Exploring the Battery Market for Electric Cars

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[1]The views expressed are purely those of the authors and may not in any circumstances be regarded as stating an official position of the European Commission.

ABSTRACT

Electric vehicles offer the possibility to decarbonize road transport and their market uptake is expected to continue over the next years. This paper describes a modeling exercise that comprises the soft-linkage of three system dynamics models, with the aim of exploring the battery market for electric cars. In particular, potential global supply-side limits such as battery material scarcity and manufacturing bottlenecks are investigated, with a focus on the European market. The results point out that, contrary to more optimistic projections, these constraints might jeopardize the market penetration of electric powertrains. Research is needed to integrate these models and further account for feedback processes.

Keywords: *electric vehicles, lithium-ion batteries, system dynamics, automotive*

1. INTRODUCTION

In 2015, road transport emitted almost 5.8 gigatons of carbon dioxide ($GtCO_2$) worldwide (IEA, 2017). At the United Nations Climate Change Conference held in Paris in the same year, the goal of more than 100 million electric cars globally in 2030 was stated (COP21, 2016). To reduce greenhouse gas (GHG) emissions from car use by electrifying the world car stock, automotive batteries are needed.

Today, different types of batteries co-exist in the vehicle market. They differ in characteristics, such as energy density (see Figure 1). Although nickel–metal hydride (Ni-MH) batteries are still used in hybrid electric vehicles (HEVs), it seems that the trend is towards lithium-ion batteries (Li-ion or LIBs) in the automotive sector.

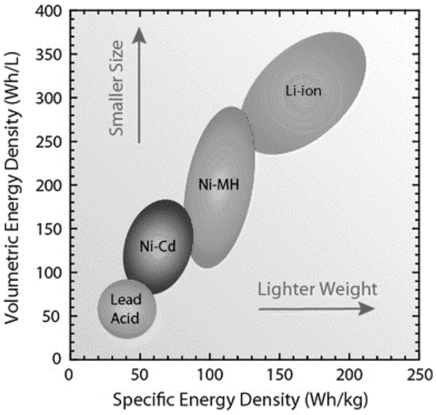

Figure 1. Battery cells, by volumetric and specific energy densities

Source: EPEC (2018)

Modeling battery supply and scarcity of battery materials using system dynamics is not new (see e.g. Figure 4 by Hoyer *et al.* in Sucky (2011) and Novinsky *et al.* (2014), who focus on the cobalt market). However, the available system dynamics literature on this topic is rather limited. The **objective** of this work is to explore the battery market and its influence on the uptake of electric vehicles (EVs), by considering potential supply constraints (see section 3). The **focus** of the paper is on the European primary market for electric vehicle batteries (EVBs), namely LIBs. Thus the use of batteries for storage in the secondary market is beyond the scope of this paper. The **structure** of the paper is as follows: after this introduction, section 2 examines available data. In section 3, the modeling exercise is presented. Section 4 shows the results. Conclusions are drawn in section 5. An appendix complements this work.

2. DATA ON THE SUPPLY SIDE

The EV (plug-in hybrid electric vehicles (PHEVs) and battery electric vehicles (BEVs)) stock in Europe is growing and, with it, the demand for EVBs. Battery manufacturing depends not only on the number of EVs sold but also on the capacity of their batteries. BEVs usually have a larger battery capacity, measured in kilowatt-hour (kWh), than PHEVs. For each of these two powertrains, larger vehicles tend to feature larger batteries. Figure 2 shows the average EVB by type of EV and size (small, medium, large) in the European car market. The category ‘small’ corresponds to segments A and B, ‘medium’ refers to C and ‘large’ to segments D, E, F, S, J and M (for the definitions, see EAFO (2017)). In that figure, both unweighted and weighted average are shown, with the exception of small PHEVs, where only the BMW i3 Rex PHEV was found for 2015. Whereas unweighted averages reflect what is available in the market, weighted averages can be considered a proxy for what consumers chose in that year. As can be seen, once sales / registrations are accounted for, the average value of the battery capacity tends to increase, with the exception of medium PHEVs. In other words, it seems European car purchasers exhibited a preference towards the models with larger EVB capacities. In the case of large BEVs, the Tesla Model S with its 100 kWh battery dominated sales in 2015.

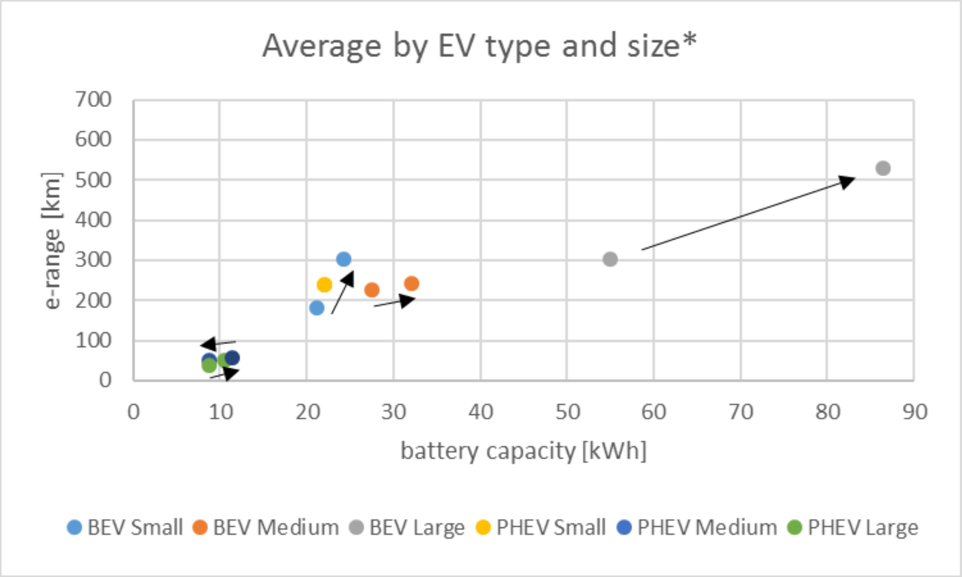

Figure 2. Battery capacity versus e-range in Europe

Source: own analysis using EAFO (2017). *Unweighted average and average weighted by sales in 2015. The arrows point towards the weighted average.

