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A disaggregated approach to model international passenger car markets and their interdependencies

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Abstract

The article presents an innovative approach to model the market penetration of electrified powertrains in passenger cars on different international markets. For that purpose, the VECTOR21 model was enhanced to depict the major car markets in a disaggregated approach. The scenario simulation incorporates the interdependencies of the varying developments on different markets. In a scenario for the German and US car market, the effect of market interdependency is shown. The results display the influence of EV policies in the US on the EV penetration on other markets.

Keywords: Market penetration, electric vehicles, interdependency, disaggregate model

1 Introduction

Electrified powertrains are a key option to reduce greenhouse gas emissions and local air pollution from passenger cars. Hence, governments all over the world have introduced measures to promote the market ramp-up of hybrid and electric vehicles [1]. In globalized markets, like the automotive, the specific development on one market can affect the development on other markets. Political measures to promote the plug-in electric vehicle (PEV) uptake in one market may impact the uptake in others. In recent years, the sales of PEV have grown on markets around the world [2]. However, in most markets the figures remain at a low level [3]. Therefore, the question which technology under which circumstances will be widely accepted by customers still prevails. Models that simulate the possible market penetration of PEV can provide answers to this question. A variety of these models can be found in the scientific literature [4], [5]. Yet, none of them consider the effects of market interdependency.

Major aspects in a consumer's purchase decision are the investment and operating cost of a vehicle [6]. These vary across different powertrain technologies and markets [7]. The economic competitiveness of electrified drivetrains is highly dependent on the cost of their energy storage, i.e. their traction battery [8], [9]. The specific cost of the currently market dominating lithium-ion battery technology are expected to decrease with an increasing market share of electric vehicles [9]. In most models that calculate the possible market penetration, the costs of lithium-ion battery systems are exogenously given [5]. Some already consider the relation of battery cost to cumulated sales [6], [10], using an experience curve approach. However, these models do not properly depict the influence of a specific market development on a technology's overall cost development.

Therefore, the presented article introduces a modelling approach that comprises the interaction of markets by linking the market development to the endogenous calculation of technology cost. The modelling approach is explained in detail within the second section of this article. All relevant scenario inputs are described in the subsequent section. Key results are shown and discussed in the concluding sections.

2 Methodology

The presented approach is based on a further development of the vehicle technology market model VECTOR21 [10], [11]. With this hybrid of an agent-based and discrete choice model the competition between conventional and alternative powertrains can be assessed. It incorporates various drivetrain technologies in four size segments (small, medium, large, pick-up). Customer agents chose their new vehicle (Figure 1) matching vehicle costs, CO_2 emissions and available refueling- or recharging infrastructure to their preferences.

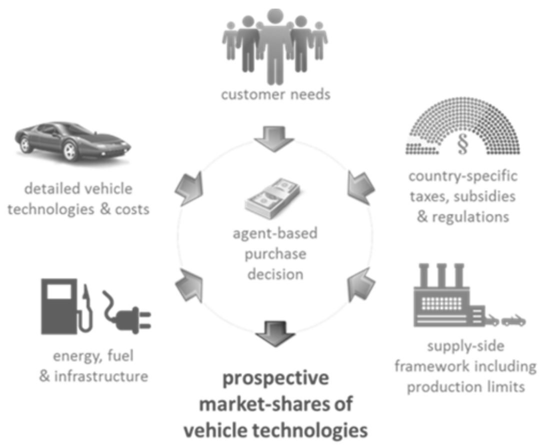

Figure 1: Model approach of vehicle technology scenario model VECTOR21 (www.vector21.de)

2.1 Disaggregation

The disaggregated simulation of markets enables the unique feature to depict the interaction between markets. Additionally, it allows the consideration of specific market characteristics, e.g. the mileage distribution of drivers, vehicle configurations (i.e. energy consumption), energy prices, taxes, and incentives for PEV. However, the bases of these characteristics differ. Some are defined on national level (e.g. CO_2 regulation in the United States) others on supranational level (e.g. CO_2 regulation in the European Union (EU)). Yet, other regulations and characteristics apply only to a subset of national regions, e.g. a selection of federal states or even an urban region. In order to consider this multi-layered structure of market characteristics, two levels are defined to which characteristics can be allocated: Markets and submarkets (Table 1). Additionally, the model allows an aggregation of markets on a top level (cf. sections 2.6 and 2.7).

