The Influence of Potential Raw Material Shortages on the Market Penetration of Alternative Drives

A Case Study for Lithium and Cobalt

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Abstract:

The traffic sector, particularly road traffic, faces challenges both from rising oil prices and ongoing climate change discussions. The only way to escape the current cycle of fossil fuel combustion is to utilize alternative drive technologies and fuels which would make it possible to reach significant emission reduction. One solution could be the usage of battery electric vehicles (BEV), but their production requires large amounts of specific raw materials such as lithium and cobalt. Shortages in these materials will lead to higher prices, which in turn might influence the diffusion of BEVs in the future.

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 and lithium as an example, the effect of increasing battery production on the demand for raw materials is analyzed. This is realized by simulating two scenarios with strong and weak market penetration of alternative drives and by determining the impact of these scenarios on the markets for lithium and cobalt.

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 utilize 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 is expected to dominate the future consumption of cars and particularly the market for alternative drives.

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 supply. 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 raw material markets and raw material 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 automotive markets and alternative drives.

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, as well as the effect on the lithium market is analyzed.

After a short technical introduction presenting all the possible alternatives and potential cost developments especially for BEV, the second part of this paper has focuses on the modeling of the purchase decision process for new cars and the modelling of raw material flows. The system dynamics methodology is a suitable approach to model these dynamic markets. The reasons for this are the flexible use of feedback loops, the simulation of stock variables for vehicle fleets and raw material stocks in use and the possibility to implement the discrete choice approach in the system dynamics model.

Drive technologies in the private car sector and the need of a global mobility model

The global demand for new cars with variations of drivetrain technologies influences the demand for specific raw materials significantly. The scope of this paper is the demand for raw materials used within alternative powertrain technologies like battery-electric vehicles or plug-in hybrid vehicles. The quantification of raw material consumption based on these technologies needs car sales forecasts on a worldwide level divided into the different technologies described below. The following paragraph lists the drive categorization used in the model (cf. Figure 1):

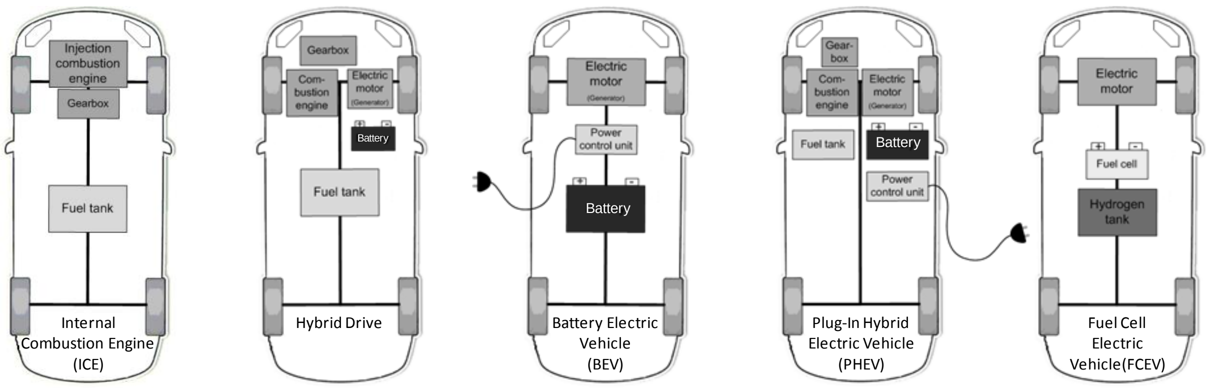

Figure 1 Considered technologies of the Global Mobility Model (GLOMO)

- Conventional Combustion Engine (ICE)

  The long history of conventional combustion engines leads to a mature technology with high degrees of efficiency and different motor types, making the technology available for different types of fuels. Gasoline and diesel are the most common petrochemical fuels, however, compressed natural gas (CNG), liquified petroleum gas (LPG) and bio fuels have gained increasing importance in the previous decade. The big advantage of the ICE is the broad knowledge of the technology and energy storage which allows the vehicles to travel long distances leading to a high acceptance among the average car user.
  Bio fuel which includes bio diesel, bio-ethanol and bio-gas is produced from organic plant materials. In recent years, bio fuel has often been regarded as one solution to renewable energy supply. 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.

- Hybrid Technology (Hybrid)

  Hybrid technology recovers electric energy from every breaking process, which is then stored in a battery. This electric energy is used for an electric motor in order to support the traction power of the conventional combustion engine, leading to a reduction of fuel, hence, higher efficiency. Literature research and comparison of current hybrid models brought us to battery sizes of about 1.5 kWh per hybrid vehicle.

- Plug-In Hybrid (PHEV)

  In order to simplify the model, Plug-in Hybrid and Range Extender are grouped together as PHEV knowing well that the battery size and fuel consumption could differ strongly. The two different concepts can be described as follows: The combustion engine supplies the electric energy for the battery-driven electric drive (range extender) or may directly contribute to the drive of the axes (power-split). In both cases a battery is needed to store the electric energy. In addition, in some cases, it is possible to charge the battery externally (Plug-In). This technology seems to be a practical solution for the common user, making just a few long distance trips per year. The typical average battery size for a range extender differs between 15 and 20 kWh, whereas PHEV are sold with less than 7 kWh batteries. The model calculation was based on an overall average value of 15 kWh per battery.

- Battery Electric Vehicle (BEV)

  The applications of electric drives for large vehicles such as locomotives or trolley buses have a long history. The high efficiency of electric drives can be seen as one big advantage, especially in urban areas. However, the problems are not related to the drive but to the energy storage on board. Currently, lithium–ion batteries appear to be the best technology able to handle high energy densities necessary to keep the weight and size of the energy storage low. The drawbacks include relatively low durability and high material costs (KÖHLER 2007). According to current studies on BEV, in the long run, production prices are expected to decrease while storage capacities are expected to increase, making full electric vehicles widely available by 2030 (TATSUMI 2007). Currently, average battery sizes of BEV can be set in a range of 20 up to 30 kWh depending on the vehicle size.

- Fuel Cell Electric Vehicle (FCEV)

  The fuel cell transfers hydrogen into electricity by electrochemical reaction with oxygen. Fuel cells are mostly combined with an electric drive and may replace batteries for electric vehicles in the longer term. The fuel cell itself is a complex technology with high maintenance and high investment costs. The main problem besides the powertrain is the tank technology. The low density of hydrogen gas leads to expensive and heavy tank technologies storing hydrogen under high pressure.

Description of the Global Mobility Model (GloMo)

This section describes how the diffusion process of alternative drives was realized in a system dynamics model combined with the utility based logit-theory and the learning-curve-theory. The model was developed on a global scale, taking into account several key regions such as Europe, the USA, Japan, South Korea and the BRICS (Brazil, Russia, India, China, South Africa) countries. The developed model is divided into different modules, which enables a better overview as well as the possibility to run the modules separately in order to analyze the individual influences and perform sensitivity analyses.
The model consists of five modules as displayed in Figure 2. In the following, the different modules and the functionality of the model is described.