As expected, the larger the battery capacity, the longer the distance that can be travelled on electric mode. Electric range (e-range) is based on the New European Driving Cycle (NEDC). Figure 2 provides useful information for the simplifying assumptions of the model. However and given the diversity in typologies within LIBs (see BU (2017)), other sources of information are needed to inform our modeling exercise.

Table 1 shows the amount of materials two types of LIBs are thought to contain: nickel manganese cobalt oxide (NMC) and nickel cobalt aluminium oxide (NCA) batteries. As can be seen, NMC batteries require manganese (Mn) and more cobalt (Co) than NCA batteries but no aluminium (Al) and less lithium (Li), graphite and nickel (Ni). In addition, the table provides data on two types of electric motors (e-motors): whereas induction motors rely heavily on copper (Cu), permanent magnet (PM) e-motors require dysprosium (Dy) and neodymium (Nd). These two rare earth elements (REEs) are ranked by Moss *et al.* (2013) as highly critical.

Table 1 – Materials, by type of EV and LIB*

			Materials [kg]								
			Al	***Co***	***Cu***	***Dy***	***Graphite***	***Li***	***Mn***	***Nd***	***Ni***
PHEV	***Motor***	PM	-	-	-	0.22	-	-	-	1.46	-
		Induction	-	-	40.00	-	-	-	-	-	-
	LIB	NMC	-	2.38	8.39	-	9.07	0.79	2.20	-	2.46
		NCA	0.23	1.44	11.41	-	12.33	1.06	-	-	7.97
BEV	***Motor***	PM	-	-	-	0.38	-	-	-	2.55	-
		Induction	-	-	70.00	-	-	-	-	-	-
	LIB	NMC	-	13.91	49.13	-	53.08	4.64	12.88	-	14.43
		NCA	1.35	8.44	66.82	-	72.19	6.23	-	-	46.65

Source: Tables 58; 61; 63 in Moss *et al.* (2013). *The assumed battery capacities are 8.2 kWh for PHEVs and 35 kWh for BEVs.

In a more recent study by UBS, a Chevrolet Bolt BEV was torn down so that insights into the components of the car, including battery raw materials, could be gained. This BEV features a PM e-motor and a 60 kWh NMC battery weighting 436 kg (of which 300 kg correspond to cell materials). The proportions of Ni, Mn and Co are roughly equal (22-24 kg) (UBS, 2017).

Figure 3 shows where the main raw materials for EVBs are sourced. When it comes to key resources for EVs, three world regions stick out:

- Sub-Saharan Africa for Co, Mn and platinum (Pt): whereas more than half of the world’s Co comes from mining activities in the Democratic Republic (DR) Congo;

South Africa is the largest extractor of Mn and Pt (USGS, 2017) (van Vuuren, 2014);

- South America for Li (though Australia led in mine production in 2016) and Cu: the so-called ‘lithium triangle’ encompasses Argentina, Bolivia and Chile (O’Brien and Nickel, 2016). The latter ranks first in Cu reserves and extraction, followed by Peru (USGS, 2017);
- Asia for REEs and other materials (e.g. Ni in Indonesia and the Philippines). Specifically, China dominates not only graphite extraction, holding 65% of the world’s total (USGS, 2017), but also the market for REEs, though its share in world output has dropped in recent years (ERECON, 2015).

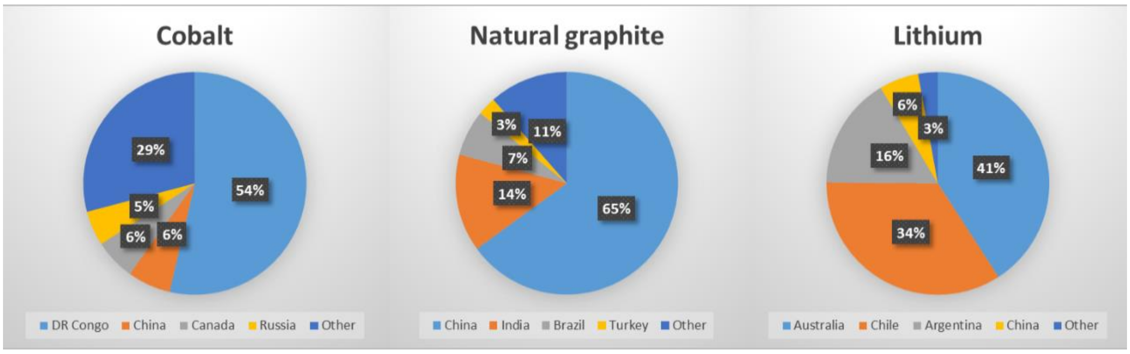

Figure 3. Extraction of selected materials in 2016, by country
Source: based on USGS (2017)

The case of platinum group metals is worth noting. This metal can be found in internal combustion engine vehicles (ICEVs) and fuel cell electric vehicles (FCEVs), but not in EVs. In FCEVs, the fuel cell system contains about 30 grams of platinum, which costs over 1,000 euros. Dependency on one or two countries for key materials might lead to situations of resource scarcity, as it became evident during the REEs crisis in 2011 (see e.g. Majcher (2015)). Two types of scarcity can be conceptualised: absolute or physical scarcity and relative or economic scarcity (Daly, 1991). Physical scarcity is illustrated in Equation (Eq.) 1, using the reserves of Li as an example.

