Interactions of production strategies and a production system's performance
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An analysis of the influence of production strategies on the final unit costs of lithium-ion batteries

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Future-oriented industrial companies are reliant on the continuous expansion and adjustment of their business units to new markets. The profitability of such new business units is therefore often linked with high investments and characterized by high uncertainty regarding the competitiveness of the produced product and the company's production system. In this context, a company's production strategy plays a crucial role because it can be seen as a blueprint for the development of the production system. A production strategy consists of four sub-strategies that address the location of a production system, the way capacities are increased, the product portfolio manufactured and the depth of vertical integration. Any modification or combination of these sub-strategies affects the production system at multiple places and in different ways, making it extremely difficult to predict the overall effect on the performance of the production system. Similarly, the resulting unit costs of a product produced by this production system are difficult to predict and it is hard to say whether the company would be competitive in a new market.

This article analyzes the interactions between different production strategies and their impacts on the final unit costs of lithium-ion batteries. A stock and flow model is constructed based on a qualitative system dynamics model that describes these interactions. The model shows the impacts of the analyzed production strategies in different scenarios. Finally, first insights into the benefits and disadvantages of specific sub-strategies can be given that depend on the overarching market for electric vehicles.

System Dynamics, Manufacturing strategy, Production strategy, Lithium-ion battery, Cost model, Technology strategy, Capacity strategy, Location strategy, Strategy of vertical integration

1 Introduction

The world's increasing volume of road traffic is a catalyst for climate change and a drain on already scarce resources. In order to curb these effects, electric mobility will play an important role in the future. Successfully managing this transformation process is a major challenge for the automotive industry. Internal combustion engines and related components will lose their relevance and be replaced by new components. In this context, the lithium-ion battery (LiB) is particularly important for electric mobility because it determines the costs and range of electric vehicles (Schade et al. 2014). In countries like Germany, the automotive industry plays a major role from an economic perspective, accounting for about 21% of the total turnover of the manufacturing sector and directly employing about 700,000 people (German Federal Statistical Office 2014). It is therefore vital for Germany to navigate a successful transformation from the conventional internal combustion engine to the electric motor. The LiB is a key component here with very high added value. But compared to the USA, up to now, no significant LiB cell manufacturing exists in Germany. Many players are reluctant to act because of the high investments needed. A major reason for the lack of activity might be that it is unclear which production strategy will achieve a competitive price level.

By using system dynamic analysis, the influence of different production strategies on the resulting production costs of a company will be examined. A bottom-up approach is applied to focus on the effects on the performance of the company’s production system.

In the following, the sub-strategies making up a production strategy are described and why it is difficult to foresee the effect of a production strategy on production system performance. Then a short literature review will be given of existing similar approaches in this field. Chapter 3 describes the main subsystems of the model, before two different production strategies are analyzed under different scenarios in chapter 4. The paper closes with conclusions and an outlook in chapter 5.

2 How production strategies influence the performance of a production system

The performance of a production system as a central unit of a manufacturing company is determined to a large extent by the production strategy used for its development (Zaepfel 2000). How this performance is determined and how it is influenced by a production strategy is described by the following illustration in the form of a causal diagram of the dynamic problem behavior.

