MARKET PROSPECTS OF ELECTRIC VEHICLES: MODELLING COMPETITION OF ALTERNATIVE AND ENHANCED CONVENTIONAL VEHICLE TECHNOLOGIES

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Abstract

Electric vehicles are competing with other alternatives and enhanced conventional vehicle technologies in the new vehicles market, driven by the need to reduce CO_2 emissions of automobiles. The simulation tool *VECTOR21* models a virtual market of vehicle propulsion technologies and customers buying new vehicles with a dynamic least-cost approach in order to fulfill specified CO_2 goals for the future car fleet. Eventually, by comparison of two scenarios calculated with the model being calibrated for the German car market, we show conditions under which alternative vehicle technologies reach a break-through on the market.

Introduction

To tackle climate change is one of the great global challenges and has become a major political goal. The European Commission and the European Council have confirmed the EU objective in 2007 to limit the average global temperature increase to a maximum of 2°C compared to pre-industrial levels. The Copenhagen Accord presented at the United Nations Climate Change Conference 2009, although not ratified yet, agrees that "deep cuts in global emissions are required according to science … to hold the increase in global temperature below 2 degrees Celsius" ([1]). While uncertainties are still eminent, today's knowledge suggests a necessary global greenhouse gas emission reduction of 15% to 50% until 2050 compared to 1990 levels, for industrialized countries the figures even point up to 60%-80% ([2]). Transport emissions make up almost one quarter of total global CO_2 emissions ([3]). Within the EU-15 transport makes up 21% of total greenhouse gas emissions. Road transport in the EU-15 contributes 93% of the transport sector's emissions and is therefore by far the most important transport emission source ([4]). Light duty vehicles emitted in the year 2000 about 2,798 million t of greenhouse gases (well-to-wheel). This represents 44% of the entire transport emissions of 6,328 million t CO_{2eq}. Hence, cars are the single most important contributors to the transport GHG emissions. Under the light of these enormous greenhouse gas emission reduction targets for the future, it is of utmost importance to look at how cars can contribute to CO_2 reductions in a sustainable thus also economical way. The work presented aims at exploring the competition between alternative and enhanced conventional vehicle technologies, including the role of customers, transport policies and other exogenous parameters. In the following the input parameters for the modeling exercise are briefly described, beginning with the characterization of the future vehicle technologies, their cost prospects, the characterization of customers in the model and the exogenous parameters influencing the scenario. The results of two scenarios showing significant differences regarding the market success of alternative vehicles are presented.

Characterization of future vehicles

Energy consumption and efficiency depend on many different factors such as driving resistance, power train concept, dimensioning, driving style and use of auxiliaries. To reflect this vast number of parameters affecting energy consumption, a comprehensive technology database has been build. For conventional vehicles with internal combustion engines like gasoline, diesel and CNG vehicles, the characterization of the energy consumption is based on an extensive literature survey taking into account a multitude of suggested combustion improvement technologies as well as other options to reduce driving resistance and/or increase of the propulsion system efficiencies ([5]). In this work start-stop and micro-hybrid concepts have been included as well.

Electric range extended vehicles (EREV), battery electric vehicles (BEV), fuel cell vehicles (FCV) and full-hybrid vehicles are assessed bottom-up with the Modelica library *Alternative Vehicles*. Modelica is a free, object-oriented description language for modeling and simulation of dynamic multidisciplinary systems (electrical engineering, thermodynamics, mechanics and control). Parameterized component

models of e.g. batteries, fuel cell systems, electrical drives and thermal subsystems are used to model alternative power trains in the corresponding vehicle models.
The specific energy consumptions of the main propulsion technologies of the vehicles used in the scenario modeling are summarized in Figure 1. The bandwidth indicated represents the utilization of various fuel reducing add-ons.

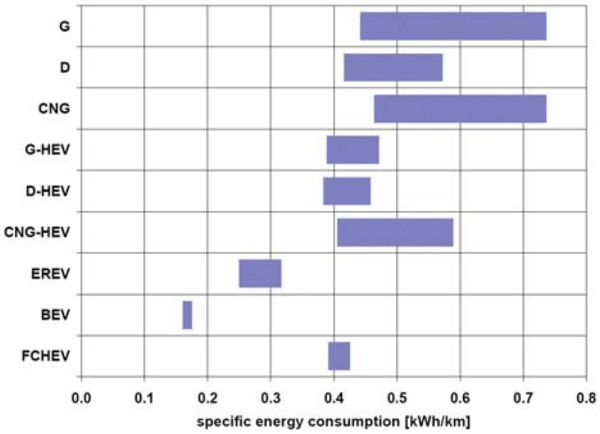

Figure 1 Assumptions for the specific energy consumption of various scenario vehicles, middle class segment (NEDC). The bars indicate the bandwidth of options depending on a multitude of improving measures ([5])