$$Li\ reserves_t = \int_0^t (Li\ discovery_t - Li\ extraction_t)dt + Li\ reserves_{t_0} \qquad \text{Eq. 1}$$

$where\ Li\ discovery_t = 0\ if\ there\ is\ no\ inflow\ to\ the\ stock\ of\ Li\ reserves.$

Once mined (outflow in Eq. 1), these materials are shipped to production sites, where battery cells and packs are manufactured. Lebedeva *et al.* (2016) estimated that the world capacity in LIB cell manufacturing reached 60 gigawatt-hour (GWh) in 2015, with almost one third of this corresponding to EVBs. Figure 4 shows how this market was structured in 2015. As can be seen, this market is dominated by Asian players. The EVB manufacturing market is projected to grow over the next years. But because of the uncertainty of EV diffusion and material availability, EVB manufacturers might have to face two extreme situations: insufficient or excess capacity.

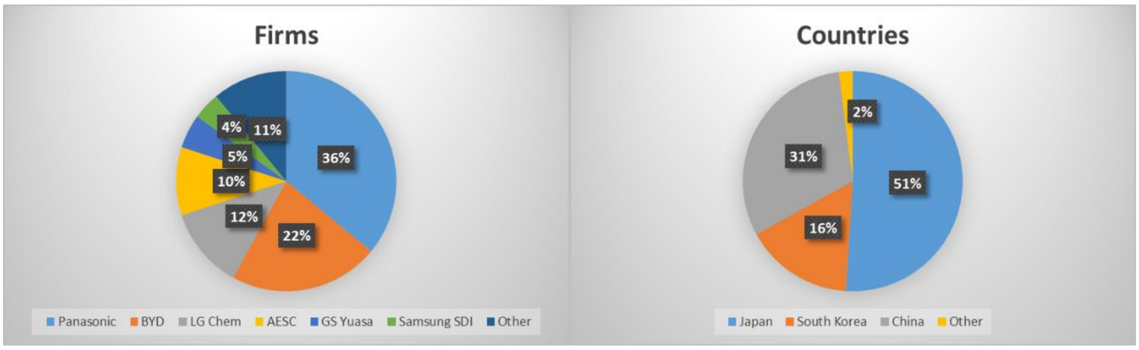

Figure 4. EVB manufacturing in 2015, by firm [left] and country [right]
Source: based on data from DB (2016)

The European Union (EU) has the ambition to become a leader in battery cell manufacturing (EC, 2018). To achieve that goal, the European Battery Alliance (EBA) is envisaged (InnoEnergy, 2018). For this to happen, investments in supply infrastructure are required. A step in this direction is the planned construction of the Northvolt factory in Sweden, which is expected to employ 2,000-2,500 people in its manufacturing facility in Skellefteå and 300-400 people in its research and development (R&D) site in Västerås (Northvolt, 2017)[1]. This year, the European Investment Bank has approved a loan of up to 52.5 million euros for this infrastructure (EIB, 2018).

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[1] For an estimation of employment effects from a 13 GWh/year battery cell factory in Germany, see also Figure 23 in (NPE, 2016).

3. MODELING BATTERY MARKET DYNAMICS

Optimistic projections of EV deployment tend to rely on demand side considerations and cost parity assumptions for ICEVs and EVs. These projections tend to neglect or downplay supply limits. Two of these supply constraints are identified as potentially jeopardizing EV market uptake: resource scarcity and supply chain bottlenecks. These were highlighted in the previous section and are considered in the modeling exercise presented in this section. It consists of the soft-linkage of three system dynamics models:

- Battery manufacturing model: a simple representation of EVB manufacturing capacity build-up. This model covers the supply side.
- The Powertrain Technology Transition Market Agent Model (PTTMAM): a comprehensive model of the EU vehicle market. To model the supply constrains of interest, a version of PTTMAM different from the one described in Harrison *et al.* (2016) was used. Specifically, a new module with EVB materials was added and the units of battery-related variables were changed from [component] to [kWh] and checked for dimensional consistency.
- The Transport, Energy, Economics, Environment (TE3) model: a representation of the car market in China, India, Japan and the United States (US), with a focus on EV uptake.

The conceptualized model interaction can be seen in Figure 5. In PTTMAM, cars are disaggregated by, among others, size: small, medium and large. Battery capacity for HEVs, PHEVs and BEVs is assumed to differ by size in PTTMAM. For model consistency, the same battery capacity values of the medium-sized cars are used in TE3, which does not disaggregate car by size. Each model independently simulates annual HEV and EV sales between 2005 and 2030[2]. This demand-side information is fed into the battery manufacturing model (thick arrows in Figure 1). Battery demand, expressed in GWh, is then derived and compared with the simulated EVB manufacturing ramp-up.

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[2] Whereas PTTMAM has a 1995-2050 time horizon, the TE3 model runs only between 2000 and 2030.

