System Dynamics Simulation of the End-Customer and Raw Materials Market of Electrified Vehicles

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Extended Abstract

Since the beginning of the 21st century, the importance of electromobility is rising significantly, benefitted by high emission standards, rising fuel costs, environmentalism and political influence (e.g. through buyer's premium or free public parking for electric vehicles). Besides electromobility, other trends like autonomous driving or mobility-as-a-service change our whole behavior. Paralleling these trends, however, factors like customer behavior, infrastructure, new competitors and technological improvements cause high volatility in forecasted market volumes for electric vehicles. It is difficult for companies to comprehend this volatility and to assess its impact not only on their own company, their logistics and also on the entire supply chain. This poses a major challenge, especially for the production of automotive traction batteries, as rare and scarce raw materials are used. By processing e.g. cobalt it is decisive to simulate the impact of the end-customer market, the raw materials market and all interactions between these two markets. This enables a company to determine the raw materials availability and adapt its production as well as its supply chain. To define the need for further research, we analyzed existing simulation models of the mobility, end-customer and raw materials market, which use a System Dynamics simulation. The mobility and end-customer market simulation is used in a wide range of tasks. In their simulation, STRUBEN and SHERMAN examine the US market for alternative powertrains and identify challenges that influence an increasing distribution of alternative powertrains. Based on the model, SHEPHERD ET AL. simulate the distribution of electric vehicles in the UK over a period of 40 years. GORBEA, on the other hand, uses a System Dynamics model to simulate the US market for electric vehicles in 2020 and YANG looks at the mobility development of a Chinese city. In addition to the work presented here, there are a number of other market simulations, which all only focus on one specific end-customer market and do not consider any relations between different end-customer markets. A large number of different parameters are examined in the scientific literature working on simulations of the raw materials market. KEILHACKER, who models an entire supply chain, investigates possibilities to avoid supply bottlenecks for rare earths. The UMBRELLA RESEARCH GROUP examines the main influencing factors of the availability of lithium and cobalt and analyses them using a System Dynamics model. Another model that investigates the longer-term availability and price development of lithium originates from SVENDRUP. In addition to the models presented, other research exists, but none of them takes into account the reciprocal effects between end-customer and raw materials markets. Consequently we found a scientific research deficit, which firstly consists of the combined consideration of the end-customer and raw materials markets as well as their interactions and secondly in modelling different end-customer markets in one simulation model. In this paper we develop a simulation, which addresses both research deficits. We model the end-customer market for Europe (EU), NAFTA (USA, Canada and Mexico) and China. Thereby we also include new mobility services and predict their

development. Further we simulate a raw materials market for Cobalt and we model all reciprocal effects between these markets.

In general, a simulation model is used to reproduce reality in order to analyze the system behavior with external and internal influencing variables. Therefore, we use the System Dynamics method. It was developed by FORRESTER and is used to create a higher understanding about the structures of complex problems. Especially STERMAN proofs the method's application in a broad field of use cases. This method enables us to model dynamic interactions as well as non-linearities and feedback loops between the system elements. First, we develop an end-customer market model for the economic regions NAFTA, EU and China up to the year 2024. We forecast the number of units for three reference cars: the VW Golf as a conventional vehicles (CV), the BMW i3 as a battery electric vehicles (BEV) and the Toyota Prius as a plug-in hybrid electric vehicles (PHEV). The aim of the market forecast is to assess the influence of different parameters and to predict the customer's decision about buying a BEV or PHEV instead of a CV. We have partitioned the simulation of the end-customer market into four modules: vehicle demand, charging, total cost of ownership and the purchase decision. The vehicle demand includes parameters such as vehicles per person, long life, mobility-as-a-service, urbanization or the gross domestic product. The charging module is influenced by the range of the battery and charging infrastructure. We define the total cost of ownership by different costs such as investment costs, operating costs and state subsidies. The purchase decision is based on the total vehicle demand and the results of the preceding modules. Secondly, we model the raw materials market for Cobalt. We investigate the Cobalt availability, differentiated into primary and secondary Cobalt. Even though we focus on Cobalt, the model has a generic set up and can be used for all battery raw materials with small adjustments. In addition to the demand resulting from the end-customer market simulation, we complement the cobalt demand with cobalt requirements of other industries. These include e.g. batteries for consumer electronics, as well as industrial applications such as high-speed steel and magnets. The model for simulating the raw materials is divided into primary and secondary cobalt modules. The primary raw materials module includes cobalt reserves, cobalt extraction and mine efficiency. The secondary raw materials module consist e.g. of recyclable cobalt-containing products after their average lifecycle time. Likewise, traction batteries flow into the available amount of cobalt as a secondary raw material after second usage, e.g. in a stationary energy storage. Furthermore, we investigate the efficiency of different recycling processes.