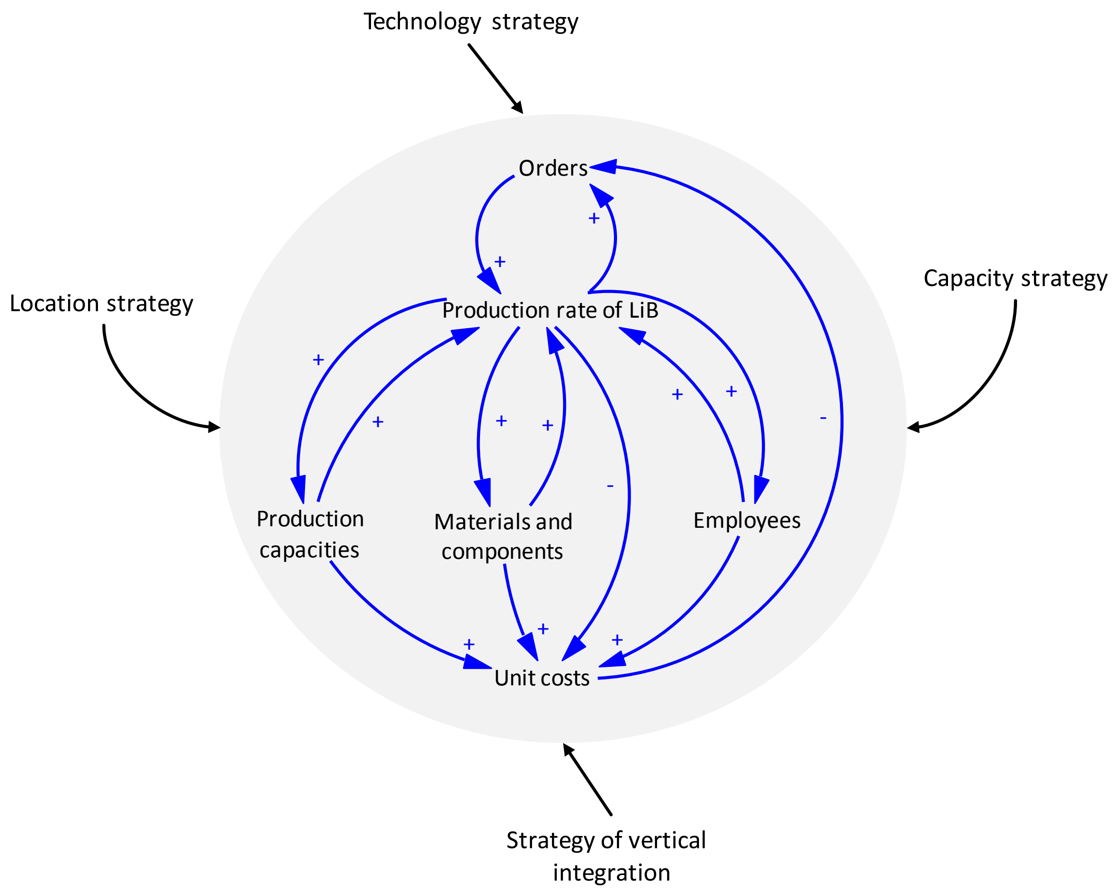

Figure 2-1: Dynamic hypotheses for the model

The production of LiB can be seen as the driving force within the depicted qualitative model and is triggered by the demand for LiB resulting from the sales market. On the one hand, the planned production determines the need for employees, working materials and components as well as the necessary production capacities. On the other hand, the feasible maximum production is determined by the availability of these key elements. Furthermore, acquiring employees, materials and production systems results in costs which have a direct impact on the final unit costs and thus the competitiveness (from an economic point of view) of the LiB product. Thereby, a comparative increase in the price level leads to a reduction in the demand for LiB.

Production strategies may directly influence one or more of the variables mentioned. The capacity strategy offers the possibility to increase capacity in a rather defensive (follow strategy) or aggressive way (lead strategy). While the first strategy is intended to avoid overcapacities in production, the lead strategy aims at always having enough capacity to satisfy demand and thus avoid any penalty for late or non-delivery.

The location strategy influences the production-relevant costs (e.g. labor costs), while it has no effect on the overall demand for LiB, because the market for LiB is assumed to be global.

The vertical integration strategy concerns the possibility to produce the whole LiB or to buy LiB cells from a supplier. The first option is accompanied by the construction of an entire cell production system, which is the most capital-intensive manufacturing step in LiB production. This investment is not necessary if the cells are sourced. One disadvantage of purchasing the cells from outside means the margin of the supplier has to be considered when calculating the unit costs.