Cost assessment of future vehicle technologies

For the future market prospects of electric vehicles, estimates of manufacturing costs for batteries and electrical equipment as well as the costs of improved conventional technologies are crucial. As a baseline, vehicle costs are estimated based on a review of sales prices of currently available passenger cars. For the small, medium and large vehicle size segment respectively 10,000 € (Diesel: 12,500 €), 15,000 € (Diesel: 17,000 €) and 30,000 € (Diesel: 33,000 €) are identified. To estimate the cost of electric vehicles, a differential cost approach is used, i.e. costs for obsolete parts are subtracted while costs for new parts are added.

The most important cost drivers are batteries and fuel cells. Production costs for high-energy Lithium-Ion batteries for application in vehicles are currently estimated at approx. 500-1,000 €/kWh. With a detailed bottom-up cost estimate taking into account materials of batteries as well as their chemical and physical properties, we consider manufacturing costs of approx. 300 $/kWh as being realistic for mass production volumes. Cost reductions result from improved materials for electrodes and conducting salts, optimization of production processes and increased quantities of raw materials. Taking into account in addition recent cost estimates from literature, a learning curve factor of 0.9 seems to be viable.
Fuel cell systems are still very expensive. We apply initial costs of 1,300 $/kW at low volumes. Starting from this value, a learning factor of 0.79 for the system is applied. Learning factors in the range of 0.80 are applied to membrane and membrane electrode assembly manufacturing. Platinum loading, power density and assembly are modeled with learning factors between 0.90 and 0.92. These assumptions result in system costs of 35-83 $/kW and 18-49 $/kW at production volumes of 1 and 10 million vehicles respectively. The system costs correspond with stack costs of 12-40 $/kW and 6-20 $/kW.

The initial production costs used at the starting point of the simulation are depicted in Figure 2. The bandwidths reflect different variants of vehicle types assessed in the model.

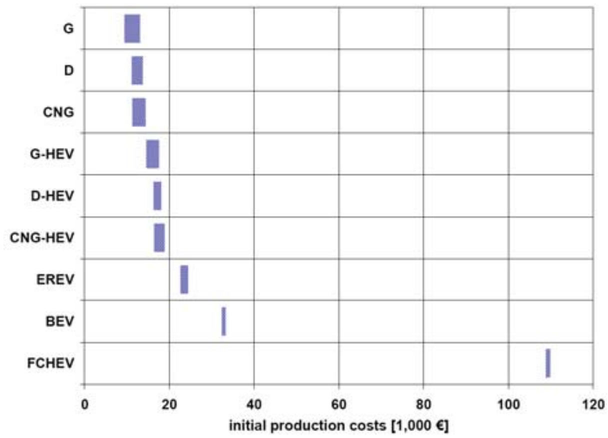

Figure 2 Assumptions on initial production costs for middle class vehicles. The bars indicate the bandwidth of different vehicle configurations.

Characterization of customers

Research indicates that a 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.

A customer model within *VECTOR21* explicitly models the decision of consumers to buy or not to buy a certain propulsion technology on a yearly basis. Customers are categorized in groups, depending on their willingness to accept innovations, i.e. new propulsion technologies. The five different types of adopters in the model are: innovators, early adopters, early majority, late majority and laggards. In addition, each adopter group is characterized by a detailed distribution of annual mileage separated into 60 classes. Besides the costs, basic requirements such as autonomous range or luggage space can be defined affecting the purchase decision as well. Modeling the market introduction process, the five different adopter groups can buy successively, first the innovators, then early adopters and so on.

In addition, each adopter group is characterized by their willingness-to-pay for a new, innovative, clean and green technology. While dedicated willingness-to-pay estimates for the five adopter groups are not available, results of other, more general studies have been applied. Some of these state a maximum WTP of 10% ([6; 7]) for new, clean vehicle technologies. This has been applied to the five adopter groups, with a linear decrease up to the group of laggards with zero WTP, i.e. they are never willing to pay more for an innovative clean technology.

In modeling the decision process, the economy itself is seen as the most important aspect in the long term. The relevant costs are calculated as the total costs of ownership, including both variable and fixed costs. Purchase costs, energy costs, non-recurring and annual taxation, penalties for exceeding the CO_2 targets as well as subsidies are part of the model. Four years are assumed to be the relevant time horizon for the purchase decision following e.g. ADAC ([8]). Further issues like loss of value, maintenance and insurance are not considered at the moment. It is assumed that new technologies introduced on the market will include warranties comparable to proven technologies which implies that these cost items will develop similar for all propulsion technologies and thus have no relative affect on the purchase decisions. The general choice of the vehicle size is incorporated within the model as exogenous factor and not treated as a dynamic variable. Further irrational aspects such as anxieties related to fire- and explosive potentials of batteries and hydrogen are not taken into account.