The validation of the model behavior is based on historical data from various databases and was compared with the results of other scientific studies. We conduct our research on three different scenarios per model and combined the scenarios with each other. Within these scenarios we vary the parameters, which are relevant for the purchasing decision of the end-customer market simulation. Further we assess the influence of primary and secondary raw materials on the availability, the development of market volumes and various recycling techniques. The results of the end-customer simulation show that the future spread of electrified mobility strongly depends on country-specific conditions. The volume varies in the three economic regions depending on the scenario. The total volume varies between 2.8 % and 22.4 % BEV share and 1.7 % to 23.5 % PHEV share in the year 2024. In Figure 1 we show the forecasted development of the BEV and PHEV market shares in Europe depending on the scenario.

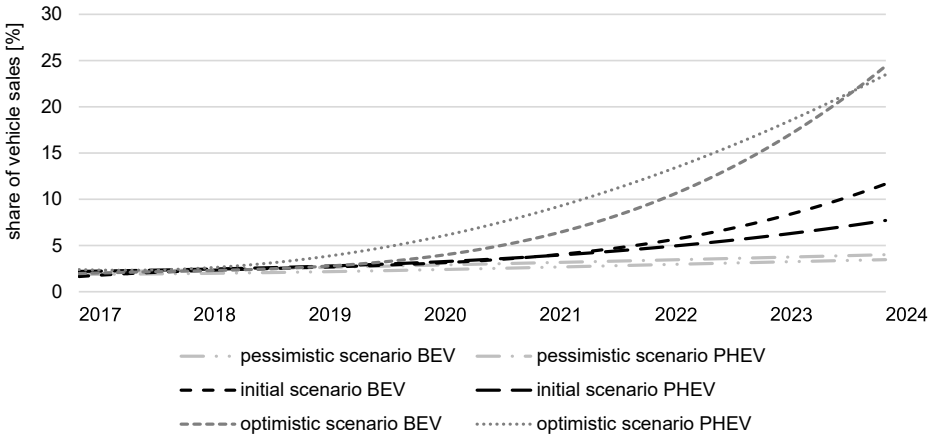

Figure 1. Forecasted development of the BEV/PHEV share in Europe

The analysis of the raw materials market for cobalt revealed three findings for the optimistic demand scenario of all three markets and the pessimistic raw materials scenario. Firstly, the cobalt demand will double by 2024. This is primarily a consequence of the growing demand for traction batteries. Secondly, from 2022 onwards, the demand for primary Cobalt will no longer be sufficient. Therefore, the demand can only be covered by secondary Cobalt. Thirdly, cobalt demand in 2024 will exceed total cobalt production, which means that supply security can no longer be guaranteed. These results are shown in Figure 2.

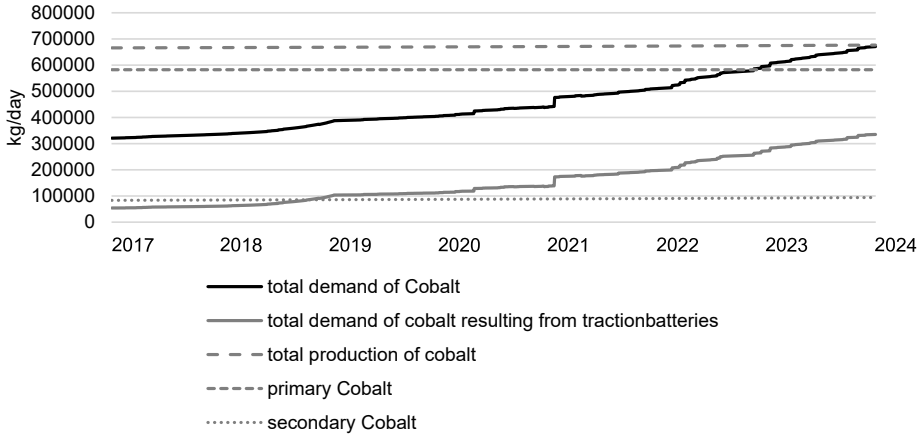

Figure 2. Results of the raw materials market simulation

Our developed simulation models offer a starting point to increase the market understanding for the mobility market focusing on electric vehicles. We consider relevant parameters including new mobility trends. With the System Dynamics simulation we can estimate the influence of each parameter and derive recommendations for further measures. In addition, the combination of a mobility and end-customer market with a raw materials market simulation provides the opportunity to identify supply bottlenecks in time and to develop alternative supply strategies. We see a demand for further research in the extension of the raw materials model to additional raw materials and the investigation of broader scenarios. Further we want to include the logistics of the raw materials to integrate local conditions of the mining countries