Finally, the last production strategy - the technology strategy - addresses the product portfolio to be produced. A company can concentrate on high energy batteries as only used in BEV (battery electric vehicles) and PHEV (plug-in hybrid electric vehicles) or additionally build high power batteries as used in HEV (hybrid electric vehicles). The high demand for HEV and thus for high power batteries means there is a possibility for a high production rate right from the outset (the demand for high energy LiB starts to increase at a later time) and thus to gather experience with LIB production. High power LiBs have a lower specific capacity (kWh) although the production steps are more or less the same as for high energy LiB. This means that the same investments in production systems have to be made as for high energy LiB (which have a higher specific capacity), which results in comparatively higher unit costs (€/kWh).

So far, there is no system dynamics approach to simulating the production costs of LiB that considers the performance of a production system. This is even more the case if performance is linked to the decision about production strategies. So while there are hardly any approaches on the battery level, there are many more studies for the overarching market for electric vehicles (EV), which triggers the demand for LiB (e.g. Struben & Sterman 2007, Keith et al. 2012 or Gomez et al. 2013).

3 System structure and basic elements

In the following, two subsystems will be described in detail. The “Sales market” and the “Production system”. The sales market simulates the diffusion of three different types of electric vehicles (EV) using a Bass diffusion model (adopted from Sterman 2000 and Bass 1969, based on Hettesheimer & Lerch 2013). The following Figure 3-1 shows the structure of the subsystem “Sales market”.

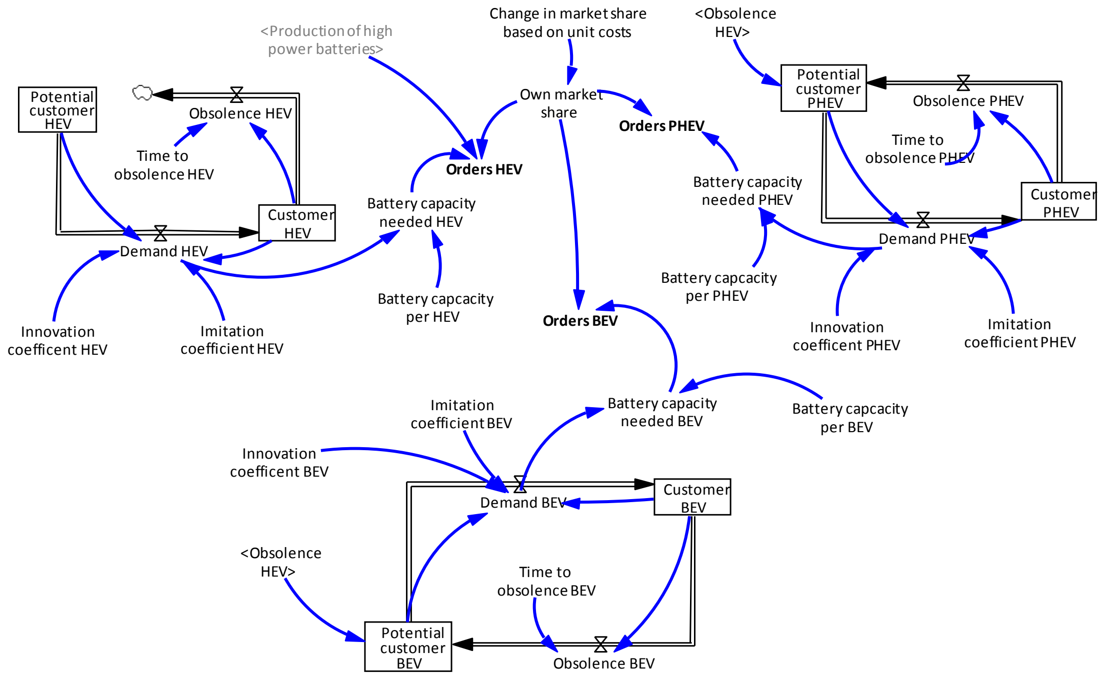

Figure 3-1: Structure of the sales market subsystem

The subsystem is further divided into three different parts, representing the different types of EV: HEV, PHEV and BEV. In each part, EV diffusion is simulated with regard to a specific customer potential and the specific coefficients of innovation and imitation. The overall demand for LiB is determined considering the EV-specific battery capacity. The three different parts simulate the global demand. The demand for a single company results from this company's market share in this global demand.