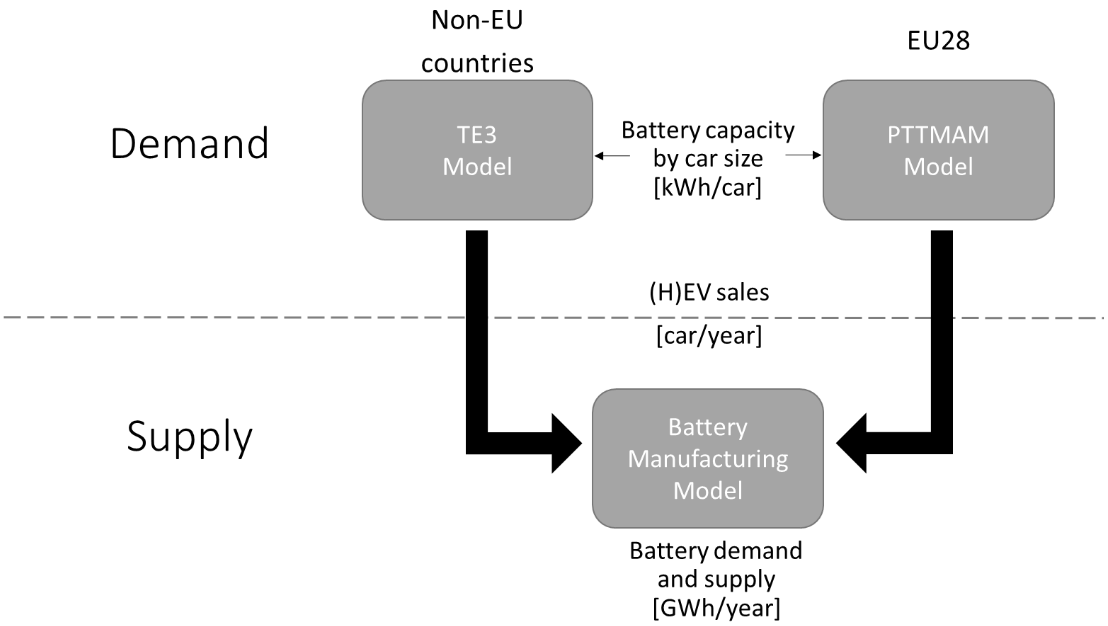

Figure 5. Overview of the modeling exercise

3.1 Modeling resource scarcity

In the modeling exercise, resource scarcity is captured by introducing price jumps for selected materials, using step functions. Figure 6 shows the default prices for key EVB materials (see also Figure 14 in the appendix).

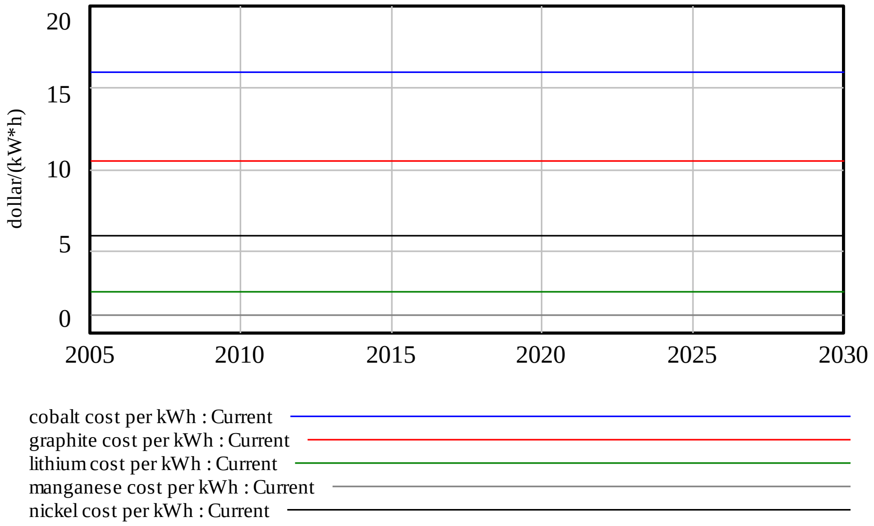

Figure 6. Battery material costs
Source: own assumptions informed by InfoMine (2017)

It is assumed that material prices affect end-user battery prices but not operations, which are captured by a learning curve (Eq. 2 shows the formulation adopted).

$$Learning\ effect_t = \left(\frac{Cumulative\ production}{Minimum\ production}\right)^{LOG_2(1-fractional\ reduction)} \qquad \text{Eq. 2}$$

The effect of introducing price shocks for Ni and Co by simulating a doubling of prices in the year 2021 on extra battery costs are shown in Figure 7. In that figure, a moderate jump in costs is visible in 2020. This can be traced to the assumption of an increase in EVB capacity (see Figure 13 in the appendix). But the stronger increase in cost between the simulation runs named ‘*Current’* and ‘*Current with price shocks’* in 2021 is the result of the material price shocks. Its impact on the cost of battery packs is shown in Figure 12 (section 4).

