SYSTEM–BASED FEEDBACK ANALYSIS OF E-MOBILITY DIFFUSION IN CHINA

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Abstract (193 words):

In the passenger car sector purchasing decisions are driven by economic factors and acceptance. Based on cost analysis, the factors which can be dedicated to different technologies are fuel costs and purchase price. The decision to buy a new car is always accompanied by comparing the costs of different alternatives. This leads to a compilation of costs and acceptance for each technology in terms of negative utility.

In this study the development of the global atomotive market with a focus on China as the most important emerging market is analyzed considering both the diffusion of alternative drives and the development of car segments.

The decision process on a micro level is solved by a Logit-Model. The realization within a system dynamics model allows the modeling of feedback loops.

As opposed to earlier studies on future automotive markets in which the availability of key raw materials for alternative drives was not taken into account, the model presented in this paper gives an example of how to simulate feedback effects from raw material markets on the diffusion of emerging technologies. For this purpose, taking cobalt as an example, the effect of increasing battery production on the demand for raw materials and raw material pricing is analyzed including the feedback of higher battery prices on the development of electro mobility. This is realized by simulating two scenarios with and without the raw material feedback loop and a subsequent comparison of the results.

1 INTRODUCTION

Over the course of the last decade global warming has become more and more important for environmental policy. The reason for increasing average temperatures and air pollution on planet earth is mainly found in the emission of greenhouse gases, which consist first and foremost of carbon dioxide. Carbon dioxide is the chemical product of combustion of fossil fuel. These emissions are emitted by industries, households and traffic. The White Paper by the European Commission (EUROPEAN COMMISSION 2011) published in March 2011 clearly declares resource efficiency and the reduction of greenhouse gas emissions to be one of the major targets of future transport.

The Traffic sector itself can be divided into three sections: private cars, public transportation and freight service. Due to an increasing population in most emerging countries, the influence of private cars will increase in future. So it seems reasonable to take a closer look at the emissions of cars and the potential possibilities to influence their emissions by state driven environmental and traffic policies.

The only way to escape the current cycle of fossil fuel combustion is to utilise alternative fuels and drives. These new technologies have to be introduced to a market which is highly dominated by technology acceptance and economic pressure.

As the emerging countries will play a dominant role in the future of the automotive market, a closer look at these markets is absolutely essential. China is one of the most dynamic markets with big megacities highly usable for battery electric vehicles (BEV). Therefore, the Chinese market will dominate the future consumption of cars and especially the market for alternative drives. Therefore, beside global Figures, most results published in this paper concern the Chinese automotive market.

The aim of this paper is the simulation of the diffusion of alternative fuels and drives worldwide, mainly based on the decision theory with a number of feedback loops in the field of demand and offer. The increasing demand for raw materials and the resulting market dynamics caused by the fast diffusion of emerging technologies have to a certain extent a strong effect on raw material prices, as raw material supplies might temporarily not meet the demand. This influences the production costs and might threaten the economic viability of the technology ending up in decreasing market diffusion which once again has an effect on the dynamics of the raw material market and pricing. This feedback effect, which is a typical aspect of the system dynamics theory, has not sufficiently been taken into account in previous studies on the development of the automotive market.
A key requirement for the diffusion and the competitiveness of alternative drives, especially of hybrid and full electric vehicles, is the availability of high capacity battery systems on commercially acceptable terms. As the cathode material is the largest component in raw material costs of a lithium ion battery (TÜBKE 2011), the effect of increasing battery demand for electric vehicles and the resulting rising global market demand on cobalt, which is mainly used for lithium ion battery cathodes, is analyzed.

After a short technical introduction presenting all the possible alternatives and potential cost developments especially for BEV, the second part has its emphasis on the modelling of the decision process for new cars, which is the core of the model used to describe the process in further detail. The system dynamics methodology is the best approach to model these dynamic markets. The reasons for this are the use of feedback loops, stock variables in model fleets and the possibility to combine the discrete choice approach with system dynamics methodology.

2 TECHNOLOGY DESCRIPTION

The next step is the evaluation of different alternative drives and their potential application in cars. This evaluation is basically the result of research in papers, magazines and books. Today's experiences with alternative drives are barely reported, so this paper is mainly based on assumptions. The following page lists the drive categorization used in the model:

- Conventional Combustion Engine (ICE)

  The conventional combustion engine has a long history. Meanwhile the technology is available for different fuel types. Gasoline and diesel can be used as well as compressed natural gas (CNG), liquified petroleum gas (LPG) and bio fuels. The big advantage of the ICE is the broad knowledge of the technology and energy storage which allows the vehicles to travel long distances (up to 600 km). These facts make ICEs highly acceptable by the general population.
  Bio fuel wich includes bio diesel, bio-ethanol and bio-gas is produced from organic plant material. In recent years, bio fuel has often been regarded as the solution to all energy problems. The truth is that the space needed to grow enough plants to supply fuel in vast amounts is not available and the risk of prioritising the available space for food production is high. However, it can be used for the already existing combustion engine without major modifications.
  Increasing the low energy density of natural gas requires either compression or liquefaction. Difficulties with liquefaction tend to be the single consideration of CNG. Compressed natural gas is normally transported by pipelines from countries where natural gas is located. The petrol station offers compressed gas via a special infrastructure. The tanks in the vehicles have to be extremely pressure resistant which increases the weight.

- Hybrid Technology (Hybrid)

  Hybrid technology recovers energy from every breaking process. Hence the more breaking processes there are the more energy can be recovered. This energy is returned to a battery to use for the electric drive. In general, hybrid means the combination of two or more different drives. A very common variant is the combination of an electric drive and a combustion engine.

- Plug-In Hybrid (PHEV)

  Plug in Hybrid is a technology which combines a combustion engine with an electric drive. The combustion engine may supply the electrical energy for the battery and the electric drive (range extender) or may directly contribute to the drive of the axes (power-split). In both cases a battery is needed to save the electricity. In addition, it is possible to charge the battery. This technology seems to be a practical solution for the commuter who makes few long distance trips.

- Battery Electric Vehicle (BEV)

  The electric drive is already partly used in cars. There are also applications for bigger vehicles like locomotives or trolley buses. Electric drives have the advantage of being highly efficient, especially in urban areas and they are constructed relatively simply as a gearbox is not required. So far the electric drive seems to be the best choice for every vehicle. However, the problems are not related to the drive but to the energy storage on board the vehicle. At the moment Lithium–Ion batteries appear to be the only technology able to handle large amounts of energy storage combined with relatively moderate costs. The drawbacks include low durability and high material costs (KÖHLER 2007). According to current studies on BEV, in the long run, prices are expected to decrease while storage capacity will increase, making full electric vehicles widely available by 2030 (TATSUMI 2007).

- Fuel Cell Electric Vehicle (FCEV)

  The fuel cell transfers energy from hydrogen to electricity by chemical reaction. Fuel cells are mostly combined with an electric drive which includes the advantages of electric drives especially in urban areas. The fuel cell itself is a complicated new technology with high maintenance costs and high investment costs. The main problem besides the drive technology is the tank technology. Hydrogen has a very low energy density, which is even lower than that of gas. Hence, there are two possibilities to raise this density: high pressure or liquefaction by reducing the temperature. Both methods need strong and heavy materials increasing the tank weight and the price.

Both hybrid and plug-in hybrid cars source their energy partly from batteries, and full electric vehicles are entirely powered by batteries. Therefore, the availability of energy storage technologies with high capacities and high energy densities is the key requirement for future development and competitiveness of electro mobility. While specific electric engines have already reached a high level of efficiency with little potential for further improvement, the development of energy storage technologies remains challenging both from a technical and economical point of view.

Until fuel cells are applicable as an energy source, rechargeable lithium ion batteries, currently widely used as energy storage in all kinds of electronic applications, are the most promising electrochemical storage for transport systems. The high energy density, which both affects the weight and the volume of the battery, is the main advantage of lithium ion batteries over other storage technologies. Figure 1 displays the energy and power densities of common electrochemical (batteries) and physical (capacitors) storage systems.