Exogenous scenario parameters

Modeling results of *VECTOR21* depend on the technical parameters of the vehicles resulting in their fuel consumption, the costs of the technologies and their corresponding learning curves as well as on the calibration of the market diffusion model. Beyond that, various exogenous factors drive the scenario results:

- One-time subsidies to the vehicle purchase price, varied by vehicle type and duration

- Annual vehicle taxes, differentiated by vehicle type
- Tax on fuel and on electricity for driving, differentiated by type of fuel/energy
- Mandatory introduction of vehicle components at a fixed point in time (e.g. after-treatment of exhaust gases)
- Non-recurring penalties for exceeding CO_2-targets

In the following, two scenarios are defined with the purpose of identifying significant differences of the market success of alternative vehicle technologies.

Scenario 1 does reflect only minor changes compared to today's situation. The crude oil price is rising by 20% from 54 €/bbl to 65 €/bbl in the year 2030. The share of biofuels is rising to a general level of 15% (petrol, diesel and CNG). Electricity, which is used for driving of cars, starts with the conventional German electricity mix with CO_2 emissions of 600 g/kWh and improves by 8% in 2030 compared to 2010. However consumer prices increases by 17 €cent/kWh to 35 €cent/kWh due to taxation of the electricity used for electric cars. This ensures constant tax revenues for the state although mineral oil tax-incomes will decrease. Hydrogen is produced from natural gas first and is shifted to electrolysis from renewable electricity later on. The price for hydrogen almost doubles due to the growing dependency on electricity as well as due to taxation. The CO_2-target of the new vehicle fleet in Germany in 2025 is 113 g/km with no further decrease. This assumes that the target of the European Commission for the year 2020 of 95 g CO_2/km in European average is reached with 5 years delay. The penalties for each gram/km emitted above the target are set to 95 €/(g/km), in line with current EC legislation. The total of new vehicles is kept constant at the current level of 3.1 million cars per year. Following the recent trend however, middle class vehicles will decrease by 10% whereas the small and large segment will grow equally ([9]). Maximum willingness-to-pay is 10% which is applied to the customers group of innovators. One-time subsidies are paid for battery and fuel cell vehicles (3000 € at the beginning) and for range-extender vehicles (2000 € at the beginning). The amount is stepwise reduced to zero after five years.

Scenario 2 refers to substantial climate protection. The perception of global warming and the need to reduce CO_2 emissions in the population is assumed to grow which is reflected in a doubling of the willingness-to-pay compared to scenario 1. The use of biofuels rises to a general level of 25%. Electricity as well as hydrogen used in road transport are produced entirely from renewable sources. The electricity price thus increases to 37 €cent/kWh including a 'mobility energy tax' up to the year 2030. The CO_2-target of the European Commission of 95 g CO_2/km (105 g CO_2/km at the vehicle level) is reached as planned in 2020. For Germany, which was generally about 8% above the European average, 113 g CO_2/km are applied for 2020. The target is further strengthened to 76 g CO_2/km in the 2030 for Germany. Also the penalties for exceeding the CO_2 target level are increased to 120 €/(g/km). Subsidies for fuel cell vehicles are increased by 2000 € compared to scenario 1 and are paid 3 years longer up to 2018. The major assumptions are summarized in Table 1.

Table 1 Summary of scenario assumptions

		Scenario 1 ‚Baseline'		Scenario 2 ‚Growth'	
		2010	2030	2010	2030
Crude oil price	€/bbl	54	65	54	65
Share of biofuels	%	0-8	15	0-8	25
Electricity: CO_2 emissions	g/kWh	600	550	20	20
Electricity: consumer price	€/kWh	0.18	0.35	0.21	0.37
Hydrogen: source		natural gas	electricity	electricity	electricity
Hydrogen: CO_2 emissions	g/kWh	350	650	25	25
Hydrogen: consumer price	€/kWh	0.16	0.35	0.21	0.38
CO_2-target new vehicle fleet	g/km	-	113	-	76
Penalty for exceeding CO_2-target	€/(g/km)	-	95	-	120
Willingness-to-pay	%	0-10	0-10	0-20	0-20
Market share (small/medium/large)	%	25/55/20	30/45/25	25/55/20	30/45/25