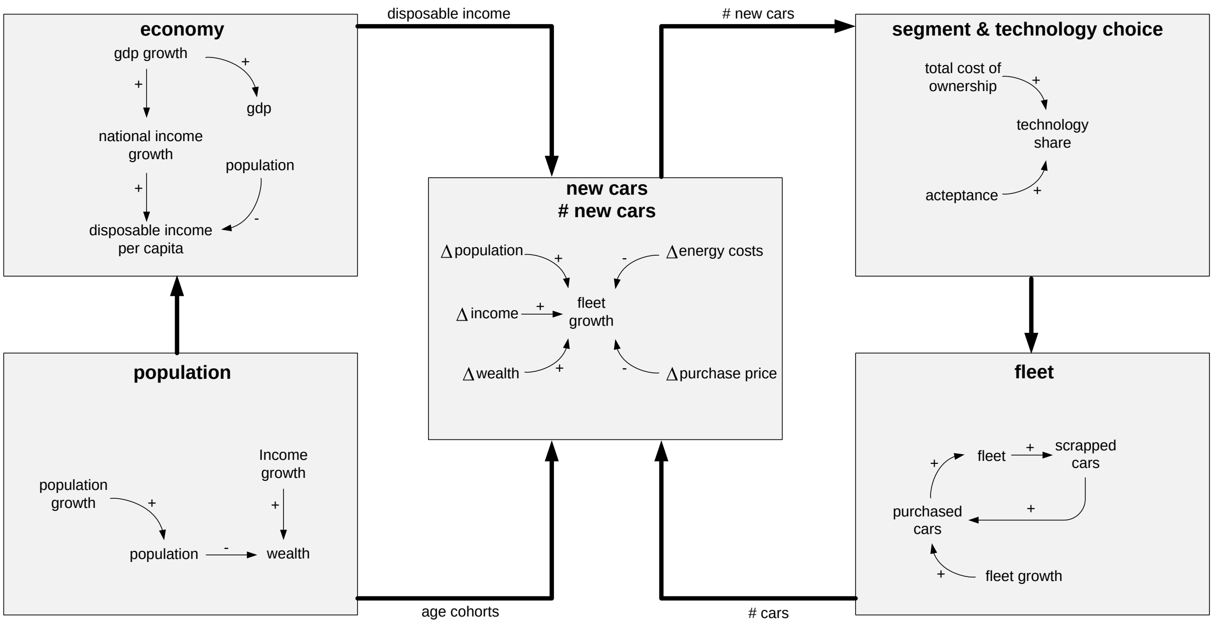

Figure 2 Simplified structure of the Global Mobility Model (GloMo)

The economic module

The core of the economic module is the calculation of the GDP per capita. This calculation is based on an exogenous literature based 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.

The population module

The second module forecasts the development of the population divided into different age cohorts. As displayed in Figure 2, the input in this module is an exogenous population growth rate. Furthermore, this module considers 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 population by age cohorts for each of the afore mentioned countries.

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.

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.

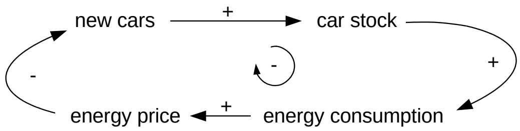

Figure 6: feedback loop for energy prices

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.

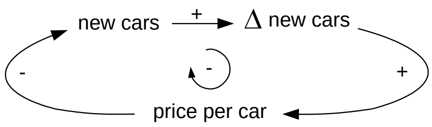

Figure 7: feedback loop for purchase prices

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.

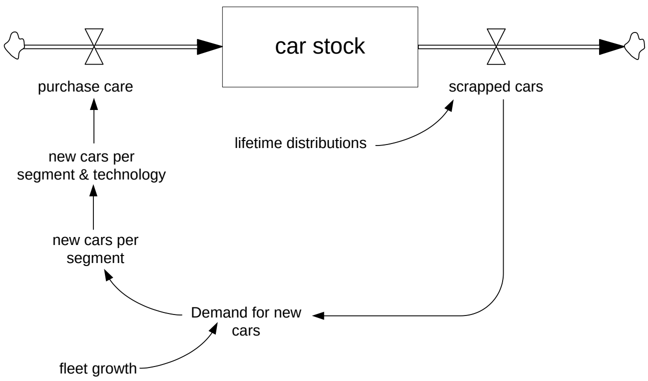

Figure 8: car stock model

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. The decision towards different drivetrain technologies is based on cost comparison applied by the logit theory (Kühn/Krail 2010).

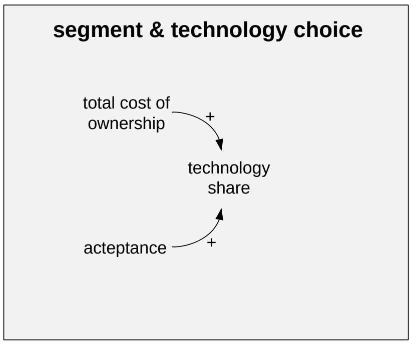

Figure 9: segment and technology choice

Current battery technologies and expected future development[1]

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.

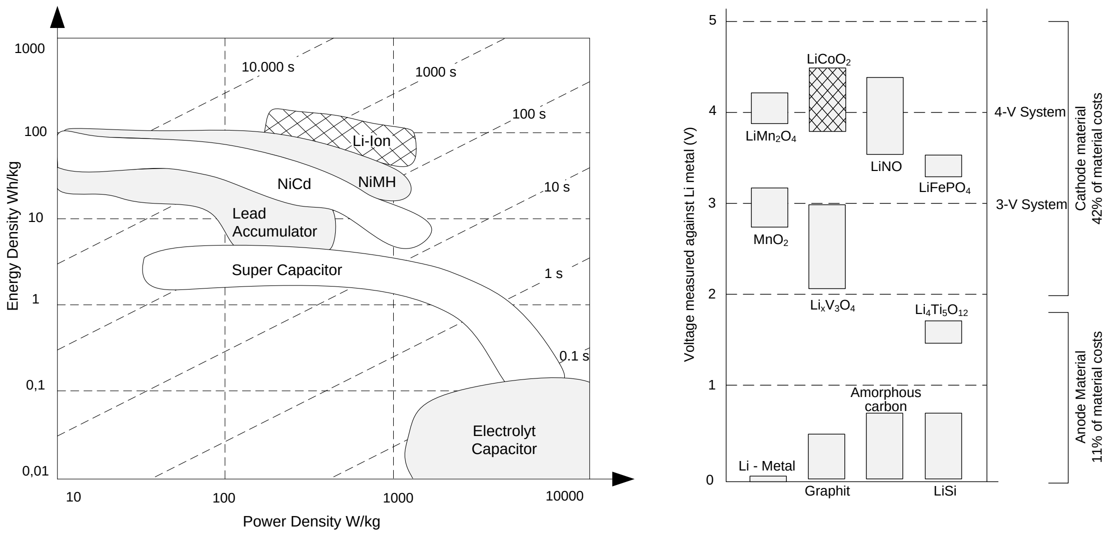

Figure 3 Energy and power densities of batteries and capacitors (KETTERER 2009)

The key raw materials for battery production

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 3 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).