The "Orders HEV", "Orders PHEV" and "Orders BEV" constitutes the central input to the subsystem "Production system" and is the trigger for the simulated production of LiB there. The model structure of the subsystem is depicted in Figure 3-2. The model structure is inspired by the supply chain model depicted in Sterman (2000). For better clarity and readability, the model is further separated into parts A and B and enlarged in Figures 3-3 and 3-4.

In part A, it can be seen that the orders simulated in the "sales market" are fed into the subsystem in step 1. In step 2, the corresponding number of battery systems is determined by the orders for LiB. Then, based on the orders for battery systems, the number of battery modules, battery cells and finally battery electrodes is submitted. After that, in step 3 (part B), a comparison is made between the numbers of orders for electrodes and the resulting desired production rate for electrodes. The maximum possible production rate is determined restricted by the installed production capacity.

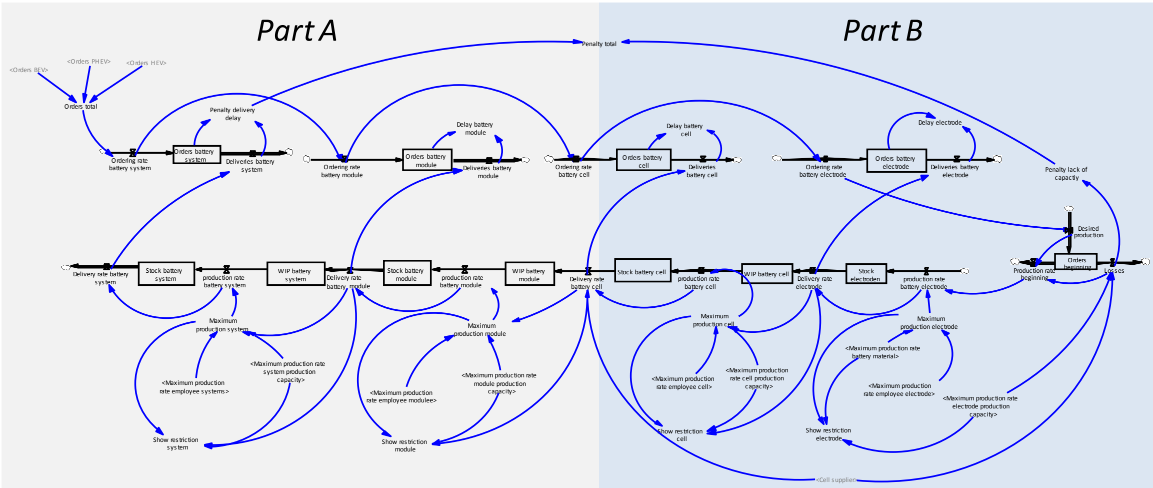