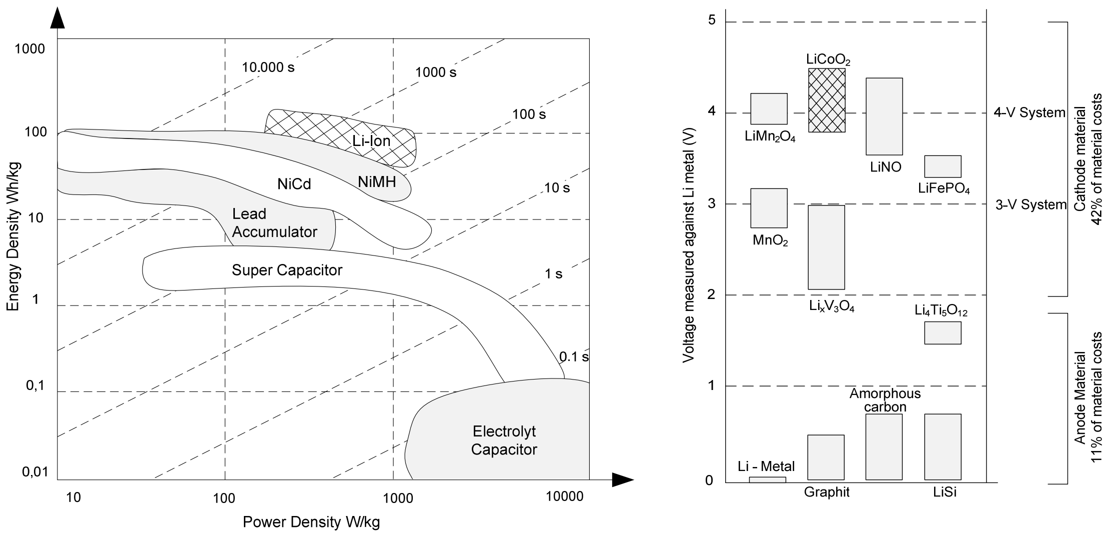

Figure 1: Energy and power densities of batteries and capacitors (KETTERER 2009)

However, there is not just one lithium ion battery system with consistent properties and characteristics. Cell technologies differ, in particular, with regard to both cathode and anode material. Figure 1 (right side) shows the electrochemical potential of different anode and cathode materials. The higher the distance between the bars in Figure 1, the higher the resulting voltage of the battery. As elementary lithium - which theoretically is the best anode material - shows high corrosion and little temporal stability, today graphite is the common anode material. Graphite is currently used in almost all lithium ion batteries for electronic applications as well as in large high power battery systems for electric vehicles of which many are still at development and demonstration stages (KETTERER 2009).

While anode material (usually graphite) amount to about 10% of the total material costs in lithium ion cell production, the costs of cathode materials constitute over 40% of total material costs (TÜBKE 2011). This is due to the high price of cobalt which is currently the main material for lithium ion cathodes ($LiCoO_2$), especially for electronic applications. However, because of its high price, its negative impact on the environment and its comparatively low capacity, $LiCoO_2$ cathodes are not likely to be used in large scale batteries for electric vehicles. Alternative materials such as $LiMnO_2$ (lithium manganese oxide), LiNiO (lithium nickel oxide) $LiFePO_4$ (lithium iron phosphate) all show different disadvantages such as low thermal stability, high corrosion, lower electrochemical potential or lower rates at which the cathode absorbs and emits free lithium ions (KETTERER 2009). In the near future mixed oxides of the aforementioned materials such as $Li(Ni_{0,85}Co_{0,1}Al_{0,05})O_2$ or $Li(Ni_{1/3}Co_{1/3}Mn_{1/3})O_2$ are most likely to be used for cathode production. Consequently, even though pure $LiCoO_2$ might not be used for large batteries in electric vehicles, cobalt will remain a key raw material for lithium ion batteries (TÜBKE 2011). In the long run, increased use of non cobalt containing materials like $LiFePO_4$ or special polymer materials is expected. As forecasting this future development is accompanied by a high degree of uncertainty, this study supposes the continuous use of cobalt in mixed oxide cathodes. The intention behind this assumption is to underline the effect of electro mobility development on the comparatively small cobalt market. Already today lithium ion battery production for electronic equipment has the largest share of the cobalt market with around 25% (ROSKILL 2010). The amount of cobalt within a mixed oxide lithium ion cell cathode (NMC nickel manganese cobalt) is estimated at 490 g/kWh (KONIETZKO 2011). By assuming continuous cobalt use for cathode production, the effect on market dynamics caused by an increasing share of electrical vehicles and the influence on battery prices which once again influences the development of electro mobility is analyzed.

3 METHODOLOGY AND MODEL DESCRIPTION

The aim of this paper was to create a simple model combining technical and economic issues as well as the system dynamics methodology and discrete choice approaches. This part will show how the diffusion process of alternative drives was realized in a system dynamics model and which further scientific methods were used within this model. The model was developed on a global scale based on the consideration of lead markets (especially the emerging countries). The combination of traditional system dynamic approaches with the discrete choice theory allows realistic modelling. The advantages are described above.

Using system dynamics as a modelling framework enables the simulation of feedback loops to create a model which is as realistic as possible. Furthermore, the system dynamic modelling is not based on the equilibrium theory of the classic economic approach. Hence, there are almost no limits in the modelling process, which may also be seen as one of the disadvantages. The main reasons why the system dynamics approach was used in this model is on the one hand the easily creatable connection to already existing modules of the ASTRA (SCHADE 2004) model and on the other hand the possible enlargement to create a more realistic, improved model. This can be realized as soon as there is more information about the diffusion process and the different technologies. Then the extension of more feedback loops will become necessary.
Within the system dynamics environment, different scientific approaches are used. The following part describes the realization of intra-model modules with the utility based Logit-theory and the learning-curve-theory.

The created model is divided into different modules. The reasons therefore are a better overview as well as the possibility to run the modules as stand-alone modules, so that every single influence can be analyzed on its own.
The following paragraph gives a short overview of the whole model as well as a detailed description of the important modules.
The model consists of five modules. The aim is to cover economic aspects as well as demographic influences. Figure 2 illustrates the model structure and the links between the modules.

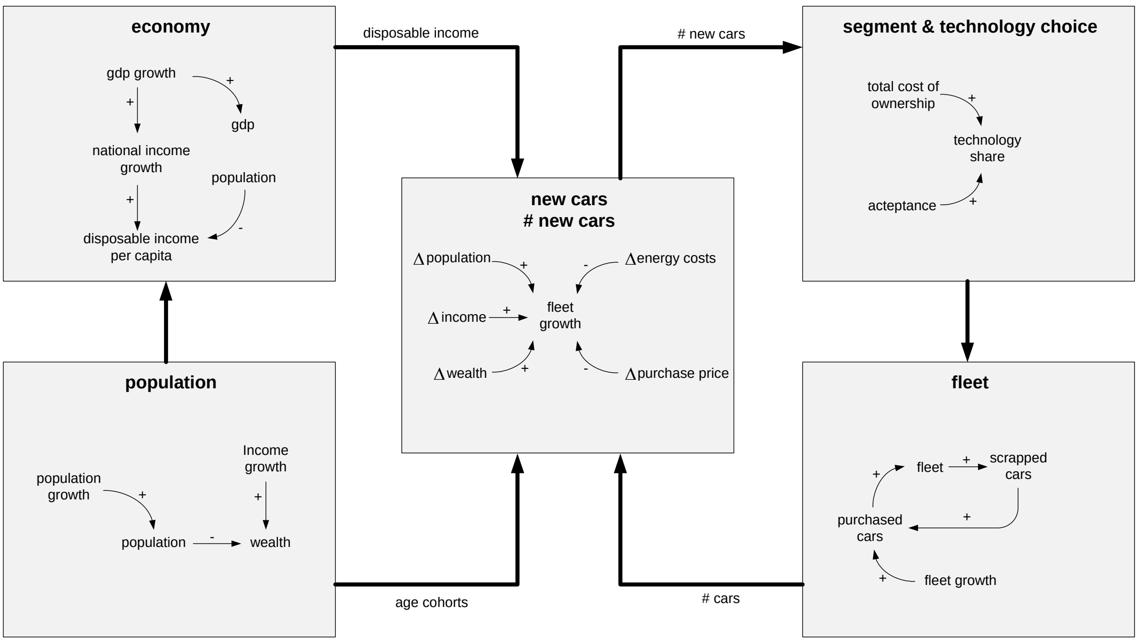

Figure 2: model structure

The economic module

The core of the economic module is the calculation of the GDP per capita. This calculation is based on an external growth rate forecast of GDP. Following the basics of the national accounting, the growth rate influences private consumption and hence the income of private households. Depending on the saving rate the disposable income may vary over time. The major output in this module is the development of the disposable income.

