1		0.01	

Three electric vehicle concepts are covered by an in-depth analysis:
- battery electric vehicles (BEV)
- extended range electric vehicles (EREV)
- fuel cell electric hybrid vehicles (FCHEV)

Advantages of BEV are local zero emission, high efficiency and low noise emission. On the other hand electrical range is much lower than for fuel cell and conventional vehicles. Extended range electric vehicles (EREV) offer significantly higher driving ranges, as an internal combustion engine (ICE) supplies energy at low battery SOC or high power demand. In contrast to plug-in hybrid electric vehicles (PHEV) top loads can be reached without assistance of the ICE, as EREV make use of a full size electric power train, similar to a BEV. The FCHEV is a serial hybrid with a small battery for acceleration and deceleration. Table 3 shows the electric ranges assumed for simulation of vehicles.

Artemis real world driving cycles [9] are used to simulate energy consumption. To obtain one single value for energy consumption the three Artemis cycles urban, road and motorway are combined using a set distribution. According to

[9], on average 29 % of all ways are driven in urban surroundings, 45 % on road and 26 % on motorway.

Table 3: Definition of the electrical range in Artemis real world drive cycles

| Power Train | Unit | Vehicle Class / electrical range | | |
		Small	Medium	Large
EREV	km	50	50	50
BEV	km	80	120	120
FCHEV	km	400	400	400

Constant auxiliary loads have been estimated for each vehicle class (small: 1 kW; medium: 1.5 kW and large: 2 kW) to account for the use of auxiliaries (e.g. heating and cooling) which is an important influencing factor for the energy consumption of electric vehicles.

In table 4 assumptions on future reductions of vehicle weight, aerodynamic drag and rolling resistance based on the initial values (table 2) are summarized.

Table 4: Definition of driving resistance reduction

| Parameter | Year / Reduction | |
	2020	2030
Vehicle weight (m)	6 %	11 %
Aerodynamic drag (c_wxA)	10 %	20 %
Rolling resistance (k_{r0})	9 %	17 %

2.3 Simulation results

Based on the assumptions stated in section 2.2 the scenario vehicles have been dimensioned. For all electric vehicles electric drive power was selected to reach the predefined driving performances (maximum speed and acceleration). Battery capacity of BEV and EREV was calculated by simulating energy consumption of the vehicles using the combined Artemis drive cycles including auxiliary load. The EREV primary energy converting unit was defined by simulating the Artemis Motorway starting with low battery SOC. During the simulation it was checked that the installed power was high enough to prevent a further decrease of the battery SOC. The fuel cell system power was set to the same value than the electric drive. A summary of the power train vehicle dimensioning is given in table 5.

Table 5: Dimensioned vehicles with the basic parameters

| Parameter | Unit | EREV | | | BEV | | | FCHEV | | |
		Small	Medium	Large	Small	Medium	Large	Small	Medium	Large
Vehicle mass	kg	1,293	1,578	1,989	1,245	1,753	2,247	1,231	1,580	2,086
Electrical traction power	kW	55	80	125	55	90	140	55	80	125
Electrical energy storage	kWh	16.2	18.9	24.3	24.3	45.9	62.1	3.2	4.5	7.1
Primary energy converter power	kW	35	40	55	-	-	-	55	80	125
Primary energy storage capacity	kg	30	38	45	-	-	-	4	5,5	8

Simulation results of all electric vehicles are shown in figure 5. BEV have lowest energy consumption and highest tank-to-wheel (TTW) efficiency. Energy consumption is in between 16.4 to 28.1 kWh/100km in 2010. EREV energy consumption in charge depleting mode is lower than for BEV due to the smaller battery weight. Energy consumption of FCHEV is at 34.6 to 70.6 kWh/100km in 2010. The highest energy consumption is reached by the EREV in charge sustaining mode (53.9 to 83.9 kWh/100km in 2010). The TTW efficiencies in figure 6 were calculated by equation (1):

$$\eta_{t2w} = \frac{W_{wheel}}{W_{input}} \qquad (1)$$

The value for W_{input} varies on the type of power train. For BEV the required battery energy including the losses during charging process and for the EREV (cs-mode) and FCHEV the energy of fuel mass have been used ($SOC_{end} = SOC_{start}$)
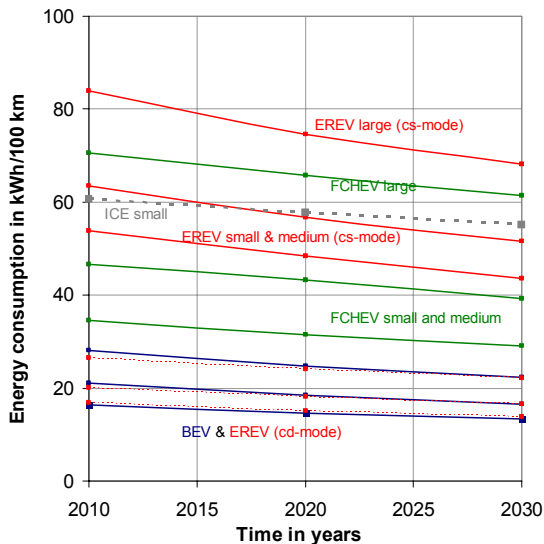