Figure 3-2: Subsystem production system

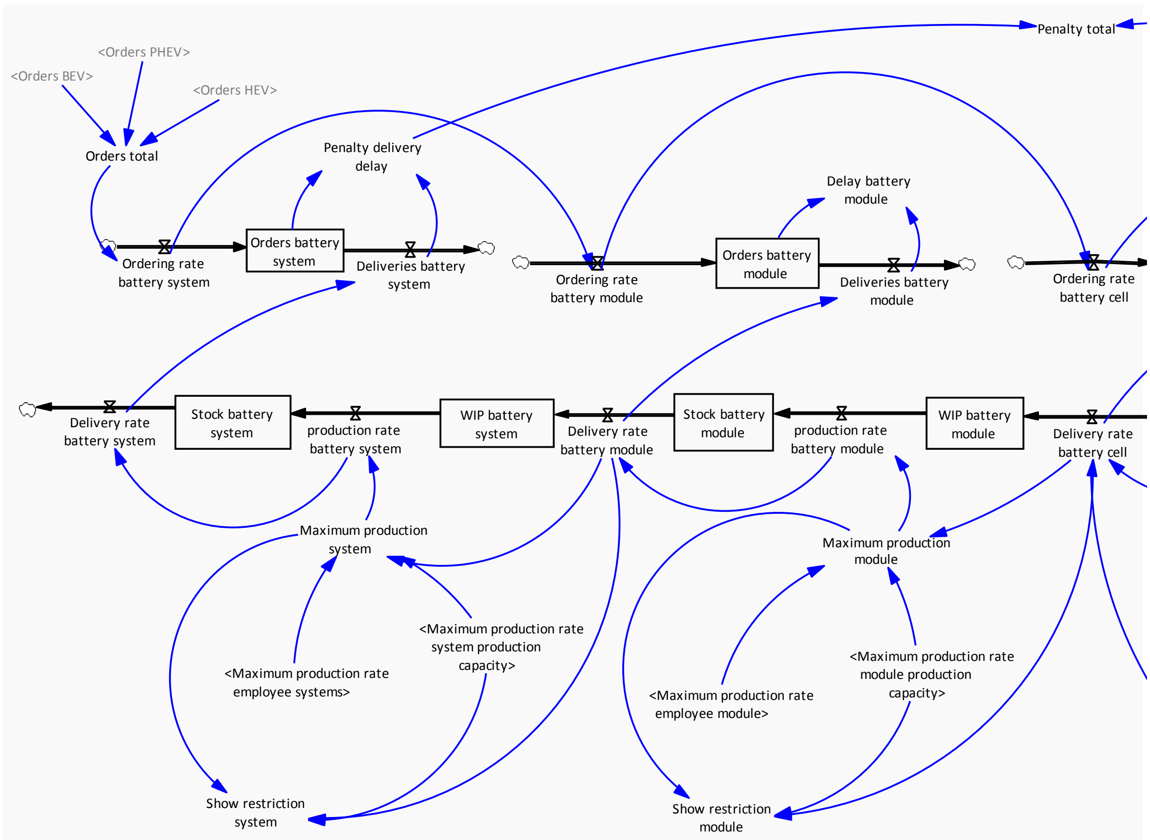

Figure 3-3: Subsystem production system - Part A

While a penalty has to be paid for orders which cannot be met due to limited capacity, those orders which can be theoretically produced form the inputs to step 4. This step represents the stages of production from the battery electrode to the final battery system as an aging chain. The maximum production rate of each stage is determined by a potential lack of production capacities, materials or employees. This comparison happens in step 5. If buying the cells from a supplier is chosen as the production strategy, then the comparison starts at the stage of battery modules and the previous steps are not taken into account when determining any restrictions. The final battery system is assembled at the end of the aging chain. Any delivery delays between the incoming order and the delivery of the final product are calculated. If the delivery time is longer than the targeted delivery time of 1 month, an additional penalty payment is included depending on the length of the delay.