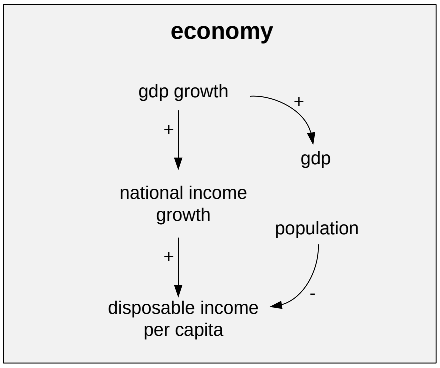

Figure 3: economy module

The population module

The second module forecasts the development of the population divided into different age cohorts. As already mentioned above, the input in this module is an exogenous population growth rate. One idea to enlarge this module is to consider the population's wealth, combining economic aspects with demographic ones (share of population crossing the poverty line). The output of this module is a distribution of the population by age cohorts.

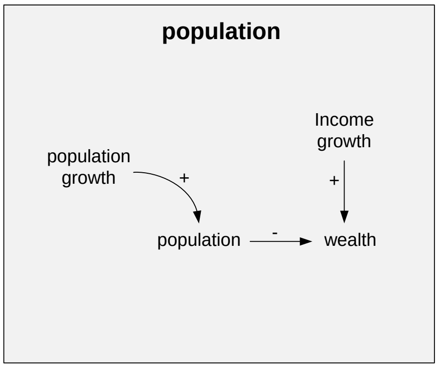

Figure 4: population module

The car fleet growth module

Compared to the first two modules, the car fleet growth module is much more complex. The inputs in this module are the results of the population module as well as those of the economic module. The core of this module is the calculation of the vehicle fleet growth. There are influences which accelerate fleet growth and others which decelerate growth. As a matter of fact, every single influence factor has to be weighted. This is done by a calibration based on historical fleet growth data. The accelerating factors are the growths of disposable income and population (aged over 18 years) Figure 5 shows the causal loop diagram of this module.

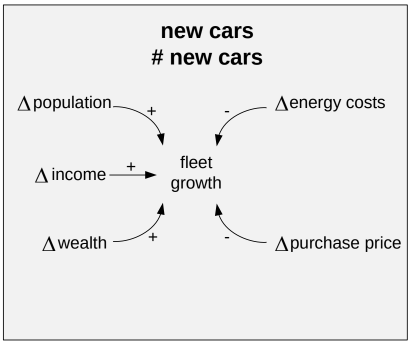

Figure 5: car fleet growth module

The module has many interactions with other modules. The two following feedback loops are essential. Feedback loop 1 (Figure 6) represents the relation between car stock and energy consumption. The larger the car stock, the higher the energy consumption and hence, due to energy shortage, the prices. High prices lead to less demand for new cars.

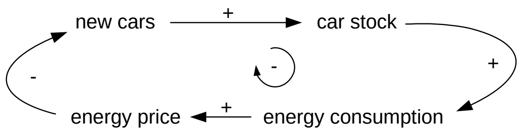

Figure 6: feedback loop for energy prices

A similar relation exists between the number of sold cars and purchase prices. The more cars are sold, the higher the likelihood of production shortage and consequently the higher the price. High car purchase prices lead to less demand for new cars.

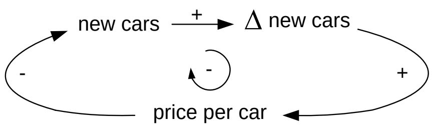

Figure 7: feedback loop for purchase prices

Car fleet model

The car fleet model is realized as a classic stock model with the car stock as level variable and the number of purchased cars as inflow corresponding to the number of scrapped cars as outflow. The simple structure is displayed in Figure 8.

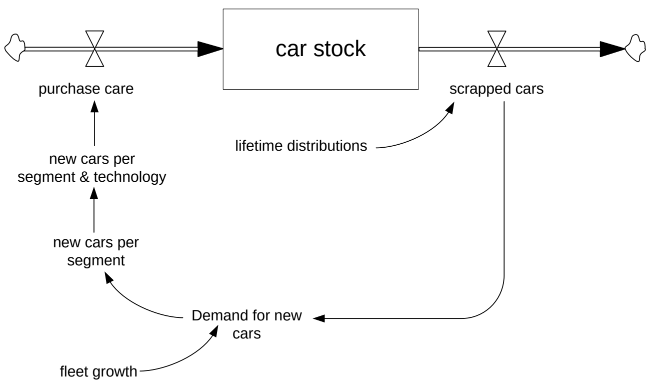

Figure 8: car stock model

The segment and technology choice module

This module is divided into two parts: a very simple segment choice part and the more complex technology choice. The segment choice is realized with a simple constant segment distribution found in the literature (Frost & Sullivan 2009). The aggregate segments used in the model are:

- Basic
- Small
- Medium and
- Luxury

The technology choice is an important part of assessing the influence of changes in battery technology. As not every technology will be available in every segment, the technology choice is based on the segment choice.

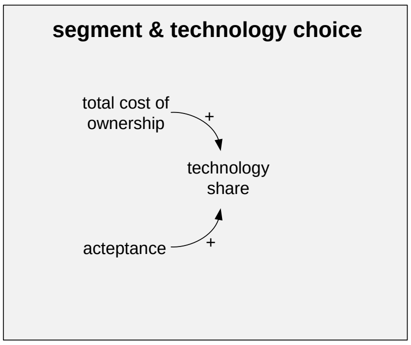

Figure 9: segment and technology choice

Taking a closer look at the decision process of the car user, it is useful to review some economic theory. The decision is driven by economic forces. So the consumer compares the costs of all alternatives before making the decision. The aim of this process is a utility based decision, where costs mean nothing but negative utility. Utility of an alternative can be expressed as the sum of a constant function plus a confounding factor simulating uncertainty (equ. 1).

$$u = v(x) + \varepsilon \qquad \text{(equ. 1)}$$

$$u = \alpha + \beta_1 x_1 + \beta_2 x_2 + \ldots + \beta_k x_k + \varepsilon \qquad \text{(equ. 2)}$$

$where$
$x_1 \ldots x_n = attribute$
$\beta_1 \ldots \beta_n = utility\ coefficient$
$\propto = level\ parameter$
$\varepsilon = confounding\ factor$

This constant function can be split into a level parameter, different attributes and the appropriate utility coefficients. So each alternative can have different attributes weighted by utility coefficients. Hence, the utility of each alternative can be calculated as the attributes are given. In practice, the utility coefficients are estimated on the basis of past values.

A person now prefers alternative i to another alternative j, as long as the utility of i is higher. The likelihood of choosing an alternative equals the likelihood of having a higher utility. (equ. 3)

$$P(i) = P(v_i > v_j) \qquad \text{(equ. 3)}$$

As already mentioned above, there is a confounding factor. A Gumble distribution of this factor leads directly to the following equation, calculating the likelihood of choosing an alternative:

$$P(i) = \frac{e^{v_i}}{\sum_{j=1}^{n} e^{v_j}} \qquad \text{(equ. 4)}$$

$where$

$v_1 \dots v_n \;:\; utility\ function\ of\ alternatives\ 1-n$

This model is also known as the Logit-model used for traffic choice models based on costs and time needed for different destinations in traffic networks. The output is normally the so-called modal split which shows for instance which percentage of the population uses public transport.

In order to model the diffusion of alternative drives the overall costs have to be calculated as follows:

$$C_i = aC_i + kC_i \qquad \text{(equ. 5)}$$

$where$

$C\ = overal\ costs\ per\ vkm,$

$aC = investment\ costs\ per\ vkm$

$kC = fuel\ costs\ per\ vkm$

$i = index\ for\ the\ different\ technologies$

In the first step of the simulation, the focus is on the costs which are influenced by the type of drive and fuel. First of all, investment costs differ significantly between hydrogen technologies, electric drives and conventional technologies. For instance, in today's urban bus market, a fuel cell bus is twice as expensive as a diesel bus. (EBERWEIN ET AL. 2009) The second big share of the total cost of ownership (TCO) is the fuel cost, which strongly depends on the type of fuel and fuel consumption. There are also costs based on tax or toll. At the moment, these costs are not dependent on the technology used. In order to simulate different scenarios with political measurements, the model is able to include these costs and also those for emissions.

All these costs taken together are considered as negative utility. The core of the model is the logit model handling all the different costs components, as illustrated in equation 6:

$$P_i = \frac{\exp(-\beta_i \cdot (\lambda_i \cdot C_i + \varepsilon_i))}{\sum_j \exp(-\beta_i \cdot (\lambda_i \cdot C_i + \varepsilon_i))} \quad \text{(equ. 6)}$$

$where$
$P = share\ of\ new\ registrated\ cars\ per\ technology$
$C = overal\ costs\ per\ vkm,$
$\lambda = factor\ Lambda$
$\beta = Logit\ factor\ Beta$
$\varepsilon = neagtive\ utility\ at\ launch$
$i = index\ for\ the\ different\ technologies$

Finally, the results are the shares of technologies. These shares lead to a composition of the car stock. The future aim is to forecast the emission of the car sector based on this composition.