Markets represent the superordinate level that can comprise multiple submarkets. The submarket level depicts the least sized fraction of a market at that the modeling is still reasonable. This requires substantial differences in submarket characteristics (e.g. EV incentives, fuel prices or customer preferences) and therefore depends strongly on the availability and quality of corresponding data

Table 1: Considered market levels in the disaggregated modelling approach

Level	**Example**	**Allocated characteristics**
Markets	EU, USA	CO_2 regulation, vehicle configuration and supply
Submarkets	Germany, Pacific region	Energy prices, taxes, mileage distribution, incentive schemes

For the purpose of this paper, the markets EU and USA are modelled. To illustrate the range of market disaggregation two different approaches are used. The US market is simulated in total by disaggregation into six submarkets: Pacific, Mountain, South Central, South Atlantic, Northeast and Midwest (Figure 1).

Figure 2: Considered disaggregation of the US market in submarkets (own illustration).

For the European Union, only Germany was selected as submarket, although prior scenario simulations featured the four largest singular submarkets in the EU [12]. The restriction to a single European submarket is made on purpose of highlighting the influence of the US market onto the powertrain competition in Germany. This simplification is, however, still suited to give some insights for the European market, since Germany represents the largest vehicle market in the European Union with about 23 % of the EU new car sales [3]. For this purpose, the model features a function to scale up the results of the submarkets to market level.

2.2 Demand side

VECTOR21 comprises up to 1,200 different customer agents per submarket. These agents represent a combination of three attributes: Five adopter groups [13] are used to characterize agents with respect to their innovativeness and willingness to purchase alternative vehicles. This attribute also governs the required minimal refueling- or recharging infrastructure for a considered powertrain and the maximum surcharge for the reductions of vehicle emissions. The second customer attribute, annual mileage, is chosen from one of 60 different values distributed between 1,000 km/year and 60,000 km/year. This value influences the energy consumption as well as the ratio of charge depleting (CD) to charge sustaining (CS) driving for Plug-in Hybrid drivetrains (PHEV) [8], [14]. The customer agents' vehicle size preference is set to match three different car size segments, i.e. "small", "medium" or "large". A fourth segment "pickup" is considered only for the US submarkets.

The share represented by each costumer agent is defined submarket-specifically. Transport surveys are used to derive the annual mileage distribution [15], [16]. The distribution of adopter types is defined according to [10]. Segment share preferences are set to match historical data.

2.3 Supply side

The supply side of the VECTOR21 model implements manufacturer strategies to optimize profits within varying legislative and regulatory frameworks. The introduction of electrified powertrain technologies induce substantial investments by automotive manufacturers [17]. As sales of electrified powertrains remain on a relative low level [2] manufacturers seek to minimize the risk involved in the investment in alternative powertrains. Hence, the supply of these powertrains is limited during market introduction phase. Therefore, for each drivetrain and vehicle market constraints of production capacities and their demand-guided annual growth are considered. This is especially necessary for the not-established powertrain concepts. This constraint reflects the duration of the build-up and establishment of production facilities of OEM and suppliers. For each drivetrain k a maximum annual growth rate z_k^{rel} and an absolute growth z_k^{abs} can be defined. The maximum supplied volume $V_{i,k}$ of a powertrain in time step i calculates as following (Eq. 1).

$$V_{i+1,k} \leq max\{V_{i,k} \cdot (1 + z_k^{rel}); V_{i,k} + z_k^{abs}\} \quad (1)$$

Furthermore, VECTOR21 considers expected future progress in various fields of vehicle technologies, e.g. increased conventional engine efficiency, lightweight components and the reduction of other driving resistances as well as mild-hybridization of conventional powertrains. These technological advances feed into discrete technology bundles for each powertrain which compete against each other on the market and thus enable a deeper understanding of relevant technological pathways. Market-specific requirements and customs are met by corresponding technological portfolios [18].