[1] This research work is an extension of a previously presented study (KÜHN, GLÖSER 2012). Therefore, parts of the technical description were adopted.

Figure 4 displays the basic functionality of a current lithium ion cell during the charging and discharging process.

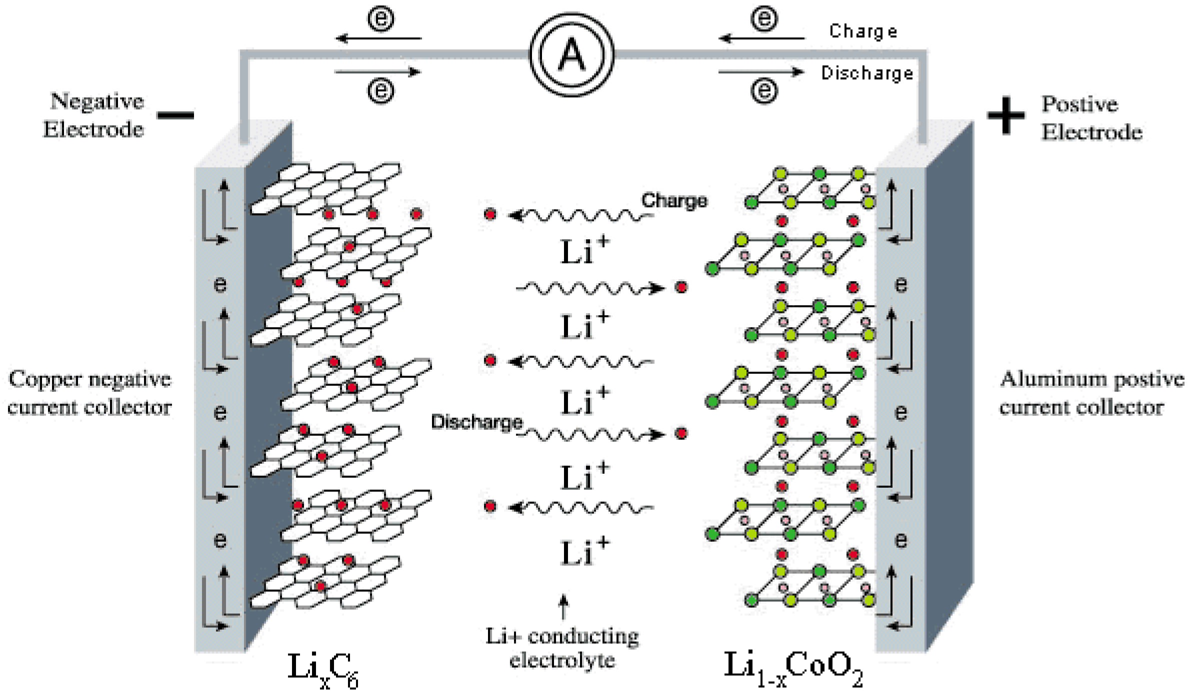

Figure 4 Design and function of an ordinary lithium ion battery (with permission from Fraunhofer ICT (TÜBKE 2011))

While anode materials (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 in future. 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 more than 35% (cf. Figure 6). 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 slightly declining cobalt use for cathode production, the effect on market dynamics caused by an increasing share of electrical vehicles is analyzed. Lithium - the key raw material for lithium ion battery production - is the lightest solid element (molar mass: 6.94 g/mol (cf. next section)). Therefore, even though the amount of lithium atoms within a cell is higher than the amount of cobalt or further electrode elements, the total mass of lithium within a cell is lower than that of cobalt. The amount of cobalt needed for cell production also depends on the cathode technology. For $LiFePO_4$ cathodes around 100 g/kWh is assumed, whereas for mixed oxide cathodes around 160 g/kWh is needed (KONIETZKO 2011, GOONAN 2012).

Current markets and material life cycles for lithium & cobalt

In this section we intend to give a short but comprehensive overview on the current anthropogenic uses and material cycles of lithium and cobalt. Therefore we developed dynamic material cycles on a global level, capturing the historical material applications and following them through their useful lifetimes up to waste management and potential recycling. In these models different forms of delay functions and lifetime distributions as well as common methodologies of substance and material flow analysis are applied.
Detailed insight into the methodology will be given in further publications in the field of 'industrial ecology'. For this study we linked these cycles with the Global Mobility Model (GloMo) to get an idea of the impact of alternative drive diffusion on the raw material demand.

Short overview of the anthropogenic life cycle of cobalt:

Cobalt is a ferromagnetic transition metal with symbol Co and atomic number 27. It naturally only occurs in chemically combined form, particularly in association with nickel and copper minerals in combination with sulfur and arsenic[2]. The free element is usually produced by reductive smelting as a byproduct of Nickel and Copper production. Around 50% of global cobalt production comes from the nickel mining and slightly more than 30% from the copper mining (FORMATION METALS 2013). 65% of global cobalt ore is mined in Africa (mainly in the Democratic Republic of Congo and in Zambia (USGS 2013)), while the metal refining is mainly performed in China (around 40% of global refining) (FORMATION METALS 2013).
The cobalt market can be roughly divided between cobalt demand for metal applications such as specific steel alloys, magnetic alloys and superalloys and cobalt demand for chemical applications such as electrodes, catalysts in chemical industries, pigments and further speciality chemicals (ROSKILL 2010).
While in the past high performance metal applications for use in turbine blades and jet aircraft engines dominated the demand, today electrodes for batteries in electronic products (mobiles (cellphones), laptops and notebooks, tablet PCs, further portable electronic equipment) are the largest market for cobalt oxides. Currently, metal applications represent around 30% of total demand while 70% of global cobalt production is used for chemical applications (FORMATION METALS 2013).
Nowadays, cobalt recycling is mainly restricted to the recycling of batteries and the recovery of catalysts in chemical industry because in most other applications cobalt is contained in such small quantities that - despite the high pricing of cobalt - the recovery is economically not feasible (ROSKILL 2010). However, the recycling rate of cobalt is often reported higher than 50%. This is due to the recycling of cobalt containing stainless steels and other high performance alloys. These recycling flows −even though they are to some extend functional and substitute primary material input for metallurgical applications of cobalt− are not

[2] Main cobalt ores are smaltite $(CoNi)As_3$; linnaeite $Co3S_4$; cobaltite CoAsS; and glaucodot (CoFe)AsS

considered as cobalt recycling in this study, because cobalt in these flows is not available as refined cobalt and may be used in other sectors, but is recycled within the steel cycle.