As well as the theory of utility based decisions, another economic theory is very important for the understanding of the model behaviour. As most alternative technologies are not yet used on the market, it is very important to forecast the key data for each technology.

The diffusion of new products accompanies changes in the production process, leading to lower prices. Only low prices accelerate the diffusion. Lower prices are generally achieved by decreasing economies of scale. That means that a higher number of produced goods lower the costs per unit. A foundation therefore is the learning process in companies. (GRUPP 1997) The original theory was applied to the industrial assembly of airplanes (WRIGHT 1936). The main point of this theory is nothing other than increasing production expenditure with higher numbers of produced units. WRIGHT (1936) assumed that the production costs would increase at a constant rate. Equation 7 shows the reciprocal power function.

$$y = \frac{a}{x^b} = a \cdot x^{-b} \quad \text{(equ. 7)}$$

$where$
$y = average\ costs\ for\ producing\ the\ xth\ unit$
$a = costs\ for\ producing\ the\ first\ component$
$x = number\ of\ components\ produced$
$b = degression\ factor$

The idealistic analysis of WIRIGHT (1936) does not consider the real progress during production of new products in detail. The realistic development of the learning curve is related specifically to each production process.

It is important for the model that the key data of each technology investment and maintenance costs will change in future. The costs will decrease due to the aforementioned learning curve. As the costs change, so will the decision towards new technologies. Table 1 shows the development of the different costs:

Type of cost	development
Maintenance costs	Decreasing due to learning effects in maintenance
Fuel costs	Decreasing fuel consumption due to higher efficiency of the drives, increasing prices due to shortage of resources
Refuelling costs	Decreasing due to learning effects and better infrastructure
Investment costs	Decreasing due to learning effects in the production process

Table 1: different costs and their future development

Mirroring the costs, tank technology will also develop in the coming years. The learning curve will lead to lighter tank systems, which will make alternative technologies competitive. The market entrance of the new technologies is closely linked to the weight and cost of the tank system. Hence, the model simulates a progression in tank technologies.

Taking all this together, the model consists of two main parts: the consumer's decision process concerning alternative drives driven by utility comparison, and the simulation of the car stock. The time horizon for the simulation is 2030. The next chapter shows the results of the simulation and comments on them.

The model calibration is based on the data found in literature. As the quality of this data is partly scarce, the calibration would be much better if there was more experience of alternative drives in the car sector. The forecast will improve once the first alternative drives are estabished on the market in the coming few years.

3 ANALYSIS AND RESULTS

The common steps after creating a model are to check validity and expressiveness. The given model combines content with scientific approaches – such as the *diffusion theory*, the *learning curve theory* and the *utility based decision theory* – and self accomplished technological assessment. Due to a lack of market exposure of most alternatives, some parameters of the model have to be estimated.

This chapter presents selected deliverables which appear interesting. Two different scenarios are considered to compare the development of BEV with and without the feedback loop for cobalt consumption and battery price development. Hence, the following scenarios have been taken into account:

Scenario 1:
Scenario 1 is based on a technology friendly development of the political framework. There will be a maximum of feebates to support consumer decisions. These feebates will reduce the purchase price of BEV as well as of FCEV. Promotion and information campaigns concerning new technologies will lead to a higher technology acceptance. The prices of the technology components are only driven by technological development. Shortage caused by an increasing demand for resources is not considered.

Scenario 2:
Scenario 2 is generally based on the political and technological framework of scenario 1. The difference is that the resource consumption will lead to higher prices due to a shortage on the market. Based on this fact, the technology choice will be influenced. As explained above increasing prices for one technology will decrease the likelihood that this technology is chosen. Figure 10 illustrates the feedback loop implemented in Scenario 2.

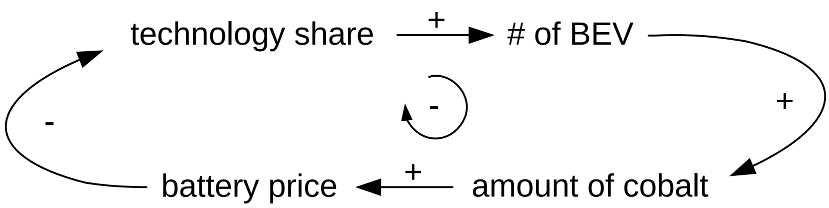

Figure 10: feedback loop of cobalt

Initially the results of scenario 1 will be presented. The assumptions for the Chinese market are – as already mentioned – a large accessibility to infrastructure (electric fuel stations) as well as a high acceptance of alternative technologies within the population. This leads to a relative high share of BEV until 2030. Figure 11 shows the total development of car sales in China until 2030.

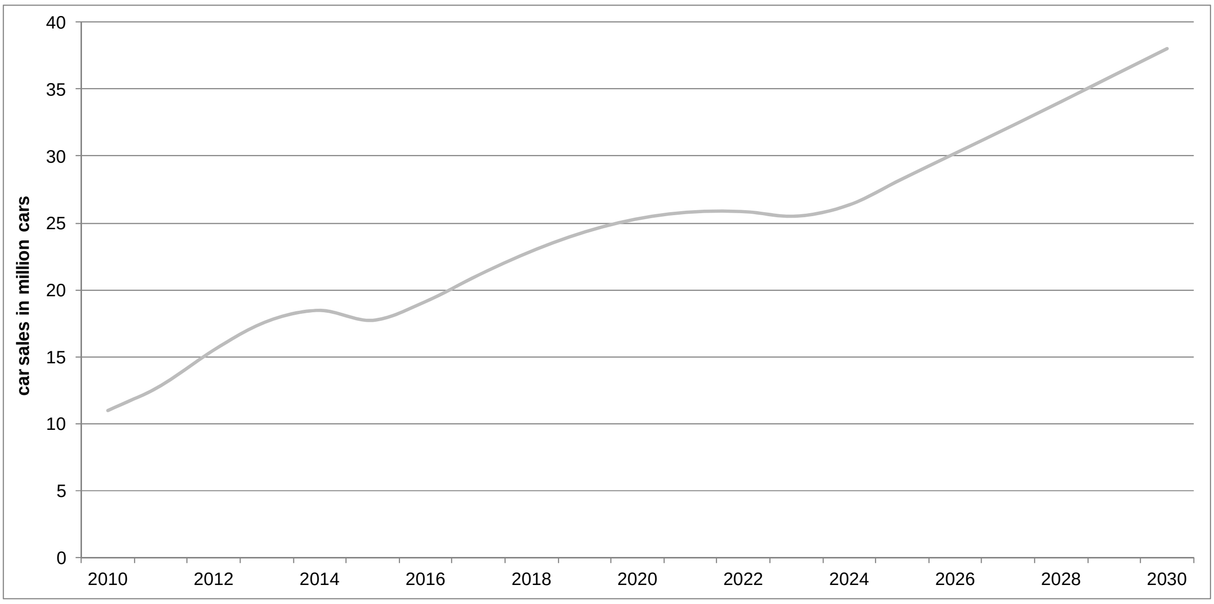

Figure 11: forecast of car sales in China

The two kinks in 2015 and 2024 are worth commenting on. On the one hand, this development can be explained by the economic development which during these years has a lower growth rate and on the other hand with the feedback loops for purchase price and energy costs after a longer period of growth. After 2020 the fleet growth based mostly on population and income growth is limited. The remarkable increase after 2024 is based on the fact that the fleet reaches a certain age and a large number of cars have to be replaced by new ones.