Figure 5: Combined Artemis drive cycles energy consumption including auxiliaries

The low energy consumption of BEV is due to high efficiency (74 % to 45 %) of the battery system and electrical drive. The much lower efficiency in the Artemis urban cycle can be explained by the high amount of acceleration phases and the resultant multiple energy conversions (battery-electrical drive-wheel-electrical drive-battery). The FCHEV efficiency is approx. half the value of BEV efficiency (39 % to 17 %) which can be justified by the efficiency of the fuel cell system at around 50 %. Efficiency of EREV in cs-mode is in between 23 % and 15 %. Only on the motorway cycle the

direct powered ICE vehicle offers higher efficiency. At high power demand and small potential of recuperating a direct traction system is more efficient as the ICE-generator unit can not run in the best operating point and the energy losses caused by several energy conversions can not be compensated.
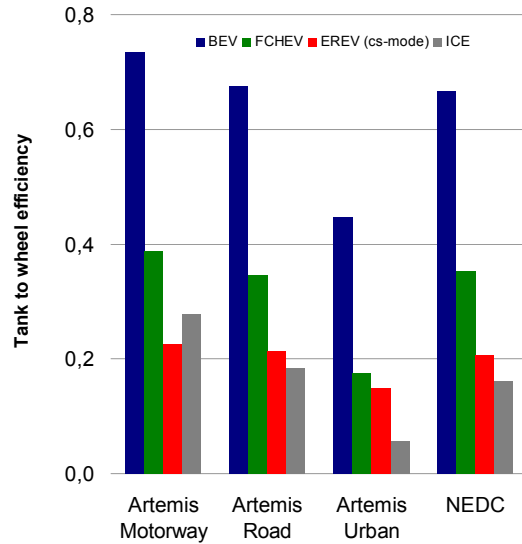

Figure 6: Tank to wheel efficiency for different power train concepts for the vehicle class small in 2010
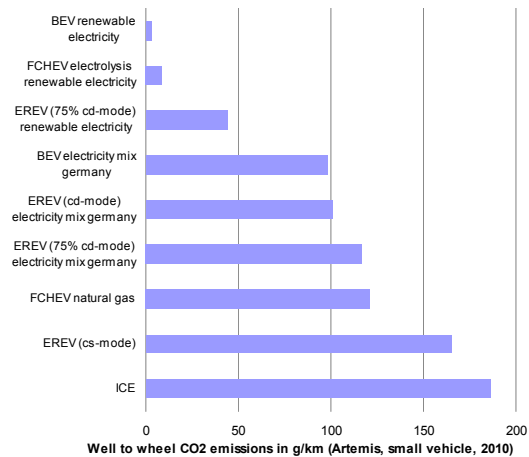

Figure 7: WTW CO_2 emission for power trains

Looking at well-to-wheel (WTW) CO_2 emissions in combined Artemis drive cycle, lowest values (3 to 44 g/km) are for BEV, FCHEV and EREV (75% in cd-mode) when operated using electricity or hydrogen from renewable energy sources (s. figure 7, small vehicle size category). With electricity and hydrogen from fossil sources WTW emissions are in between 99 to 121 g/km. Highest values are for EREV (cs-mode) and conventional ICE vehicles (165 g/km / 186 g/km).

3 Technology cost assessment

Besides vehicle energy consumption, for a profound judgement on future market prospects for vehicle technologies, sales prices and therefore manufacturing costs are a key relevant parameter. For the analysis, baseline vehicles are defined for three passenger car size categories: small, medium and large (s. section 2.2). Production costs and retail prices for technically more advanced vehicle variants with lower energy consumption are consecutively derived.

3.1 Internal combustion engines

Manufacturing costs for baseline gasoline, diesel and compressed natural gas (CNG) vehicles are estimated based on sales prices of currently available passenger cars. As a conversion factor for production costs to retail prices excluding tax, a value of 1.35 is applied, as discussed in literature [10]. This mark-up includes profit of the vehicle manufacturer as well as costs and profit of the dealership. Furthermore, value-added tax (VAT) is added.

Individual technical measures for optionally reducing energy consumption are identified and associated manufacturing costs are estimated, according to literature as well as manufacturer data [10, 11]. Examples for technical measures are direct injection for gasoline vehicles, downsizing and turbocharging, variable valve control, exhaust heat recovery, improved aerodynamic efficiency, improved transmission and reduction of vehicle curb weight.