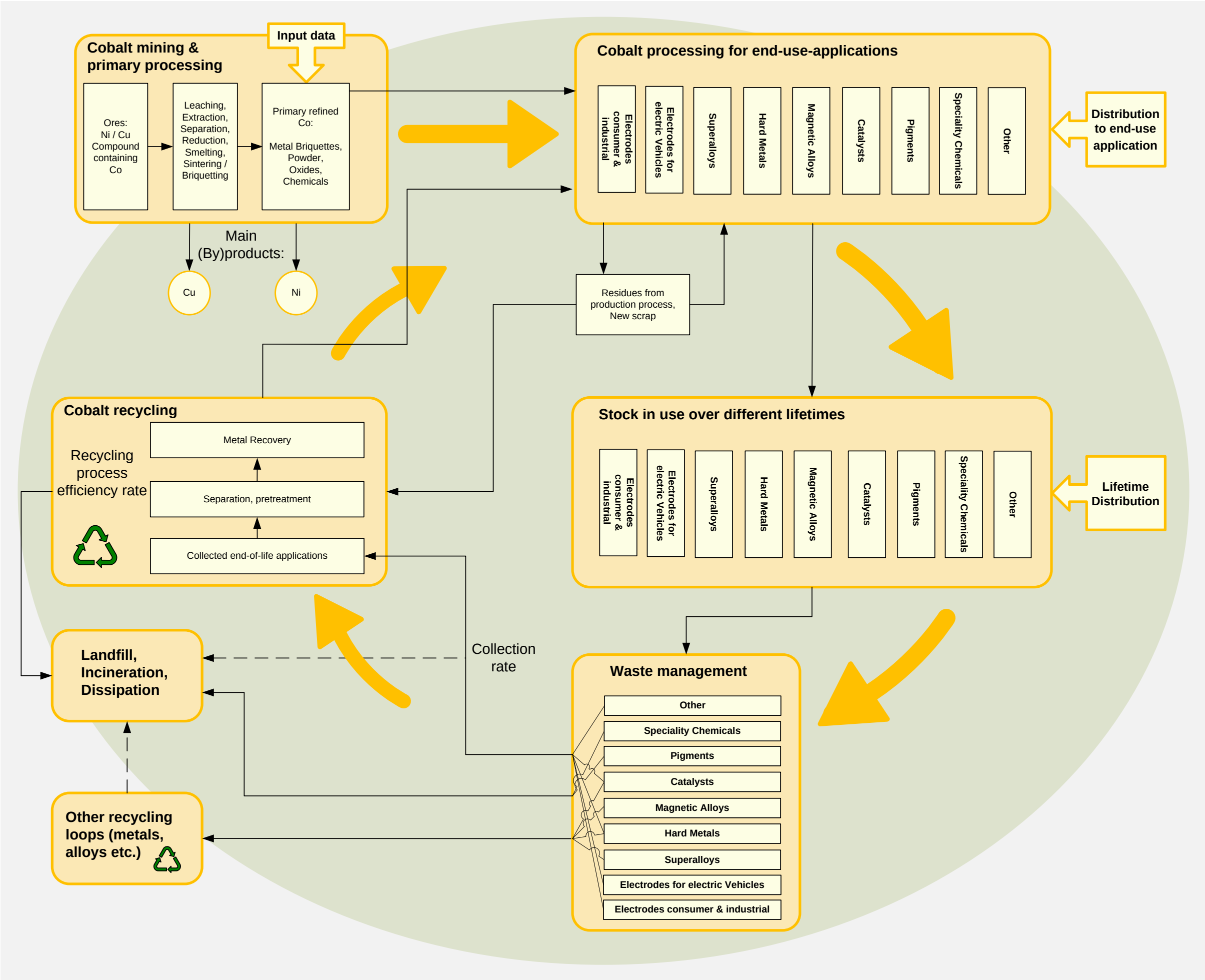

Figure 5 The life cycle of cobalt - simplified illustration of the substance flow model

Figure 5 shows the general global life cycle of cobalt the way it was implemented into a system dynamics software. Figure 6 displays the market shares of cobalt by weight in metallic or oxidic form for the years 2000 and 2012.

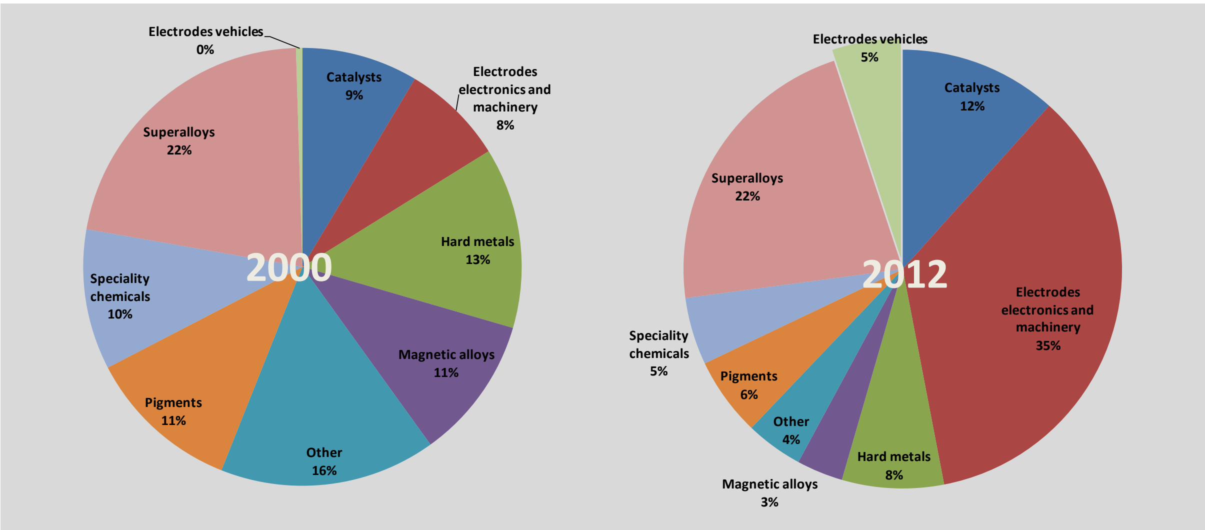

Figure 6 Sectoral global market share (by weight) of cobalt 2000 and 2012 (ROSKILL, FORMATION METALS, USGS)

Short overview of the anthropogenic life cycle of lithium:

Lithium belongs to the alkali metal group of chemical elements. It is the lightest metal and the least dense solid element. Lithium is highly reactive and flammable and due to its high chemical potential it has become a key element for high energy-density battery production. The most important source for lithium are specific salts in brine lake deposits containing lithium chloride. However, lithium is also produced from a hard silicate mineral called spodumene, particularly in Australia (GOONAN 2012, USGS 2012). The salt lakes in South America contain about 75% of known global lithium resources. Main producing countries are Chile, Australia, Argentina and China (USGS 2012).