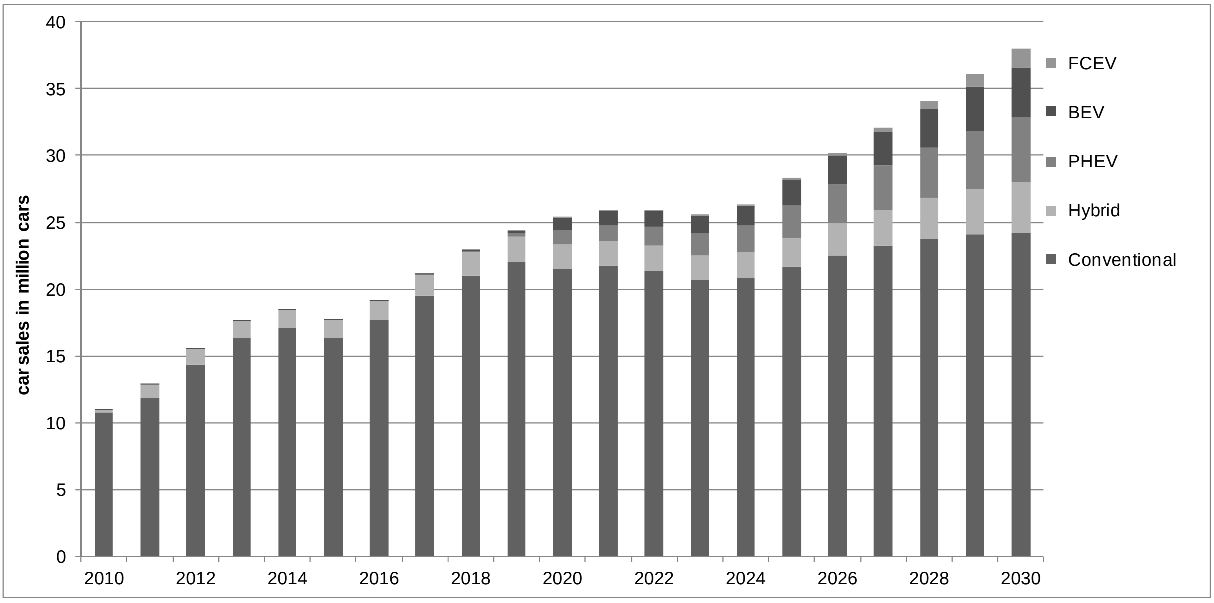

Figure 12: Forecast of technology share of newly purchased cars in China

Figure 12 shows the development of the shares of alternative technologies until 2030. Only hybrid technology enters the market early. The reasons therefore are affordable prices and high acceptance. The next technologies which will have a remarkable share of car sales will be BEV and PHEV. They are expected to significantly enter the market around 2020 and their share will be more or less evenly distributed between the different segments. FCEV will be the technology which is expected to enter the market last. This is mainly due to technical problems of H_2 storage and the lack of infrastructures.

The core of Scenario 2 is the activation of a feedback loop between the amount of cobalt used in batteries for new electric vehicles and the price for batteries used in these vehicles. As already mentioned above, the changing rate of the price depends on the acceleration of the global cobalt demand. Of course cobalt is not the only critical raw material for electric vehicle production. However, the intention of this study is to analyze the effect of increasing battery production on the demand for raw materials and the resulting raw material pricing, taking cobalt as an example which is the main raw material for cathodes within lithium-ion-batteries (see section 'conclusions')
Figure 13 shows the changes of the battery price (scenario 2 compared to 1), which is highly dominated by cobalt pricing.

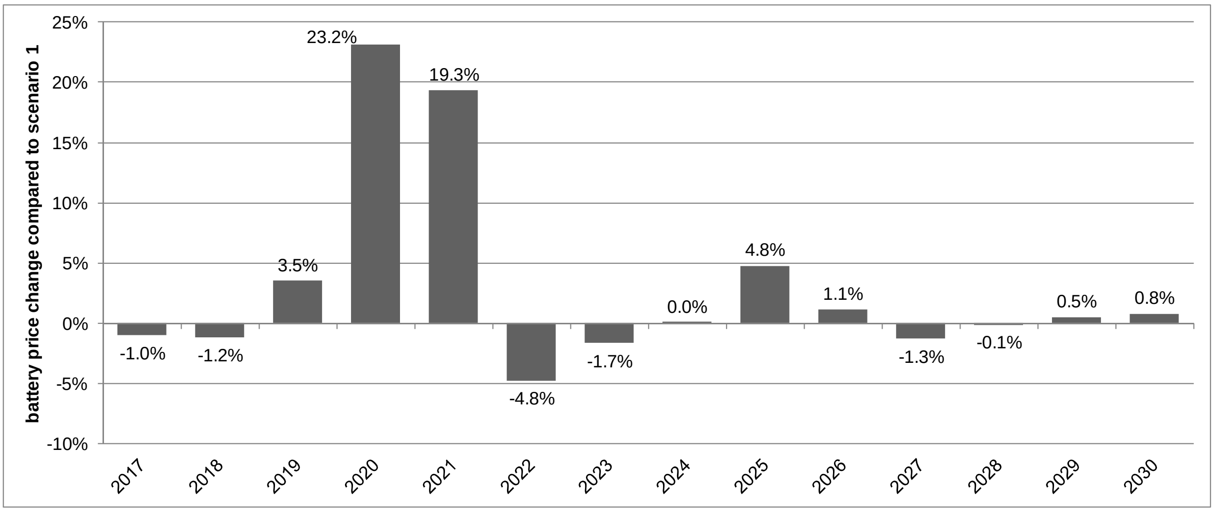

Figure 13: Differences in battery prices: Comparison of Scenario 1 and Scenario 2 (China)

The diffusion of BEVs drives the demand for cobalt. Between 2017 and 2019 the demand for cobalt is expected to grow moderately as BEV sales remain comparatively low (Figure 14). The acceleration of the curve is therefore negative. According to the modeling results, after 2019 the demand will rise quickly. Hence the acceleration of demand development turns positive which lets the price for battery raw materials rise significantly. Higher prices slow down the sales of BEV. As the total fleet growth is not affected, people will switch to other technologies. This leads to a normalization of the cobalt market and hence decreasing prices. The demand for BEV will rise again and so forth.

Furthermore Figure 14 displays the enormous impact of BEV diffusion on the cobalt market. With the assumptions described on page 6 (490g Co per KWh Lithium-Ion-Cell) BEVs will have a market share of around 90% by the year 2030, while the global cobalt demand is more than 15 times higher than in 2010. Even though this scenario is quite unlikely, as substitute materials such as $LiFePO_4$ are expected to be used in larger amounts, Figure 14 underlines the potential impact of emerging technologies on raw material demand.

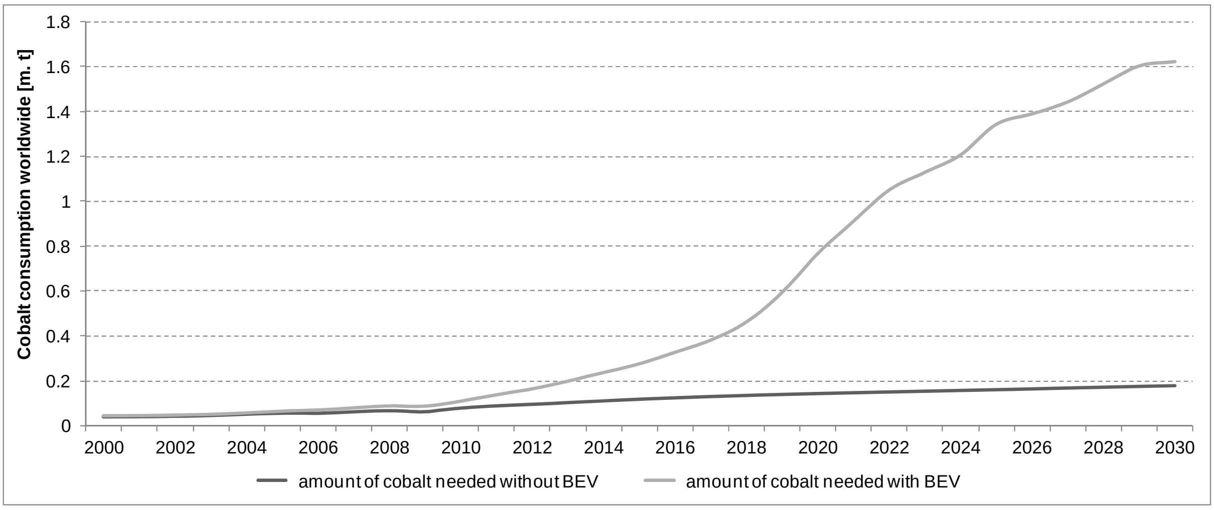

Figure 14: Forecast of the cobalt consumption with and without BEV (worldwide)

As a result of the price development in Figure 13, the amount of BEV will change. Figure 15 shows that the changes to scenario 1 are relatively small compared to the price changes. The explanation for this is very simple: The model structure leads to the fact that changes in TCO are only one component which leads to decision changes. Others, such as general technology acceptance, are not affected by the price development. Hence the effect of these price changes is small but visible.