2.4 Regulatory Frameworks

National and supranational regulations are considered in this work. Thus, taxes, incentives and bonus/malus at vehicle purchase as well as annual vehicle taxes, value added taxes and fuel and energy taxes are separately considered for each submarket. For a comprehensive overview of relevant regulations see [19].

Special attention is paid to CO_2 regulation - a major driver of a vehicle fleet's technological development. In contrast to the aforementioned regulatory measures the CO_2 regulation is implemented on market level.

A major assumption of VECTOR21 is that OEM ensure to meet the given CO_2 targets in order to avoid penalty fees, and, more importantly, damage to their reputation. Therefore, the model is calibrated to meet the exogenously given CO_2 target in each time step. In case the target is not met, prices of vehicles on the corresponding market are increased cautiously according to their CO_2 emissions before the model algorithm repeats the purchase decision. These price adaptions implement a burden-sharing among vehicle size segments and submarkets with an increased burden for larger vehicle sizes and submarkets with higher customer innovativeness. In this way the contributions reflect the customer budget. There has been no final rule on the implementation of the worldwide harmonized driving cycle (WLTC) in the EU or the US. Hence, CO_2 regulations are considered with the market specific cycle emission. These are the corporate average fuel consumption (CAFE) for the US and the new European driving cycle (NEDC). To allow for a comparison of values, US consumption values are converted in MJ/km or g_{CO2}/km.

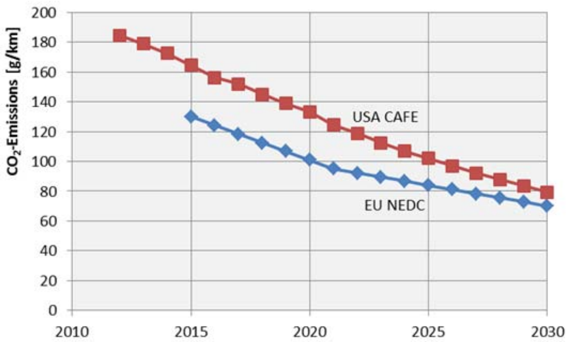

Figure 3: CO_2 fleet emission targets in the EU and USA (own scenario based on [20]–[23])

2.5 Purchase decision

The VECTOR21 customer purchase decision modelled in a two-step process, in line with purchase decision theory [24]. First, customers scan the corresponding market for available vehicles and exclude those that do not match their own requirements, e.g. for refueling and recharging infrastructure. These vehicles are not further considered. In the second step the remaining vehicles are rated according to their relevant costs of ownership (RCO) and CO_2 emissions.

RCO comprise purchase cost, resale value, maintenance and repair cost, fuel and energy cost, motor vehicle taxes as well as any given purchase tax or monetary incentive.

$$RCO = I \cdot (1+r)^n + \sum_{t=1}^{n} \left(A(t) \cdot (1+r)^{n-t}\right) - R \quad (2)$$

A vehicle is purchased for the effective price I at the beginning of the ownership period n. The effective price includes the technology cost, any given taxes and incentives and resembles the amount a customer has to pay when buying a vehicle. Technology costs are calculated bottom-up to cover a technologically detailed cost development over time. The annual costs $A(t)$ of each year t during the ownership period are accounted for at the end of the corresponding time period. They consist of fixed and variable annual costs. Taxes on motorization, if applicable, are fixed annual costs. Variable annual costs are the sum of fuel and energy cost as well as maintenance and repair cost. Residual values R are calculated based on literature findings [25]. The discount rate r is considered to calculate the accumulated value of the RCO.