	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% 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 8: Individual technical measures and fuel economy packages (medium size gasoline vehicle)

Individual measures are summarized into fuel economy packages, as shown exemplarily in figure 8. Each fuel economy package later on is made available for potential customers who optionally may choose a corresponding vehicle variant at higher costs but at the same time lower energy consumption than the baseline vehicle. Thus, the potential for future fuel economy improvements of ICE vehicles is taken into account.

3.2 Electric vehicles

For electric vehicles, costs for non-necessary ICE technical parts are deducted from overall costs of the baseline vehicle variant, while supplementary necessary parts are added. For example, for hybrid electric vehicles (HEV) 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.

Generally, 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, for the analysis 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 [12].

3.2.1 Batteries

Current production costs for high-energy Lithium-ion batteries for use in vehicles are at approx. 500 to 1,000 €/kWh [13].

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 [14]. 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 of raw materials ordered (economies of scale).

Summarizing recent publicly available 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 % (s. figure 9), i.e. manufacturing costs would be reduced by 100 - 88 = 12 % for each doubling of cumulative number of units produced.
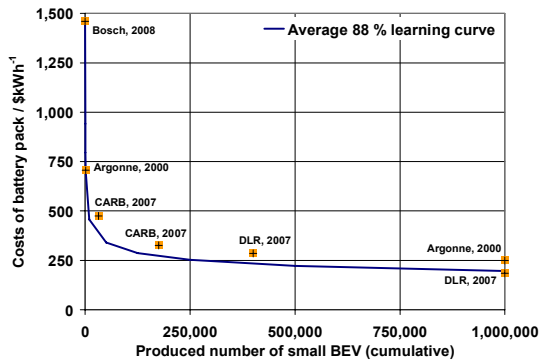
Figure 9: Production cost estimates for high-energy Lithium-ion battery packs [13, 14, 15, 16]

Figure 10: Production cost estimate for fuel cell stacks for platinum market price 20,000 $/kg [17, 19, 20, 21]

3.2.2 Fuel cells

For fuel cell stacks, platinum loading of the catalyst, necessary for a fast running fuel cell reaction, has been reduced remarkably in the past. During the 1960s for the first application of a PEFC in NASA Gemini mission a platinum loading of approx. 55 mg/cm² was necessary, compared to approx. 0.7 mg/cm² for a modern automotive fuel cell stack [17]. 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, with near-term target values set at 1,000 mW/cm² by the U.S. Department of Energy (DOE) [18].

An analysis of cost structure of PEM fuel cell stacks reveals that approx. 90 % of production costs at high rates is for material, with electrodes making up more than 80 % of total production costs at high volumes [19]. Using a bottom-up cost model for assessing future costs for fuel cells at high production volumes leads to the conclusion that 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 [17]. This is for mass manufacturing processes, improved stack power densities, as well as lower platinum loading and a platinum price of approx. 20,000 $/kg. Figure 10 shows the result in comparison to previous studies.
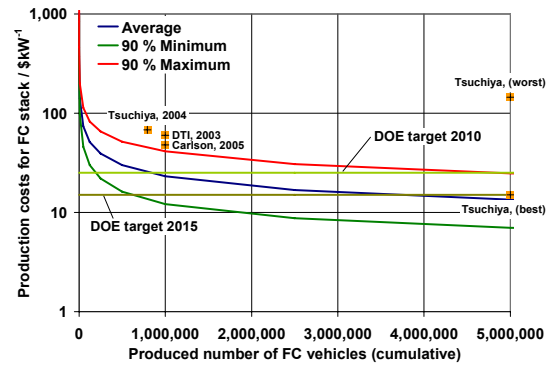
4 Scenario model

Using a new computer model, *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).

4.1 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 [22].

4.2 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 [23].

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. [24] 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 11).
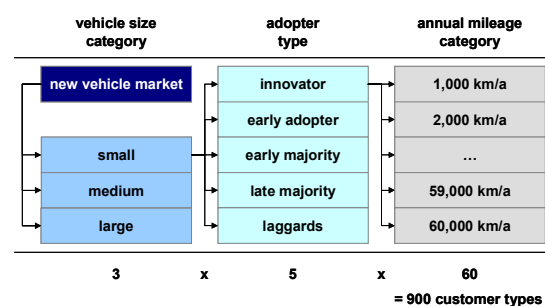

Figure 11: Schematic illustration of customer subgroups within the model *VECTOR21*

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.