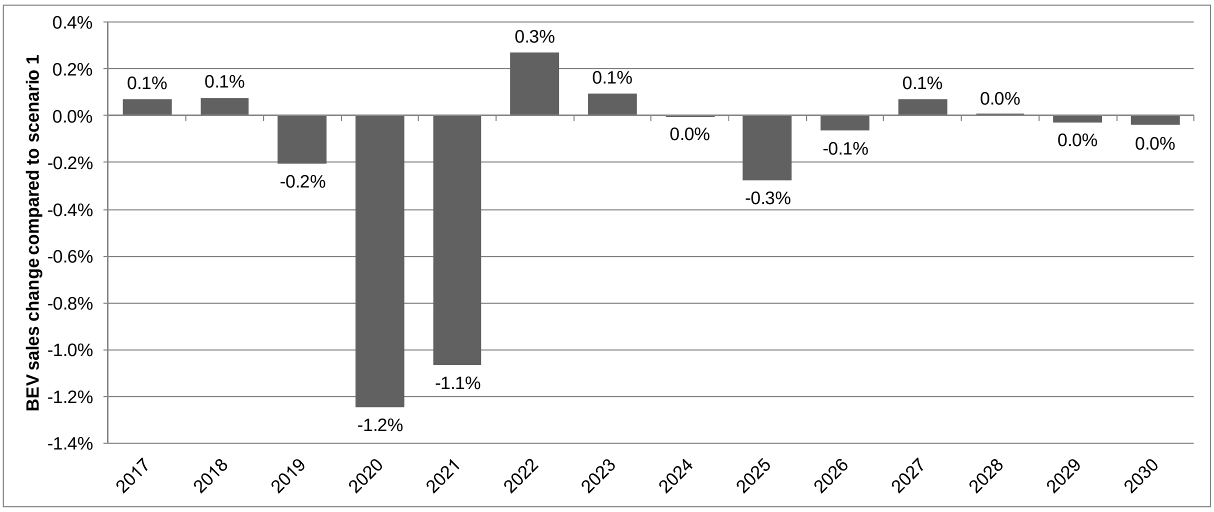

Figure 15: Differences in BEV sales Scenario 2 compared to Scenario 1 (China)

As BEVs are expected to significantly enter the market after 2017, the values in Figure 15 are only displayed from 2017 to 2030. Figure 15 highlights the decreasing diffusion of BEVs due to high raw material prices in the first years of stronger market penetration. After the first price shock (2020/2021), the demand for BEVs is expected to decrease due to expected high prices. The decline in demand results in decreasing prices followed by a recovery of demand. The results are typical system dynamic waves.

4 CONCLUSION

The main objective of this paper was the system based analysis of the diffusion of alternative drives under the circumstances of restrictions on the raw material markets. The theoretical basis therefore was the diffusion theory on a macro level as well as the utility based decision theory on the micro level.

The simulation and analysis were based on a model using the system dynamics software VENSIM as a foundation. The main advantages of using system dynamics are the dynamic and mostly unlimited possibilities to model coherencies which do not rely on equilibrium processes like most economic models. The choice of new alternative drives or fuels at every single registration is based on comparing cost and acceptance; the higher the difference, the more distinctive the decision towards one alternative. This utility based decision process with the likelihood of deviation was realized by using the logit model, already known from traffic decision models. In this model, both feedback loops influencing the number of purchased cars and the technology choice were realized.

The feedback loop for technology choice was considered in two scenarios. The first scenario without feedback while the second scenario takes into account the effect of higher BEV diffusion on raw material market dynamics and pricing.
Despite of relatively high influences of increasing raw material demand on battery prices, the feedback effects of cobalt pricing on technology choice are relatively small, differing from -1,2% to +0.3% of total BEV sales compared to the scenario without feedback effects. The reason therefore is that battery costs are – along with other costs and acceptance - only one influence on the technology choice.

As the inclusion of further raw material markets involves considerable efforts in terms of time and expenses - and the intention of this paper was to introduce the methodology of taking feedback loops for raw material markets caused by emerging technology diffusion into account - in this study only cobalt as a main component of battery cathodes was considered. However, further work will be done on both including other critical raw materials and on improving the feedback mechanism of price building.
Further critical raw materials, whose availability and pricing will affect the development of electro mobility are (among others) lithium, the second key raw material for lithium ion battery systems, neodymium and dysprosium which are essential for the strength and heat resistance of permanent magnets within electric engines and copper which is used for the coil of electric engines and all kinds of electric cables and electronic connections (Howerver, copper is one of the largest metal markets is not expected to be strongly affected by BEV diffusion).
In this context, further research work on alternative drive diffusion seems very important as many car producers in industrial countries risk high dependencies on essential raw materials and competitive disadvantages caused by unequal supply situations and high raw material prices.

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System-based feedback analysis of E-mobility diffusion in China

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Abstract

In the passenger car sector, purchasing decisions are driven by economic factors and acceptance. Based on cost analysis, the factors which can be attributed to different technologies are fuel costs and purchase price. The decision to buy a new car is always accompanied by comparing the costs of different alternatives. This leads to a compilation of costs and acceptance for each technology in terms of negative utility. In this study the development of the global automotive market, with a focus on China as the most important emerging market is analyzed considering both the diffusion of alternative drives and the development of car segments. The decision process on a micro level is solved by a Logit-Model. The execution within a system dynamics model allows the simulation of feedback loops. In contrast to earlier studies on future automotive markets in which the availability of key raw materials for alternative drives was not taken into account, the model presented in this paper gives an example of how to simulate feedback effects from raw material markets on the diffusion of emerging technologies. For this purpose, taking cobalt as an example, the effect of increasing battery production on the demand for raw materials and raw material pricing is analyzed, including the feedback of higher battery prices on the development of electro mobility. This is accomplished by simulating two scenarios with and without the raw material feedback loop and a subsequent comparison of the results.

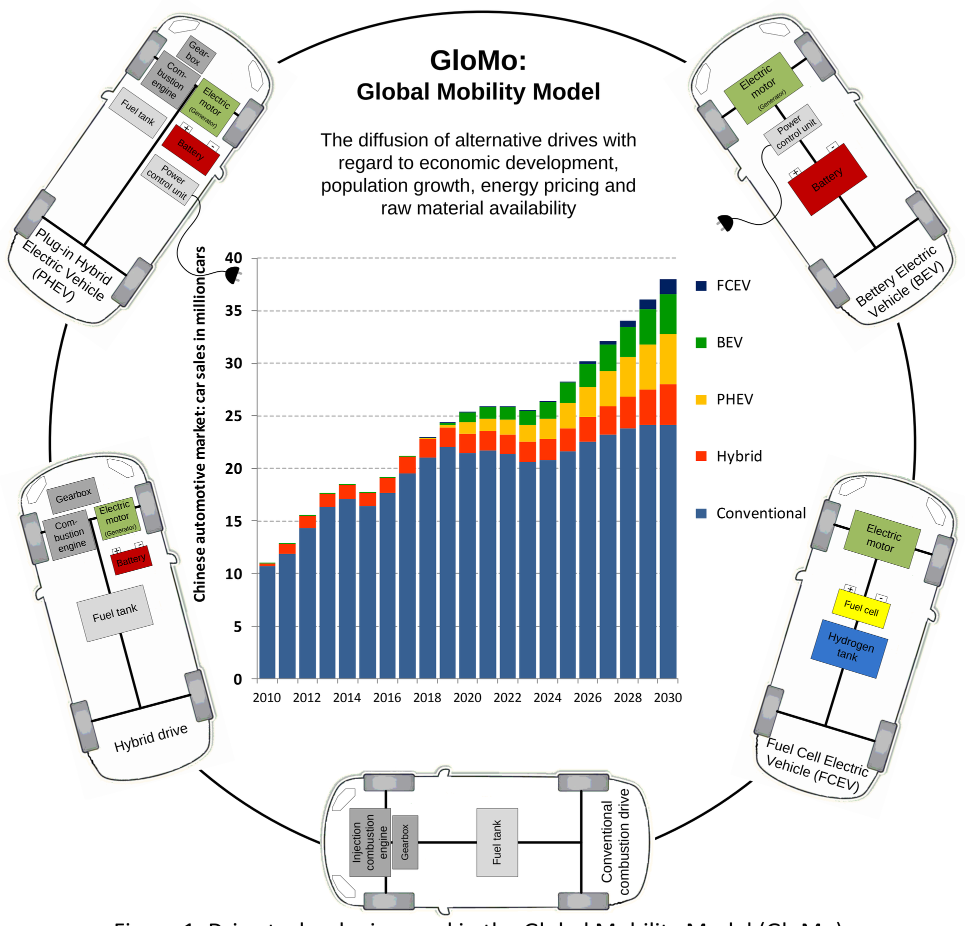

Figure 1: Drive technologies used in the Global Mobility Model (GloMo)

Introduction

Both resource efficiency and the reduction of greenhouse gases, particularly carbon dioxide emissions, are one of the major targets of future transport. In this context alternative drives will gain growing importance - not only from an economic point of view due to continuously increasing prices for fossil fuels. In this study a global mobility model (GloMo) was developed to analyze the future automotive market and the diffusion of alternative drives with regard to the economic development, population growth and prosperity, and energy and raw material pricing. The following technologies are taken into account (see Figure 1 on the left side):

- **Injection combustion engine (ICE):** Combustion engine for gasoline, diesel, compressed natural gas (CNG), liquefied petroleum gas (LPG) and bio fuels
- **Hybrid drive:** Hybrid technology recovers energy from every breaking process, which is stored in a battery and used for the electric drive.
- **Plug-in-hybrid drive (PHEV):** Also combines a combustion engine with an electric drive. In addition, it is possible to charge the battery.
- **Battery electric vehicles (BEV):** Electric drive that sources its energy from a large battery.
- **Fuel Cell:** The fuel cell transfers energy from hydrogen to electricity through a chemical reaction. Fuel cells are usually combined with electric drives.