2.6 Technology cost development

Experience curves are used to endogenously calculate the future technology costs of key components in electrified powertrains (Eq. 3). These curves reflect the improvements in the manufacturing process that are gained with increasing production numbers.

$$K(P) = K_0 \cdot L^{log_2\left(\frac{P}{P_0}\right)} \quad (3)$$

K_0 represents the initial production cost at the initial cumulated production amount P_0. $K(P)$ corresponds to the cost of production at a cumulated amount P. The learning rate L depicts the factor by which the production cost decrease when the production scale doubles. Hence, the sales of alternative powertrains in one year trigger the sales in later years, as costs decrease when cumulated sales increase. Previous versions of the VECTOR21 model only considered the specific development of one market as input for the experience curves. By scaling the resulting sales to a global level, the demand in units of a technology could be derived. Basis for the upscaling was the relation of the global volume of car sales to the volume of the modelled (sub)market. However, this approach implies the same development for the technology demand on all global markets.

2.7 Market linkage

In order to model the interdependence of markets, an appropriate interface must be defined within the model. Models that are used to analyze the interaction of entire economies commonly use imports and exports [26]. As it is not the purpose of VECTOR21 to examine the international trade of vehicles, a different interface was defined. In VECTOR21, the aforementioned endogenous cost calculation of vehicle components can be used. Following each simulation step (i.e. year), the technology sales of all submarkets are cumulated. This sum then serves as input to the experience curve (cf. section 2.6). The model features the possibility to define the level of aggregation (cf. section 2.1). When assuming a long-term convergence of production costs across markets, only one global experience curve per technology (e.g. lithium-ion traction battery) should exist. Thus the global technology costs depend on the sales on each individual submarket. However, high volume markets have, depending on the EV market development, a higher weight to influence the technology costs, than low volume markets.

The VECTOR21 considers individual vehicle prices for each market, since empirical evidence suggests that the convergence of production cost (and retail prices) of cars is not achieved [27], [28]. Differences in labor costs and the existence of market barriers for imports can be named as major reasons for to the divergence [28], [29]. Since the VECTOR21 considers only a common OEM per market, manufacturer's pricing strategies that may lead to differing retail prices are not considered within the model. However, vehicle prices may indeed vary across submarkets just as supply constraints (cf. section 2.3).

The fact that market-specific CO_2 targets have to be met only on average of all submarkets induces a coupling also between submarkets and vehicle size segments: Additional emissions of one submarket vehicle segment can be compensated for in a different vehicle segment and submarket. These linkages are accounted for in the VECTOR21 burden-sharing CO_2 algorithm.

In this way, different attitudes of market-specific customer groups towards alternative vehicles can be reflected, while at the same time, regulatory requirements of a given vehicle market are matched (cf. section 2.4).

3 Key assumptions and data

In order to assess the impact of market interdependence, two exemplary scenarios are calculated using the described modelling approach.

Scenario 1 is defined as reference scenario and reflects an extrapolation of today's situation, considering only minor changes over time. Crude oil price and therefore prices of conventional fuels increase moderately. Electricity is generated according to the submarket-specific mix, with a moderate increase of renewable energy production.

The CO_2 regulation is set to current legislation and is extrapolated for the years not yet covered. The number of new registrations is held constant at today's level. The same applies to vehicle segment shares. Hence, the observed trend towards sports utility vehicles (SUV) is neglected. This assumption can be made as this article focuses on the analysis of market interdependence rather than the calculation of the vehicle fleet's energy consumption and emission.

The key difference of Scenario 2 to the reference scenario is modelled market linkage. In the reference scenario, which resembles the present situation, the technology costs of the two considered markets differ. Hence, the cost of lithium-ion batteries are determined by individual experience curves. Scenario 2, however, reflects a situation in which two large vehicle markets remove all market barriers to reach the convergence of production costs and thus share a common experience curve for lithium-ion batteries. Such a convergence could be realized by, e.g., a free trade agreement. Table 3 gives a comprehensive overview of the main scenario parameters used. These are valid for both shown scenarios.

3.1 Vehicle energy consumption and production cost

Each vehicle market comprises distinct vehicle configurations. Their corresponding energy consumption, see Table 2, is based on the market-specific driving cycle. For the German market gasoline (G), diesel (D), hybrid electric (HEV), plug-in hybrid electric (PHEV) and fully electric (BEV) powertrains are considered. For the US market, an additional flex-fuel powertrain is taken into account. Flex-fuel powertrains are slightly modified gasoline powertrains that allow the usage of alternative fuels with a high percentage of bio-ethanol (i.e. E85).