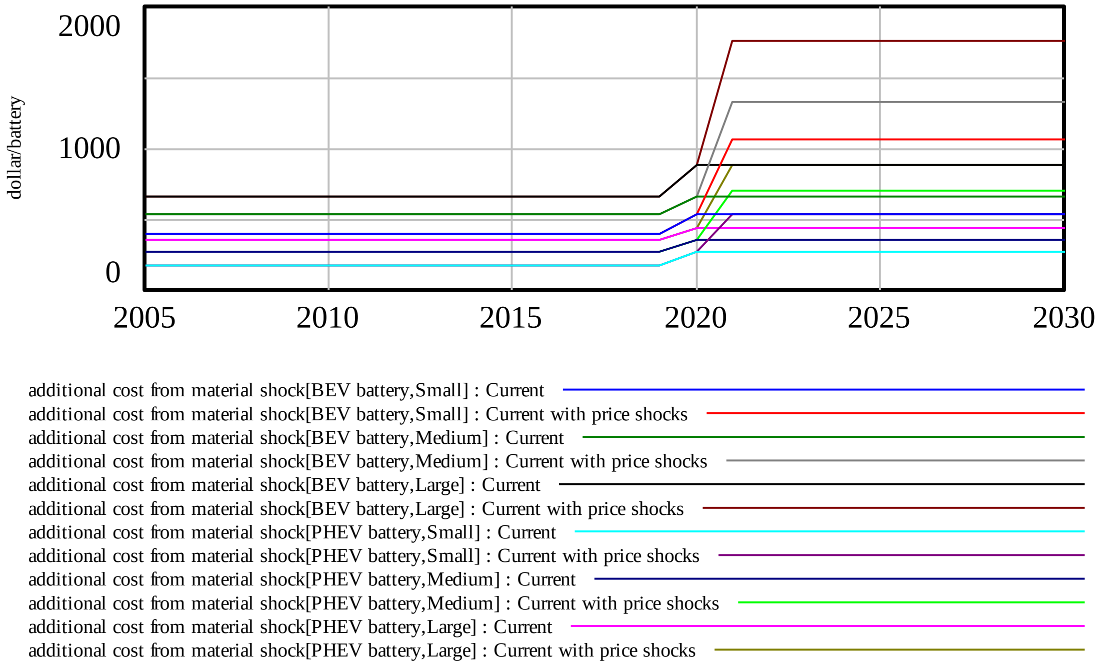

Figure 7. Extra battery costs from Co and Ni price shocks

3.2 Modeling supply chain bottlenecks

Figure 8 shows a stock-and-flow formulation of the battery manufacturing model. For simplicity, the assumed average lifetime of the battery manufacturing plants is as long as the model time horizon. The information for the variables ‘EU car sales’ and ‘rest of the world (RoW[3]) car sales’ comes from the other two models. The stock variable ‘planned EVB manufacturing capacity’ partially depends on country-specific new plant capacity.

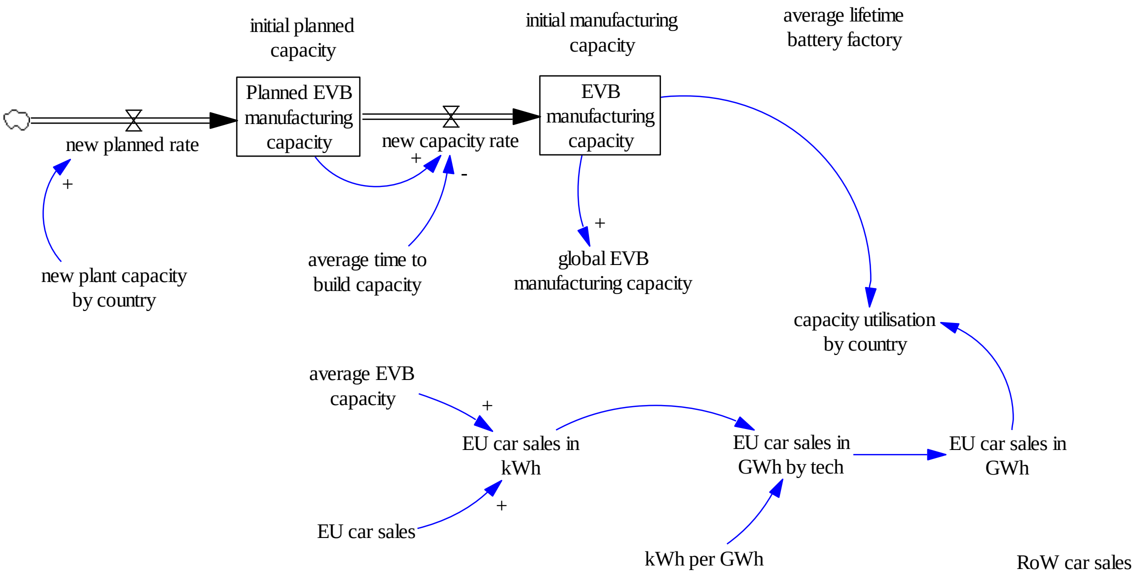

Figure 8. Overview of the battery manufacturing model

Figure 9 shows the manufacturing plans until 2023 for two gigafactories[4]: Northvolt in Europe and Tesla in the US. Whereas Tesla expects to reach a battery manufacturing capacity of 35 GWh/year by 2020, Northvolt plans to scale production by reaching 32 GWh/year by 2023, up from 8 GWh/year in 2020. In that figure, a ramp function has been used, however it remains unclear whether this adequately reflects Northvolt’s plans. Further into the future, TerraE plans a manufacturing capacity of 34 GWh/year in Germany by 2028 (TerraE, 2018).

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[3] *De facto* China, India, Japan and the US.

[4] The metric ‘gigafactory’ is becoming standard in this field ever since Tesla opened its Gigafactory 1 in Nevada in 2016. It refers to a manufacturing capacity of 35 GWh per year.

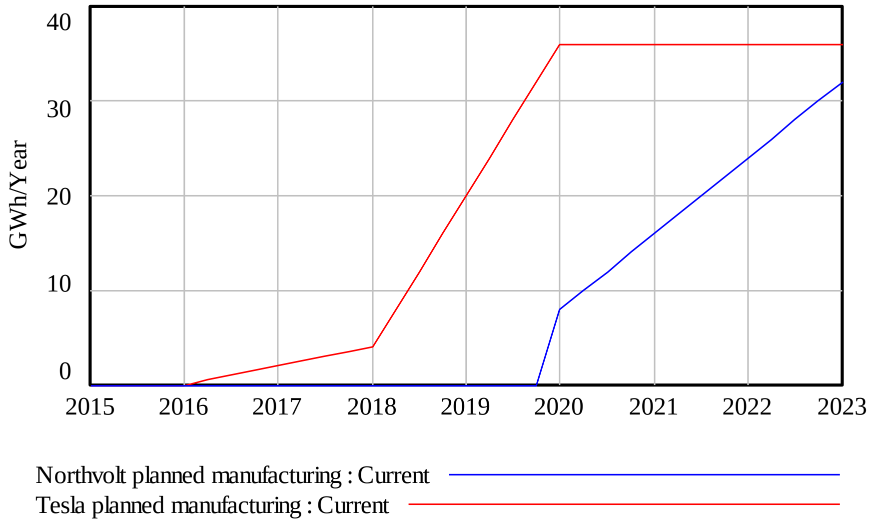

Figure 9. Manufacturing plans in selected automotive battery gigafactories
Source: own assumptions based on Northvolt (2017) and Tesla (2018).