Methodology and model description

Model Overview:

The system dynamics model is divided into different modules, whose relations are displayed in Figure 2:

- **Economy:** Forecast of GDP growth and the key dependent income factors
- **Population:** Forecast of population and wealth (share of people living above the poverty line)
- **Purchased new cars:** Simulation of car fleet growth based on population and economy module
- **Segment & technology choice:** Total cost of ownership (TCO) and acceptance based decision within different segments
- **Fleet:** Realized as a stock model based on purchased cars, scrapped cars and fleet growth (see Figure 3)

Discrete choice of technology and segment:

The segment and technology choice module integrates the LOGIT approach within a system dynamics environment. The LOGIT is a utility based discrete choice approach which takes TCO as well as acceptance factors into account. Different alternatives are compared with its utility (costs). The calculation is based on uncertainty due to the consumer's lack of information. The major output is the likelihood of each alternative drive to be chosen by a new car buyer.

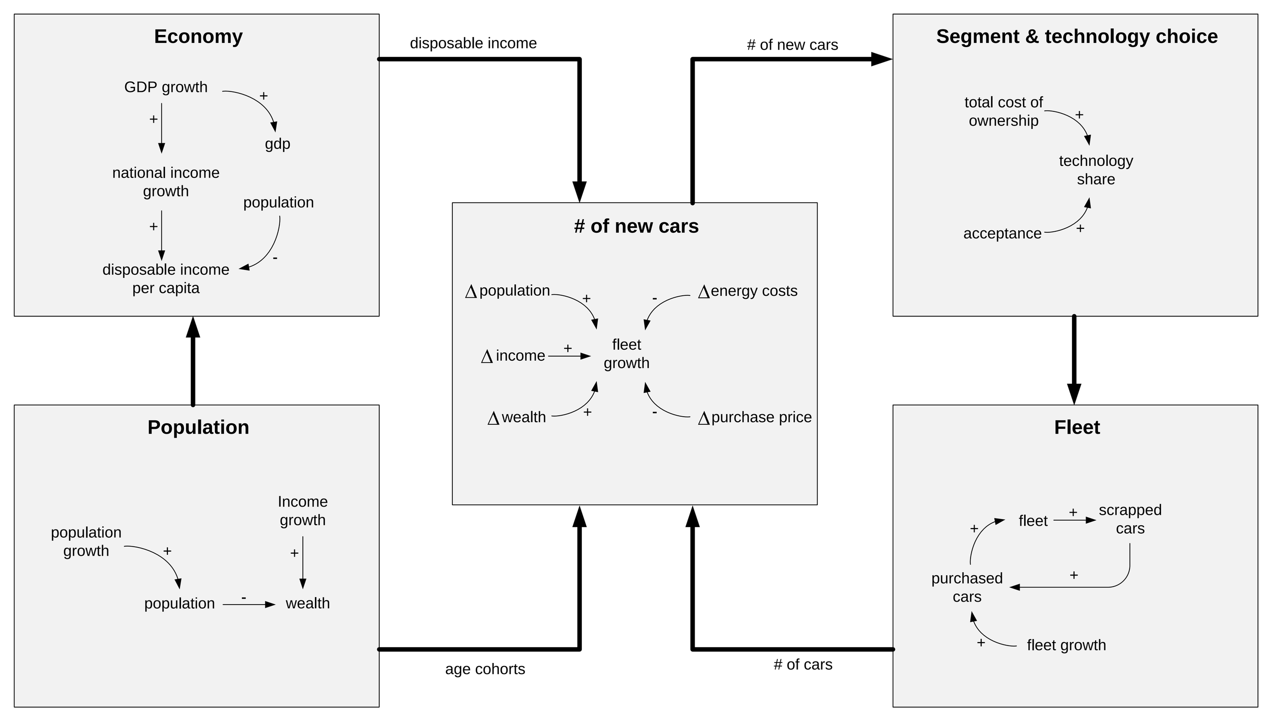

Figure 2: Overview of the Global Mobility Model (GloMo)

Feedback effects:

1 Cobalt – battery price feedback:

The more BEV are sold the higher the demand for cobalt, the higher the price. High prices will change the decisions of the buyers towards other technologies.

2 Car stock energy consumption feedback:

The more cars are in the stock, the more fuel will be consumed. Higher fuel consumption leads to higher prices and hence to fewer new cars.

3 Car price feedback:

The more cars are sold, the higher the price for new cars due to higher raw material demand and production capacity restraints.