Results

In scenario 1, petrol cars keep playing the leading role in the vehicle market up to 2030. However, starting with the year 2015 and the step-wise increase of CO_2-targets for the new vehicle fleet, the conventional petrol vehicles are replaced by petrol hybrid vehicles in all three vehicle size classes. Due to the introduction of “Euro 6” and its cost-intensive exhaust gas after-treatment, the share of diesel cars decreases in all three segments. Increasing product volumes of hybrid components lower their costs due to learning effects. Accordingly, diesel hybrids enter the market. With a considerable increase of CNG prices due to the phasing out of the CNG tax exemption in 2018, CNG vehicles are superseded for a short while until the CO_2-targets are further tightened. Fuel cell vehicles are able to position themselves in the market due to the subsidies of 3000 € paid per vehicle. However the cost reductions due to growing numbers produced are not high enough to keep them competitive after the reduction of subsidies. Battery and range-extender vehicles do not gain significant market shares due to the low CO_2 advantage compared to other concepts. This is caused by the high CO_2-WTT-emissions of the electricity used. The evolution of the new vehicle market in scenario 1 leads to a decrease of the share of diesel vehicles of 50% until 2030, an increase of CNG vehicles to 5% and to about 850,000 electric vehicles in the fleet in 2030. In total, the CO_2 emissions of cars are reduced by roughly 30% in 2030 compared to the year 2010. The results for scenario 1 are depicted in Figure 3.

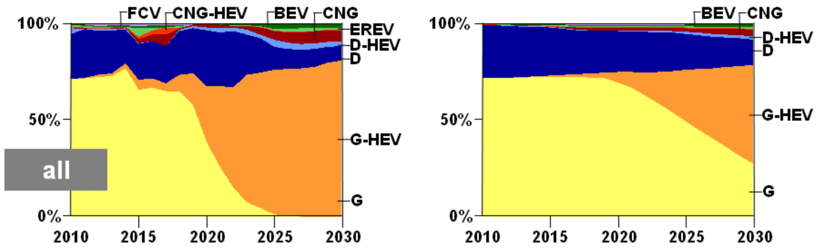

Figure 3 Results of scenario 1 (baseline) : market shares of the new vehicle market (left) and development of stock (right).

As mentioned above, scenario 2 is a dedicated and speedy climate protection scenario. Although the oil price development is identical to scenario 1 and the share of biofuels is considerably higher, the scenario shows an entirely different picture towards alternative and electric propulsion technologies. Fuel cell vehicles, battery and range-extended vehicles reach a market share of 80% in the year 2030. Due to the high CO_2 reduction potential of hydrogen and electricity together with the ambitious CO_2-targets, the customers tend to buy more innovative technologies. The CO_2 emissions of cars are thus reduced by more than 80% in 2030 compared to 2010. However, the price for the CO_2-reduction is born by the customers which have to face a 23% increase in cost of ownership compared to a 10% increase in scenario 1. Subsidies of battery and range-extended vehicles reach a total of 500 million Euro in both scenarios while subsidies for fuel cell vehicles are significantly higher in scenario 2 (1,000 M€). In total, subsidies of 500 M€ in scenario 1 and 1,500 M€ in scenario 2 are paid. For comparison, the German scrapping bonus (“cash for clunkers”) in the year 2009 had a budget of 5,000 M€.

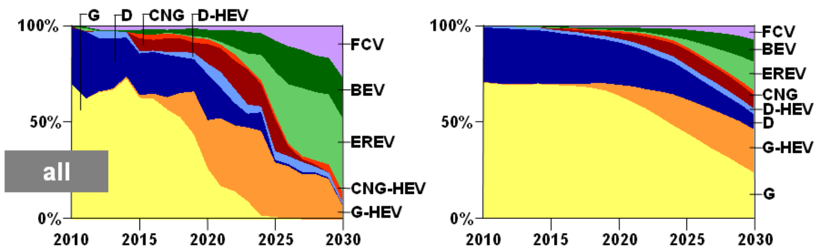

Figure 4 Results of scenario 2 (growth): market shares of the new vehicle market (left) and development of stock (right).

Conclusions

The model emphasizes the role of the customer and, more importantly, the role of transport policies and targets. Under the conditions and targets of scenario 1, gasoline hybrid technology seems to be sufficient to reach a 30% CO_2 reduction. The cost-benefit ratio of battery electric and hydrogen fuel cell vehicles is not convincing due to the high CO_2 emissions of the electricity used. The number of electric vehicles stays below the political target set by the German Government of 1 million in 2020. The use of renewable electricity and hydrogen seems to be a precondition for the market introduction of electric and hydrogen vehicles. With tighter CO_2-targets, alternative technologies gain significant market share. However the cost increase for consumers of 23% is considerably high. The results show also that due to the variety of customer profiles and the suitability of different propulsion technologies to respective vehicle sizes, a variety of technologies can succeed on the market at the same time.

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