What if consumer and/or business confidence in EVs suddenly plummets and these plans do not materialize? Figure 10 shows a simulation where post-2020 global EVB manufacturing capacity stagnates.

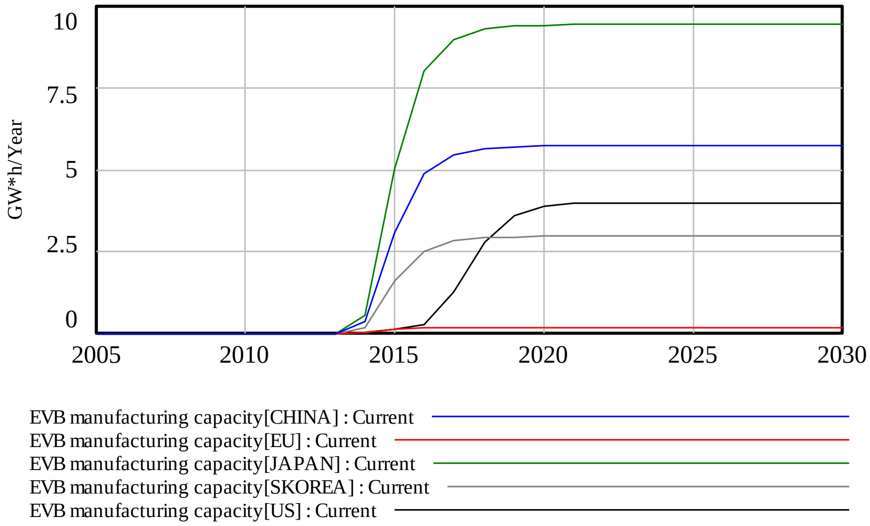

Figure 10. Simulated battery manufacturing capacity without plans, by country
Source: own assumptions based on Lebedeva *et al.* (2016) and DB (2016)

4. RESULTS

The behavior of the structure depicted in Figure 8 can be seen in Figure 11 which, in contrast to Figure 10, takes into account the plans mentioned in the previous section. Several remarks are pertinent: (i) the simulated values of the variable 'global EVB manufacturing capacity' (red line in the chart) are the same under the '*Current with plans'* and '*Current with demand'* runs; (ii) because of data unavailability prior to 2015, EVB manufacturing capacity becomes available in the supply model in 2015 (hence the initial mismatch between supply and demand); (iii) the run '*Current with plans'* reflects the ramp-up of the Tesla gigafactory in Nevada as well as the planned capacity in Europe, excluding the announced but not yet confirmed Tesla gigafactory in the continent; and (iv) additional investment in capacity from Asian countries has not been assumed for simplicity.

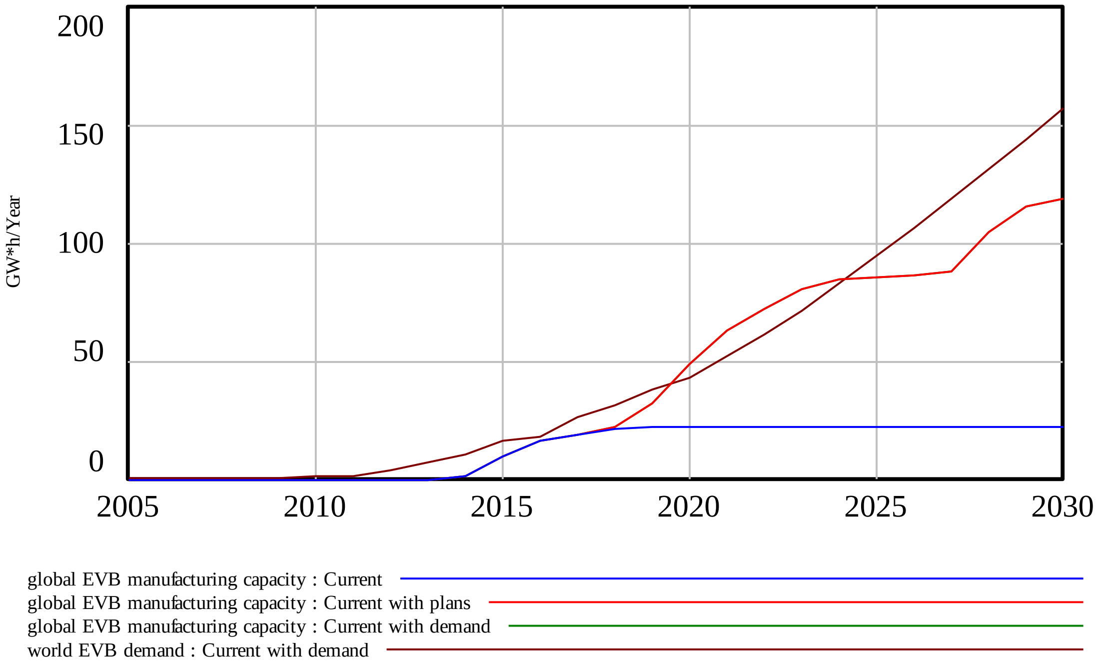

Figure 11. Simulated global battery demand and manufacturing capacity with plans

As can be seen in Figure 11, a bottleneck in EVB production starts to emerge soon if no additional EVB manufacturing capacity is created in the system. If however plans materialize, early imbalances between demand and supply may exist, depending on the time lag in capacity build-up. When new manufacturing capacity becomes available, global battery supply and demand for electric cars are kept in balance until 2024. For the period 2020-2024, relatively high capacity utilization levels are simulated. Between 2025 and 2030, simulated demand exceeds supply. This is unrealistic, as it is reasonable to expect that EVB manufacturers forecast by 2024-2025 the historical growth trend and add new capacity. As pointed out before, over-optimism in their forecasts could however lead to excess capacity.