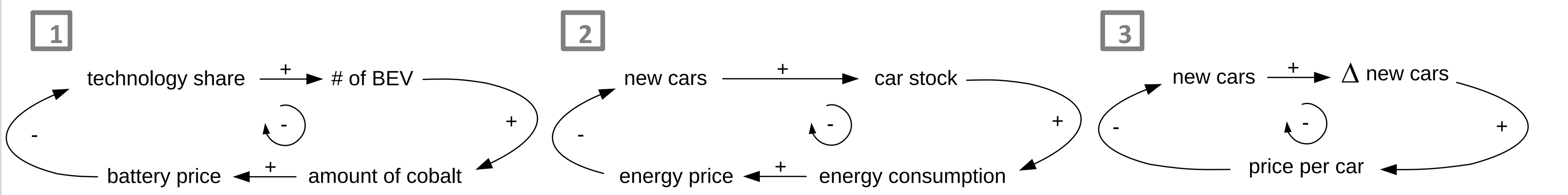

Figure 3: Feedback loops within the model

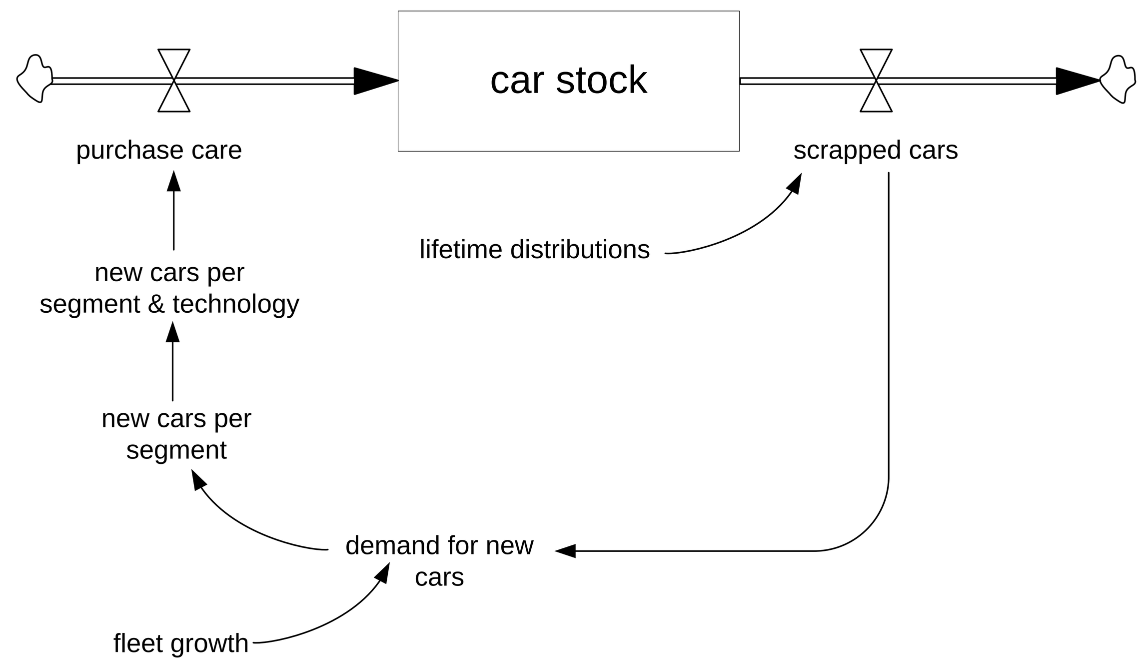

Figure 3: Detailed description of the car fleet module

Simulation results: GloMo's main output

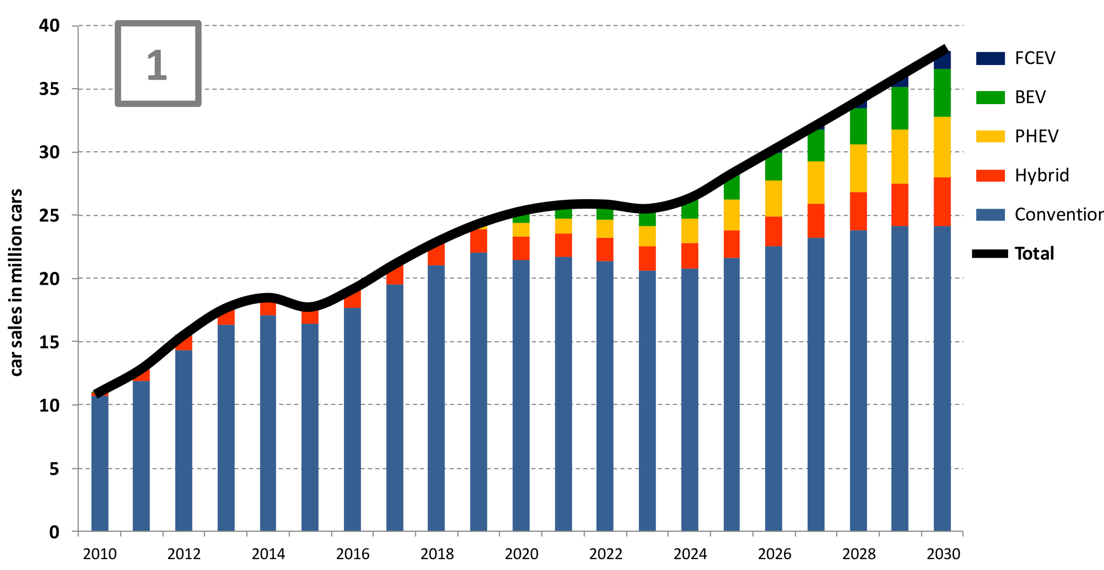

Figure 4: Forecast of the sales by technology in China

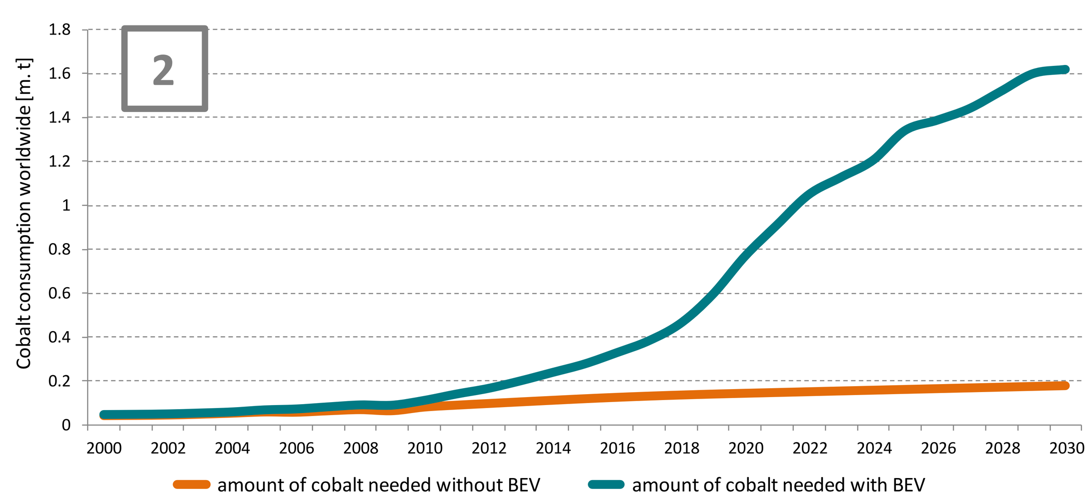

Figure 5: Worldwide cobalt consumption with and without BEV sales

1 Simulation results baseline scenario:

According to the baseline scenario the traditional combustion engine (ICE), with up to 60% of the total sales in 2030, will still be the dominant drive technology. As BEVs will appear in basic and small segments, the success of PHEV will be limited to bigger segments. Due to an early market stage, FCEV will remain on a low level. The total car sales in China will increase up to 37 million cars per year in 2030. Thus car sales will quadruple compared to 2010.

2 Cobalt consumption with and without diffusion of BEV:

The cobalt consumption of BEVs is significantly high compared to the worldwide market volume. The introduction of BEVs and PHEVs into the market will lead ti eight times as much cobalt being needed worldwide. In 2030, 1.6 Million tons of cobalt are needed to satisfy both car manufactures and other industry sectors.

3 Price changes of cobalt under consideration:

Due to this development, prices will change according to demand changes. Higher battery prices lead to less demand and hence a less significant decrease of the amount of cobalt. This feedback loop creates oscillating prices and demand. At the early stage of BEV introduction, the price variation from the baseline scenario with up to +22% quite high.

4 Feedback of cobalt's price changes on BEV demand:

The influences of price changes on demand of BEVs is rather small. Even in case of price changes up to +22% the demand for BEV varies only by -1,2% (costumers will choose other drive technologies). Reasons therefore are comparable small changes of the total car price as price changes of batteries do not change the total price of a BEV significantly.

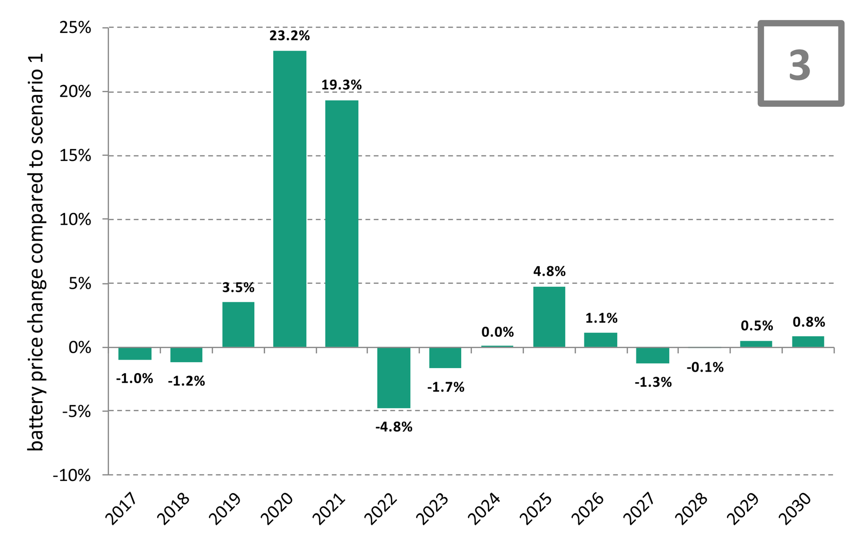

Figure 6: battery price change caused by demand changes

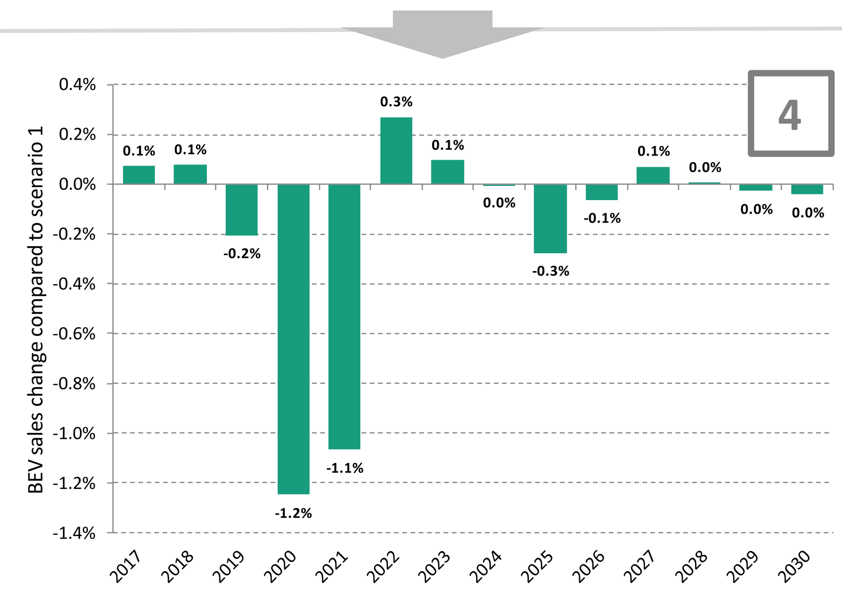

Figure 7: changes in BEV demand due to volatile battery prices

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