Table 2: Energy consumption of 2020 model year medium segment powertrains. Powertrain configurations differ by market.

Market	Unit	G	HEV	PHEV	BEV
EU /NEDC	MJ/km	1.16	1.04	0.33	0.43
	l/100km	3.7	3.3	1.1	12.0 (kWh)
	g/km	85	76	24	0
USA /CAFE	MJ/km	1.54	1.02	0.46	0.38
	mpg	47	72	158 mpge	167 mpge
	g/mile	70	47	21	0

The technological improvement and hence the respective energy consumption is considered by discretely defined technology bundles for each powertrain. The input data on efficiency gains and their related costs is based on a meta-analysis of studies on future efficiency improvements [18]. The defined technology bundles are not altered in the two shown scenarios. Figure 4 illustrates the sources of the considered energy consumption improvement for a midsized gasoline powertrain. It shows a comparison of the technologically most advanced model (model year ~2028, 0.91 MJ/km) to the baseline model (model year 2010, 2.15 MJ/km). The additional production cost amount to 5,930 EUR_{2010}. Only the configuration for the European market is shown. Within the scenarios, configurations for all considered powertrains in all markets are provided. As standard consumption values deviate from real world consumption, real consumption values are used in the RCO calculation, whereas standard consumptions are used for regulatory VECTOR21 algorithms, e.g. tests against CO_2 targets. The real world energy consumption of the aforementioned vehicle only decreases to 1.13 MJ/km.

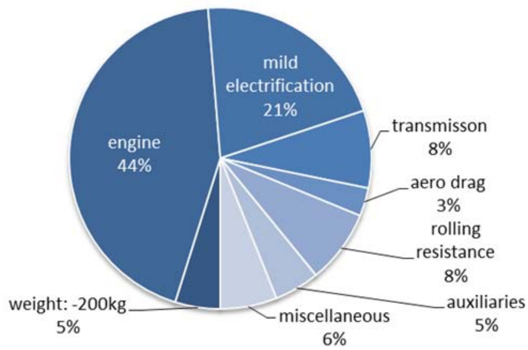

Figure 4: Sources of energy consumption improvements for a gasoline powertrain in the medium segment (2010-2030, NEDC based, own illustration).

Figure 5 depicts the comparison of medium segment powertrains in 2020. The difference in price (before taxes) between a gasoline and Diesel powertrain in the EU amounts to about 3,000 EUR_{2010}. The exhaust treatment alone increases the production cost by about 1,200 EUR_{2010} [30].

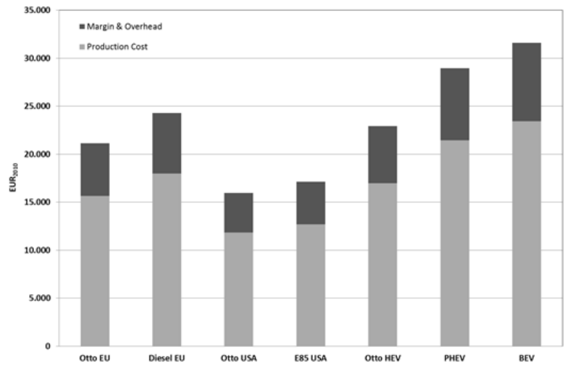

Figure 5: Production costs and net prices of medium segment powertrains in 2020.

Flex-fuel powertrains cause additional costs of 1,200 EUR_{2010} to conventional gasoline powertrains in the US. It has to be noted, that the model endogenously calculates the cost of electrified powertrain components. For the analysis shown in Figure 5 a price of 325 EUR_{2010}/kWh was assumed for the traction battery at system level.