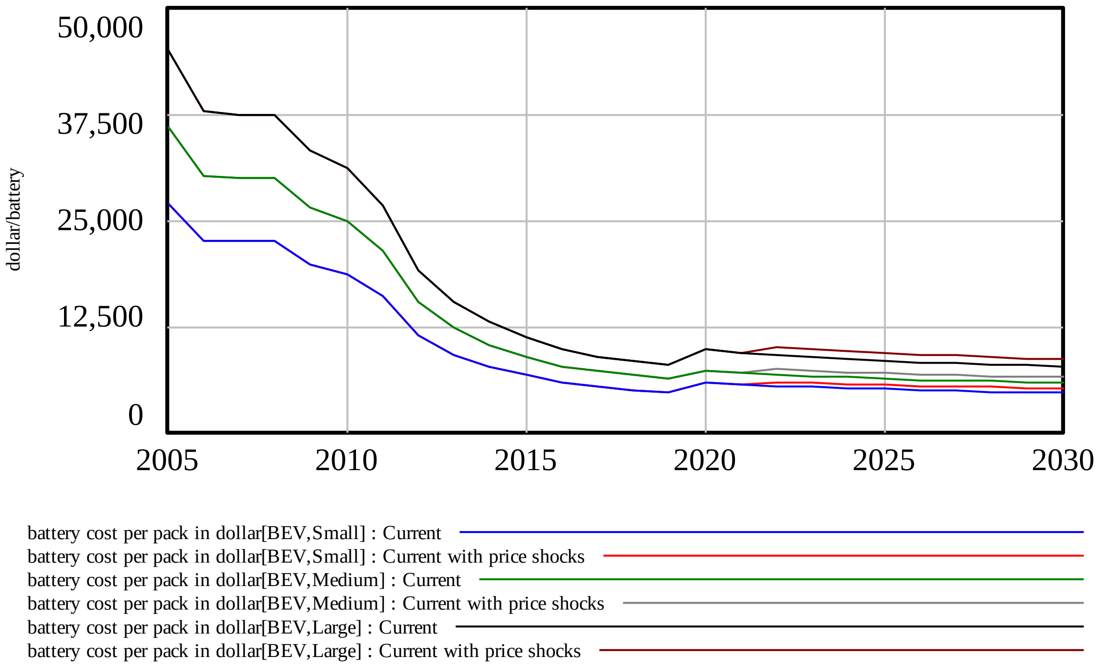

Figure 12. Simulated battery cost as a result of material price shocks

Figure 12 shows the impact the assumed material price shocks (cf. section 3.1) has on the cost of the battery pack, specifically for small, medium and large BEVs. An analysis of the information available in the aforementioned UBS study reveals that the estimated cost of the Chevrolet Bolt BEV battery is 145 dollars/kWh at the cell manufacturing level and ca. 200 dollars/kWh at the pack level (UBS, 2017). Chung *et al.* (2016) assume that Japanese battery manufacturers set a price margin of ca. 24%. Rising battery material costs may leave battery end-user prices unaffected by reducing the price margin or, as assumed in this work, be transferred to the price as an additional cost.

5. CONCLUSIONS AND DISCUSSION

In sum, a modeling exercise using three system dynamics models was conducted to explore the battery market for electric cars in Europe. The main objective of this work was to consider explicitly supply-side aspects that may condition the market penetration of electric cars. I conclude that the scarcity of battery materials and possible manufacturing bottlenecks have the potential to slow down growth in electric car sales.

A series of major limitations can be pointed out in this work. The most important one is the possibility of hard-linking the three models, which would allow a more transparent communication of feedback loops and also open up the opportunity to model additional feedback processes by endogenizing key variables. Specifically, the PTTMAM and TE3 models have the potential to be integrated into a single model, which could receive information from the battery manufacturing model (i.e. a new arrow from supply to demand in Figure 5). Second, the assumption of constant EVB prices and exogenously determined shocks to reflect resource scarcity is very crude. Sterman (2000) describes a commodity market model that displays oscillatory behavior. Introducing a similar formulation in our main model appears particularly desirable, both for theoretical and empirical reasons, in future research. Third, other relevant electric car markets such as Norway, Canada and South Korea have not been considered. Fourth, new evidence is needed to better calibrate the supply model. Fifth, the assumption that EVs need two batteries over the vehicle lifetime raises interesting questions related to the second-life (e.g. used as an electricity storage device) battery market and battery recycling. Finally, the prospects of new developments in battery chemistries, material substitution effects and the potential for greater energy density have been neglected. All these require further investigation.

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APPENDIX

I assume that the average lifetime of the EVB is shorter than that of the vehicle, which implies that a battery replacement is needed. In addition, beyond a certain cost reduction threshold of the battery, average capacity increases to enable greater e-range (see Figure 13).