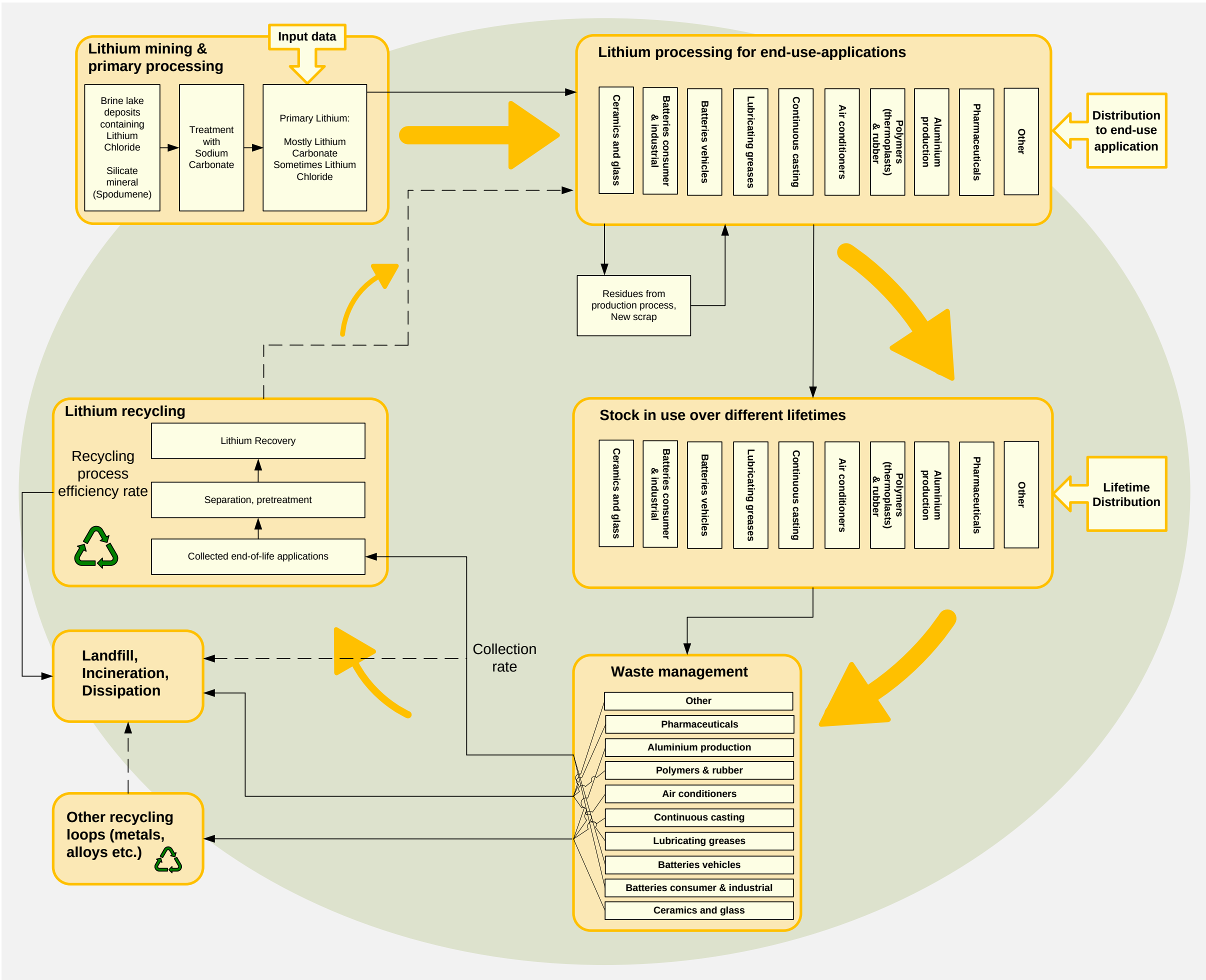

Figure 7 The life cycle of lithium - simplified illustration of the substance flow model

The lithium market can be divided between lithium compounds and chemicals sourced from further treatment of lithium minerals (mostly lithium carbonate) and lithium minerals consumed directly for glass or ceramic production (ROSKILL 2010).
In glass and ceramic production as well as in continuous casting processes lithium is used as a flux to produce materials of higher physical properties by absorbing impurities and preventing oxidation. Beside battery production, this is the most important market for lithium compounds.
Alloys containing lithium, mainly with aluminium but also with copper and manganese are used for lightweight materials in aircraft industries. Lithium staerate produced from lithium hydroxide is used for lubricating high performance greases.

Lithium hydroxide and lithium peroxide are the salts mostly used in confined areas for carbon dioxide removal and air purification. Further small markets for lithium compounds are the use within polymer and rubber production and the use in pharmaceuticals.
Due to the relatively low pricing of lithium carbonate, there is currently almost no recycling of lithium from postconsumer products.
Figure 7 shows the general global life cycle of lithium the way it was implemented into a system dynamics software. Figure 8 displays the market shares of lithium compounds by weight of elementary lithium for the years 2000 and 2012.

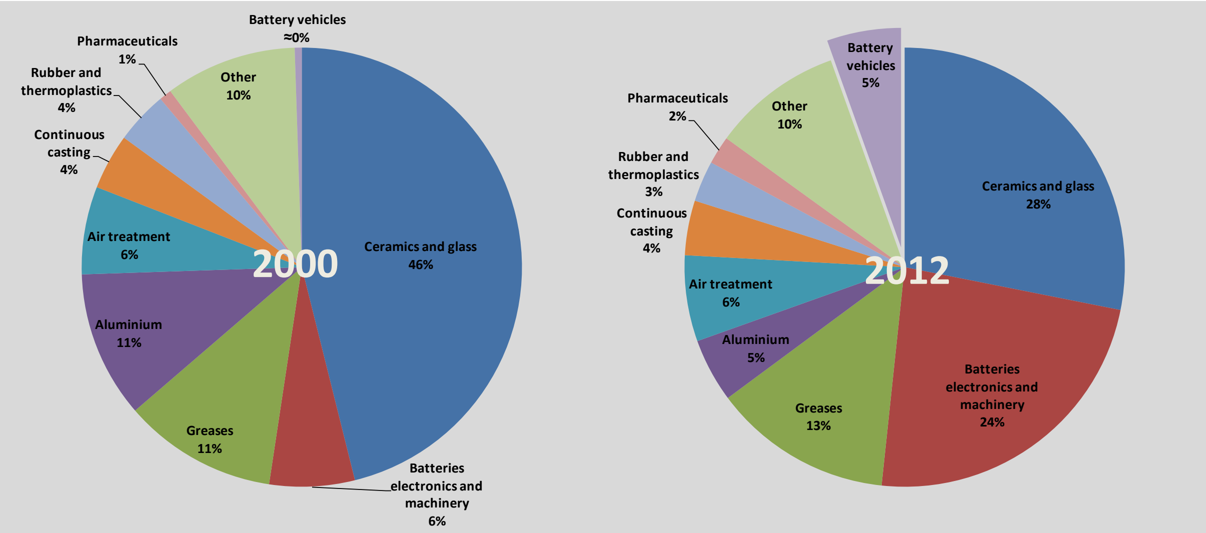

Figure 8 Sectoral global market share (by weight) of lithium 2000 and 2012 (ROSKILL, USGS)

Scenarios of alternative drive diffusion and their effect on raw material markets

The output of the GloMo model on an aggregated global level is illustrated below (Figure 9). Two different scenarios were developed, one with strong diffusion of alternative drive technologies (Scenario 1) and one in which mainly the hybrid technology strongly enters the market whereas battery electric vehicles, plug-in hybrids and fuel cell cars remain a niche market (Scenario 2). Both scenarios end with about 120 Million car sales worldwide in 2030.