4.3 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 12 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.
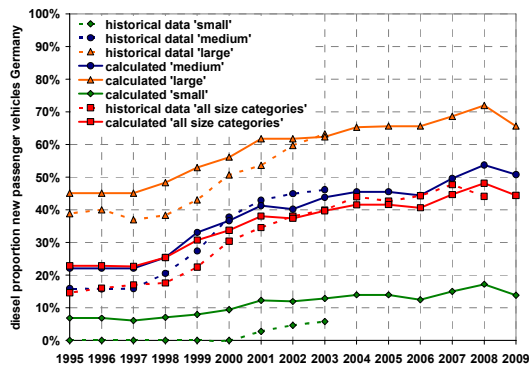

Figure 12: Model results vs. real historical developments for the proportion of diesel passenger cars in Germany

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.

5 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*.

5.1 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

Table 6: 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 %

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 6).

5.2   Results – new vehicle fleet

Figure 13 shows the results of the two scenarios for the new vehicle market in Germany between 2010 and 2030.
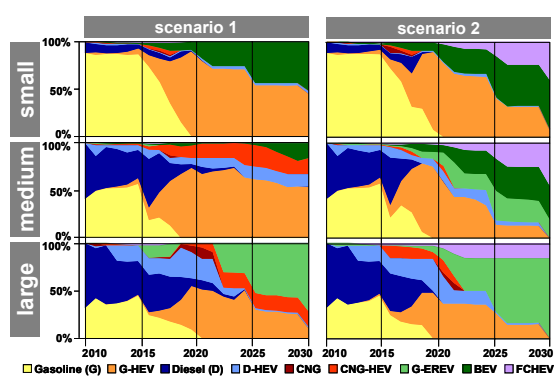

Figure 13: Market shares new vehicle market – differentiated by size categories

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 14 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.
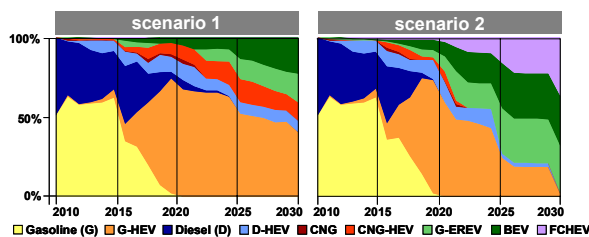

Figure 14: Market shares new vehicle market – sum of all size categories

Figure 15 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.
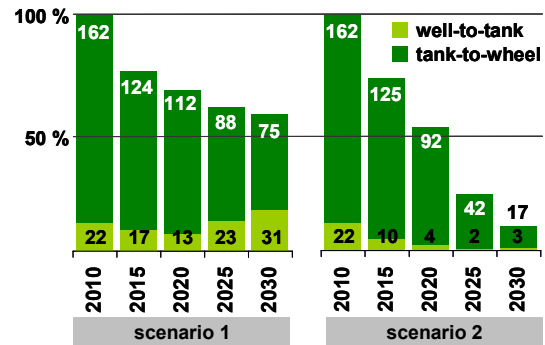

Figure 15: CO_2 emissions new vehicle fleet in g/km

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).

5.3 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 16). 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.
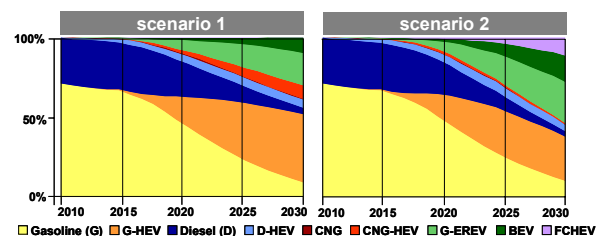

Figure 16: Market shares vehicle stock

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 17). WTT emissions would decrease from approx. 19 to approx. 12 / 2 million tons.
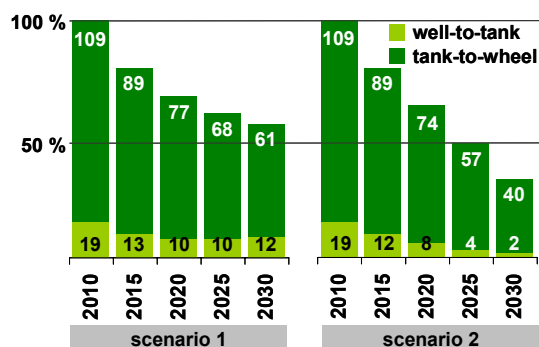

Figure 17: CO_2 emissions vehicle stock in million tons

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.

6 Conclusion

The analysis of various vehicle concepts using the Modelica *AlternativeVehicles* library clearly demonstrated the predominance of electric vehicles regarding the overall degree of efficiency, especially in an urban environment. Nevertheless, production costs at today's low volumes are markedly high, with significant reduction potentials for the future, as bottom-up cost models show.

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.

Acknowledgments

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