3.2 Traction battery cost

The model calculates the cost of traction batteries endogenously, using experience curves. The battery cost reduction potential originates in the implementation of improved materials (learning-by-searching), the optimization of production processes (learning-by-doing) and economies of scale. Input data, i.e. learning rates for the shown scenarios, are based on a meta-analysis of published cost estimates for lithium-ion battery production [9], [31]. However, the experience varies across markets leading to substantial differences in production costs. Labor and material costs are the major reasons for these differences [29]. Though, the cost of labor is more affected by location [29]. Hence, input values in the reference scenario are adjusted to reflect this imperfect market situation. This is realized by providing a cost curve for each market. Current production of lithium-ion battery cells for automotive application amount to 1,300 MWh in the EU and 4,600 MWh in the US [29]. The application of learning rates derived from the meta-analysis results in average specific production costs of 394 EUR_{2010}/kWh in the US and 476 EUR_{2010}/kWh in the EU. For the purpose of this article, it is neglected that most automotive battery cells are produced in China with an installed capacity of 11,240 MWh. Reason for this is that the import of cells is also associated with costs, which need to be added.

Table 3: Basic parameters considered in the shown scenarios

Parameter	**Unit**	**2015**	**2020**	**2030**	**Source**
Oil Price	EUR_{2010}/bbl	60	54	76	IEA, WEO 2015, New policies scenario
Electricity price Germany	EUR_{2010}/kWh	0.20	0.28	0.32	BMU, Leitszenario 2012
Electricity price USA		0.12	0.10	0.10	EIA, AEO 2014
CO_2-intensity electricity Germany	g CO_2/MJ	152	88	55	BMU, Leitszenario 2012 Szenario C
CO_2-intensity electricity USA		55	52	49	EPA eGRID 2012 and ANL GREET model
CO_2-regulation EU	g CO_2/km NEDC	2015: 130	2021: 95	70	Current regulation until 2021, extrapolation
CO_2-regulation USA (combined cars and light trucks)	g CO_2/km CAFE	2015: 164	102	79	Current regulation until 2025, extrapolation

4 Results

4.1 New vehicle fleet

Figure 6 shows the results of the reference scenario for the US new vehicle fleet between 2010 and 2030. The results of the six modelled submarkets are aggregated according to their sales share. From 2020 onwards HEV begin to gain substantial market shares. In 2020, the average market share for the US amounts to 6 %. However, the results vary across submarkets. HEV market shares in the Pacific submarket will have reached 10 % by that time. Simultaneously the market share for PHEV reaches 6 % in the Pacific submarket, equaling the national average of HEV. The Mountain submarket brings up the rear in terms of EV market shares: 3 % HEV and 2 % PHEV in 2020. Pacific and Northeast, however, surpass the national average. These differences across submarkets are due to the additional monetary incentives given in some states and different electricity generation mixes. Interestingly, BEV market shares develop quite evenly across the US submarkets, reaching about 15 % market share in 2030. Flex-fuel vehicles play an important role in the transition to a less emission-intensive passenger car fleet. Their average market share amounts to 18 % in 2020 and decreases only slightly to 16 % in 2030. As these vehicles still allow the usage of conventional gasoline, a substantial effect on the emission of the passenger car and pickup truck fleet remains questionable.

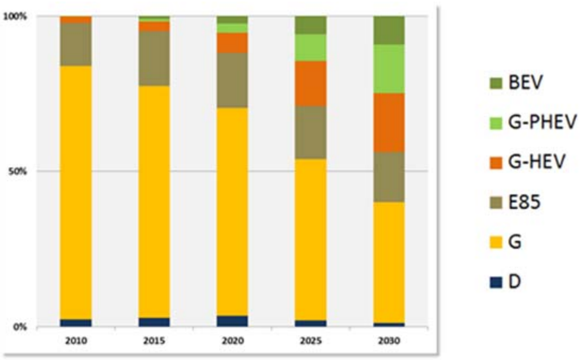

Figure 6: Results of the reference scenario for the US market.

In Figure 7 the results for the German new car fleet are shown. The market share of HEV experiences a strong growth from 2018 onwards. In 2020, their share reaches already 24 %. This can be explained by the tightening CO_2 regulation and their increasing competitiveness compared to e.g. Diesel powertrains, which suffer from increasing costs for exhaust treatment. Costs of conventional gasoline vehicles increase with the introduction of further fuel-saving technology bundles in order to meet the CO_2 regulation targets. With growing demand the production costs of EV powertrain components decrease, making PHEV and BEV more affordable in the long term.