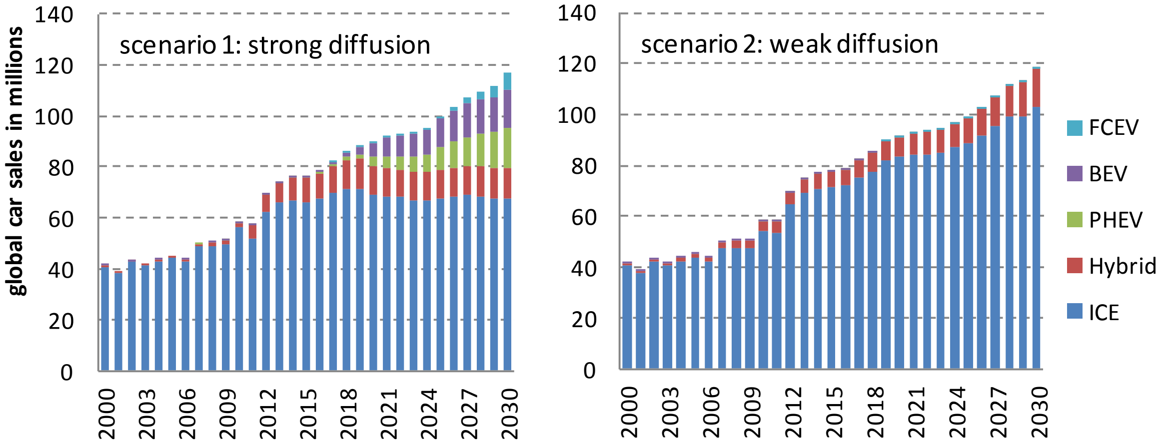

Figure 9 Scenarios of market penetration of alternative drive technologies

As the strong diffusion scenario sets an optimal political and economical framework for the diffusion of alternative drive technologies, about 40% of all purchased cars will not be driven by a conventional combustion engine. Scenario 2 takes into account that both cost development and technological progress of the alternative powertrains might remain on a low level. Hence, only the hybrid technology enters the market in considerable amounts. Both scenarios are strongly influenced by emerging markets such as China, India and Brazil while the currently leading role of the TRIADE (USA, Japan and EU) will decline. Until 2030 more than 60% of all new cars are estimated to be sold in the BRICS- countries.
For further calculation concerning raw material consumption of electric vehicles, the following battery sizes are used:

- **Hybrid: 1.5 kWh**
- **PHEV: 15 kWh**
- **BEV: 25 kWh**

Based on these assumptions, the effect of the two scenarios on the markets of lithium and cobalt was analyzed by linking the Global Mobility Model (GloMo) with the dynamic raw material cycles described above. As illustrated on the following pages, the impact of scenario 1 (strong diffusion) is enormous, whereas scenario 2 has almost no impact on the raw material market. This underlines the planning uncertainties both mining companies and battery or car producers are confronted with. However, without high investments in further primary production facilities there will not be any significant market penetration of BEV and PEV. Securing the raw material supply of cobalt will become even more challenging as cobalt is mainly a byproduct of nickel and copper production which makes its availability dependant on the development of nickel and cobalt markets.

Effect of the two scenarios on the global cobalt market:

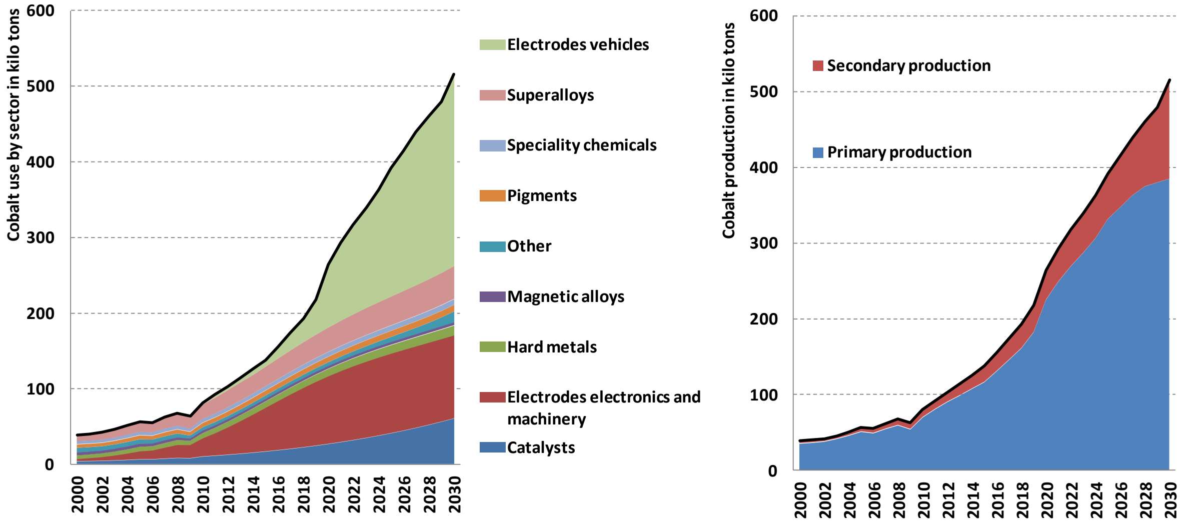

Figure 10 Impact of scenario 1 (strong diffusion) on the cobalt market

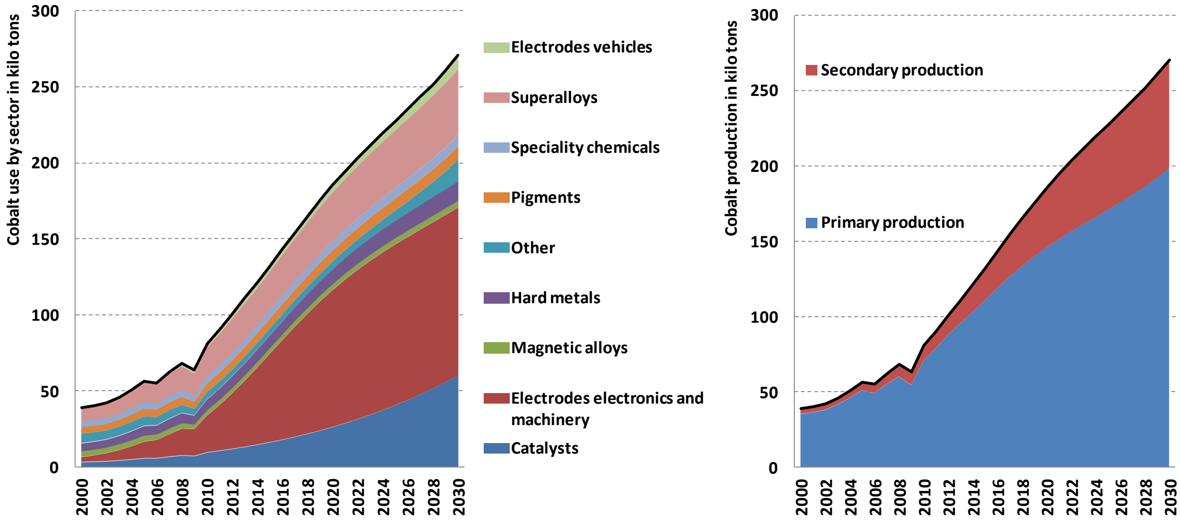

Figure 11 Impact of scenario 2 (weak diffusion) on the cobalt market

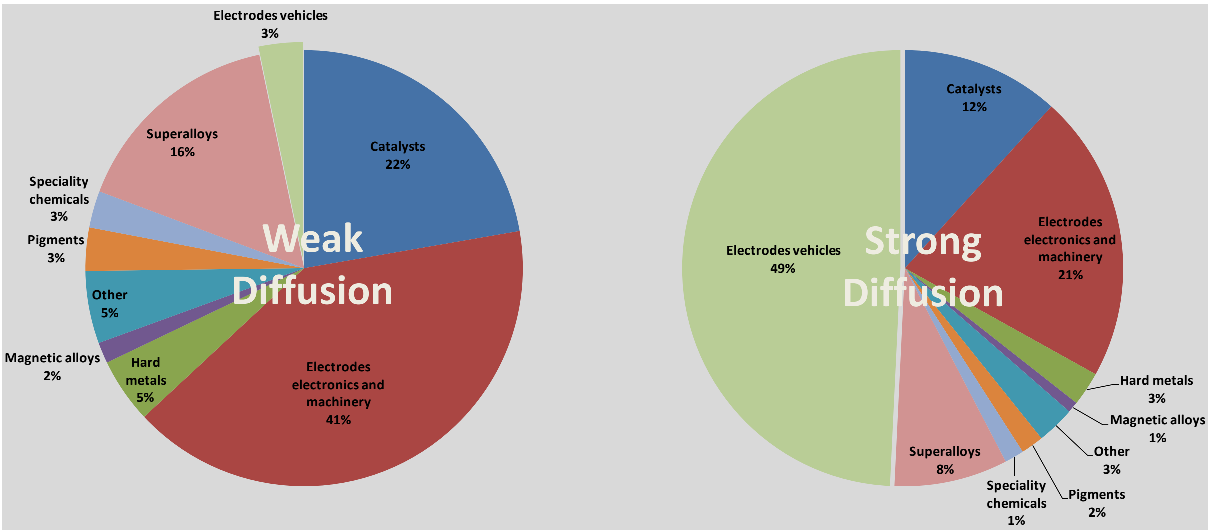

Figure 12 Effect of the two scenarios on the cobalt market shares in 2030

Effect of the two scenarios on the global lithium market:

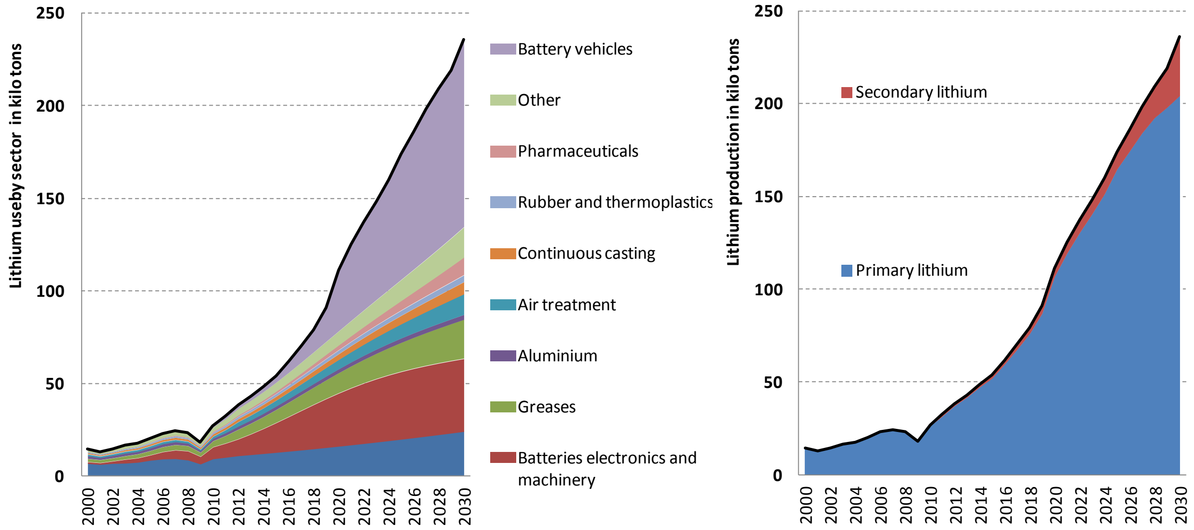

Figure 13 Impact of scenario 1 (strong diffusion) on the lithium market

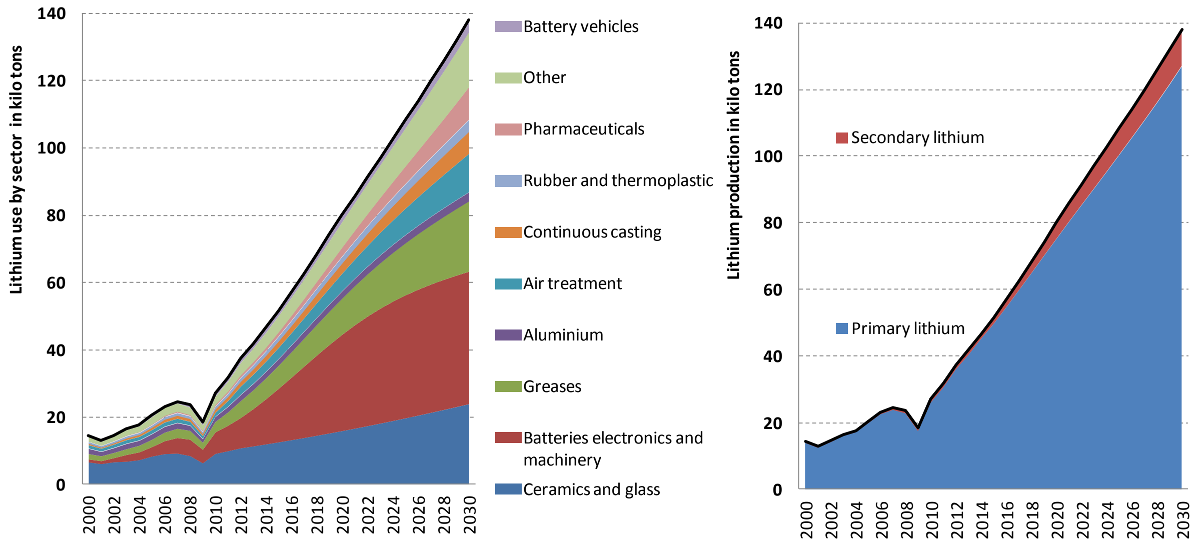

Figure 14 Impact of scenario 2 (weak diffusion) on the lithium market

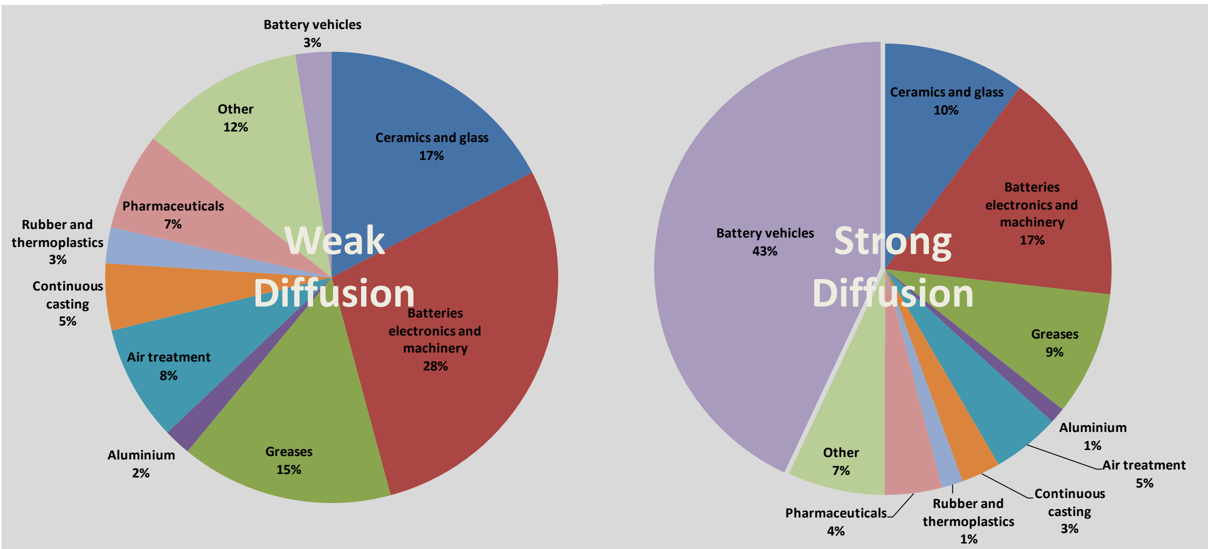

Figure 15 Effect of the two scenarios on the lithium market shares in 2030

Conclusions and future research work

The main objective of this paper was the system based analysis of the diffusion of alternative drives under the circumstances of restrictions on raw material markets.
The results of the GloMo model linked with dynamic raw material cycles show that the scenario with a strong diffusion of alternative drives - even though dominated by the hybrid technology which contains only small sized batteries of around 1,5 kWh - has a deep impact on the demand for battery raw materials. Both lithium and cobalt have got high reserves, consequently the depletion of these materials due to the increasing use for new technologies is not at issue. However, raw material reserves in this context are surely the wrong indicator to measure potential material scarcity. The decisive question one has to ask is if today's production facilities and current mining projects are able to meet future demand.
Therefore, further research work with a more precise examination of the sensitivity of different markets on higher raw material prices as well as the potential of material substitution has to be performed. Figure 16 describes the approach we are currently developing to meet these scientific challenges.

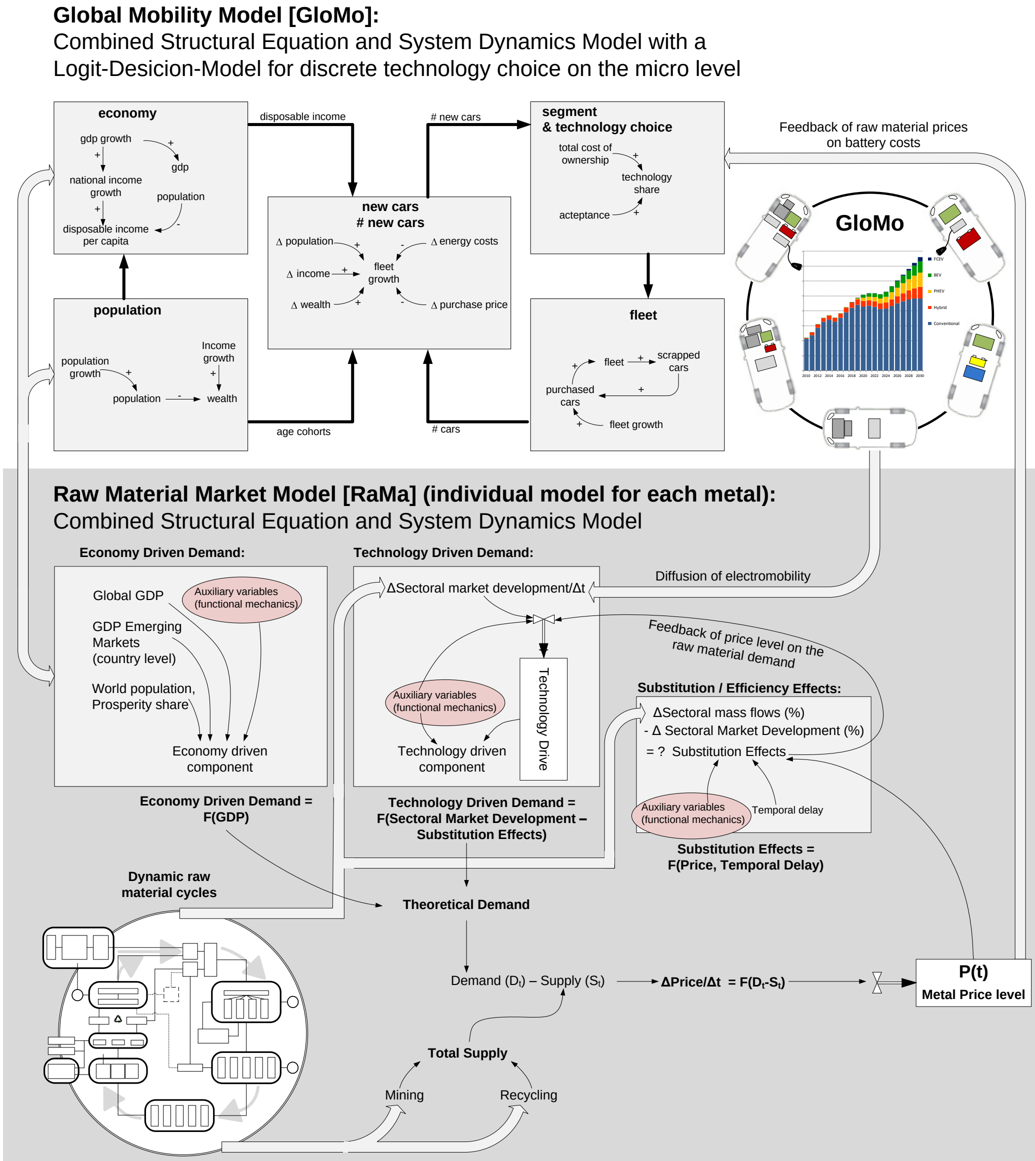

Figure 16 Enhanced modeling approach to analyze the sensitivity of different markets, particularly alternative drives, on increasing raw material pricing.

5 References

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