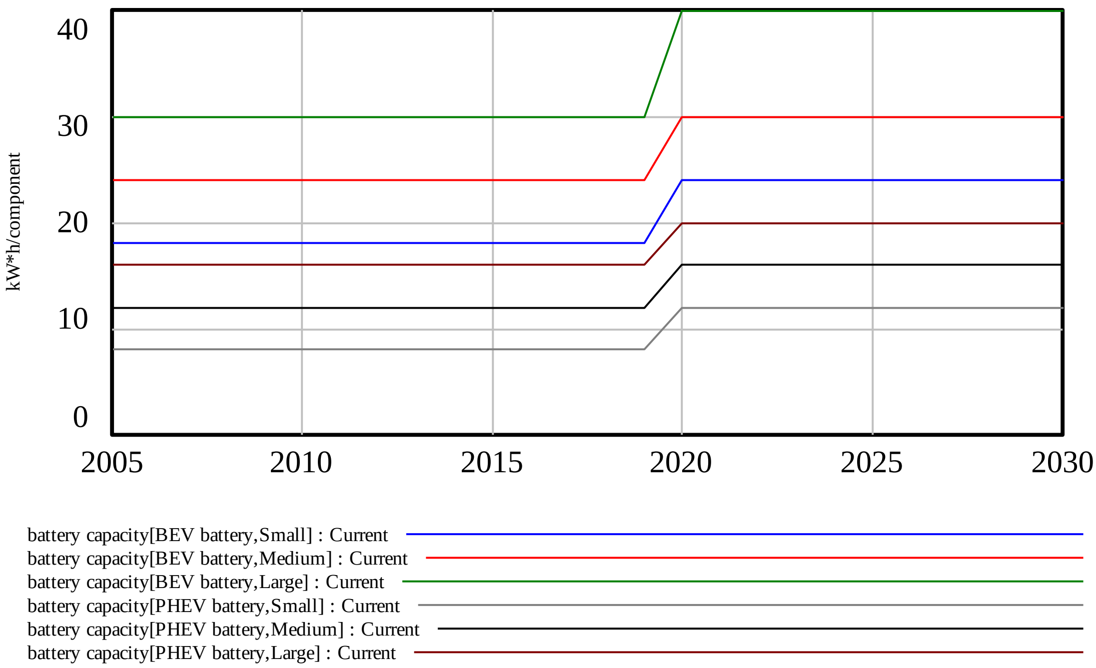

Figure 13. Simulated EVB capacity

The structure of the model that leads to the prices shown in Figure 6 can be seen in Figure 14. For reasons of visibility, subscripting has been deliberately avoided.

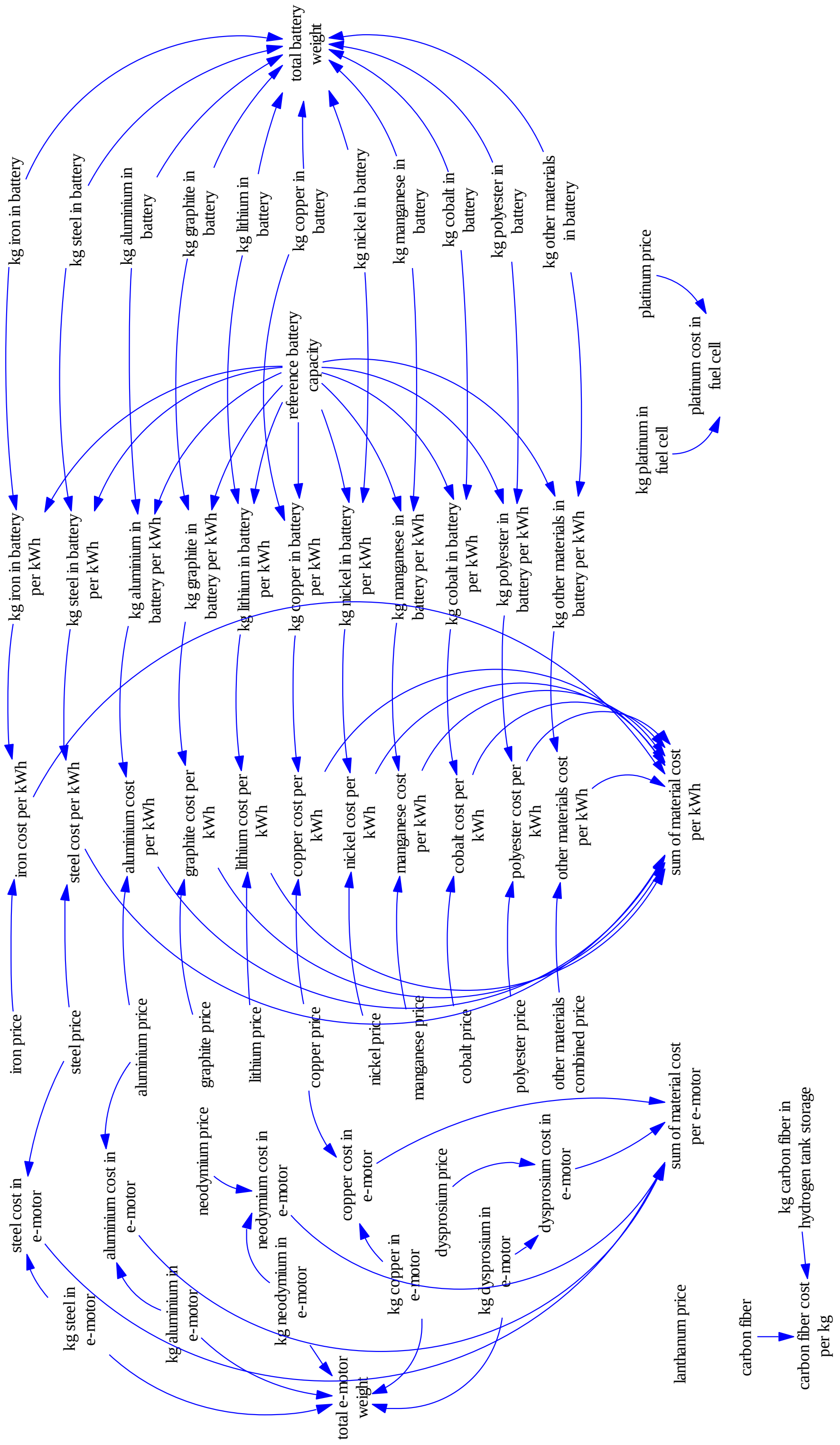

Figure 14. Excerpt of the main model with a focus on materials