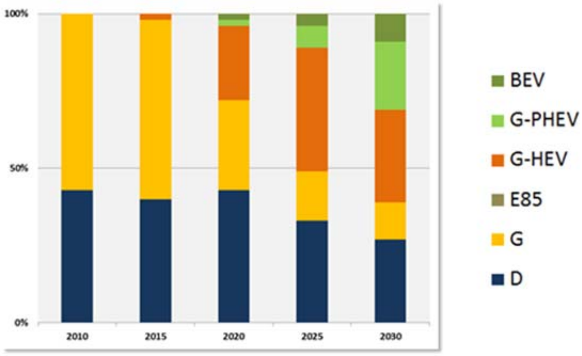

Figure 7: Results of the reference scenario for the German submarket

4.2 Effect of market interdependence

The competitiveness of fully electric powertrains in the US can be partially explained by the relatively higher demand in other electrified powertrains like HEV and PHEV. With their aggregated volume of about 5.2 million new vehicles per year, the more progressive submarkets Pacific and Northeast influence cost curves in the US. Therefore, prices of EV decrease in submarkets, even when their EV market shares are insignificant.

This spillover effect can also be observed on the superordinate market level. Once there are no additional costs involved when accessing a global market for EV components, more progressive submarkets can even influence the costs in any market and submarket across the world. In scenario 2 such a situation is simulated. Figure 8 illustrates the impact on the aggregated powertrain market shares as relative difference to results in the reference scenario. For that purpose the absolute results of all submarkets are summed up and compared between the two scenarios. As the aggregated volumes of electrified powertrains are comparatively low up to the year 2025, the existence of only one global cost curve has a substantial impact on their market shares. With increasing market shares differences decrease. The established powertrains show an opposing trend. At first their market volume causes only a slight relative reduction. In the long term, as the electrified powertrains take some further market shares, the impact grows.

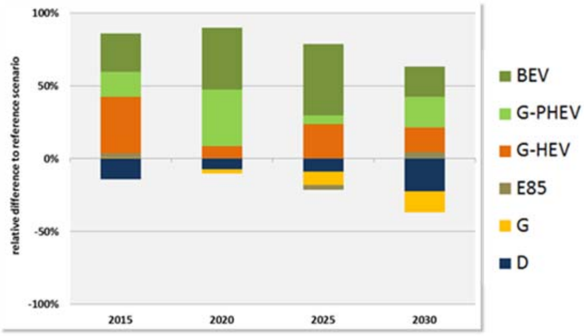

Figure 8: Relative differences of aggregated market shares between scenario 1 (reference) and scenario 2 (free trade)

In scenario 1 the production cost of traction batteries reach a minimum of 247 EUR_{2010}/kWh in the EU and 229 EUR_{2010}/kWh in the US. The cumulated sales of EV (HEV, PHEV and BEV) amount to 4.5 million in Germany and about 16 million in the US. Thus, explaining the difference in production cost. In scenario 2 the global production cost of traction batteries reach a minimum of 179 EUR_{2010}/kWh. This results in cumulated sales of 23.4 million EV between 2010 and 2030. This corresponds to 14% additional sales.

5 Conclusion

The comparison of new vehicle sales scenarios in Germany and the US with and without market interaction shows that these interactions can have a strong effect on the combined market uptake of alternative powertrains. The positive market interactions are a major driver of the EV-uptake: Assuming a tightening CO_2 regulation with 2030-targets of 70 g/km (NEDC) in the EU and 79 g/km (CAFE, cars and trucks combined) in the US, EV can reach market shares of up to 61% in Germany and 44 % in the US in 2030. Assuming no transaction costs between markets, an additional three million EV can be registered in these regions. However, the market penetration of EV might be hampered substantially if, upon reversion, significant market barriers between the US and Europe apply to components of electrified powertrains, i.e. lithium-ion batteries.

Future work should incorporate the Chinese car market in order to better evaluate the market interdependency and overall fleet emission.

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