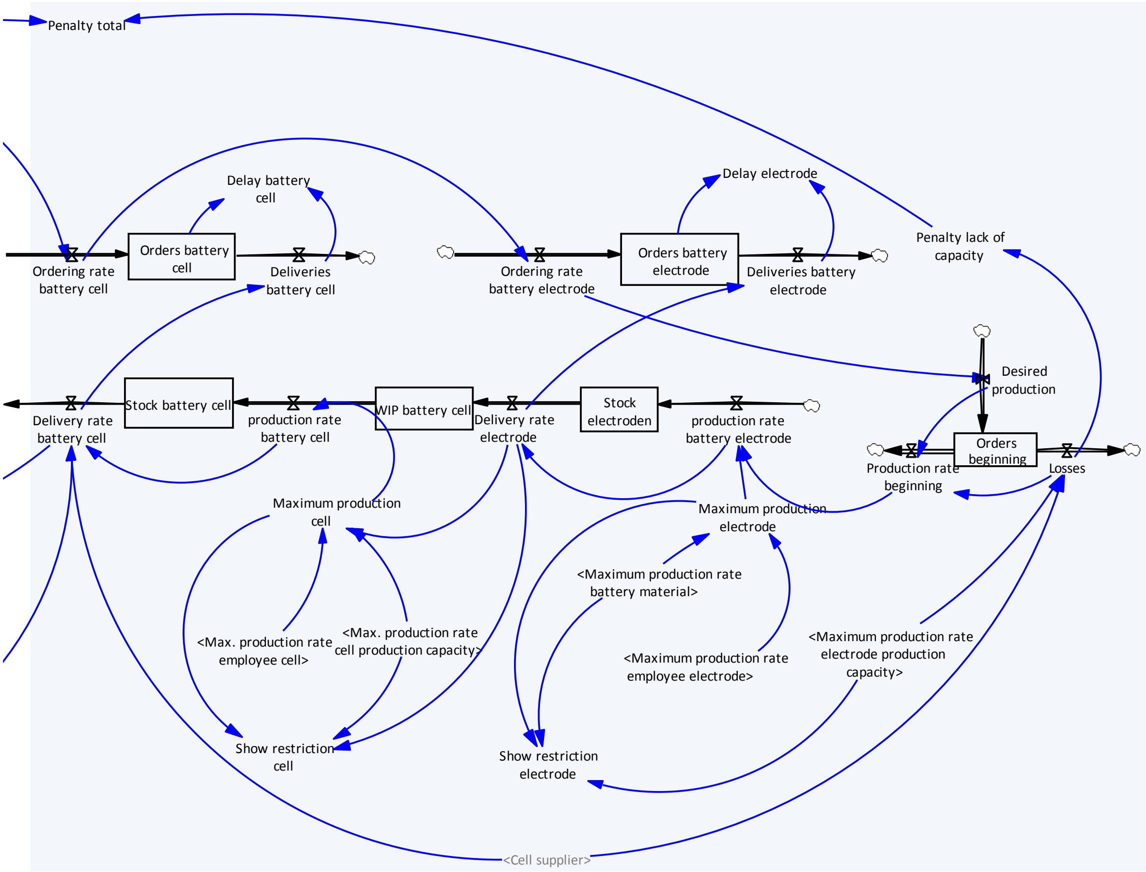

Figure 3-4: Subsystem production system - Part B

Thus the final unit costs are calculated by taking into account the costs for the depreciations for the production system, for materials and additional components, the labor costs, other costs (such as for warranty, Selling, general and administrative expenses,..) and the penalty payments for late or non-delivery.

4 Simulation runs and tests

Various simulation runs and tests are conducted in order to test the dynamic hypothesis and the effects of different production strategies as well as to obtain a deeper understanding of the system's behavior.

The underlying data about the potential customers for each type of EV (HEV, PHEV and BEV) are derived from a model developed for the "Office of Technology Assessment at the German Bundestag", which is based on the European transport model "ASTRA" (see Fermi et al. 2012 and Schade et al. 2014). The specific amount of production capacities, employees and materials needed to produce a specific number of LiBs are based on the BatPaC model (ANL 2012). The materials, production systems and employees are calculated bottom-up from 18 materials or components and 23 production steps for the two different kinds of LiB (high power or high energy batteries). The simulation period covers 15 years (180 months) until the year 2030. Post 2030, other battery technologies might be more favorable (Thielmann 2012).

Two different types of production strategies will be examined within the scope of this paper. On the one hand, strategy 1 produces high energy LiB as well as high power LiB, production capacities are constructed according to a lead strategy, the site is situated in the USA and the whole battery is produced (including the battery cell). On the other hand, strategy 2 focuses more on avoiding investments that would be necessary for the production of two types of batteries or a whole battery system. Capacities are increased carefully and, in line with this cost-oriented thinking, the plant is situated in China. According to the composition of the production strategy, the two strategies will be defined as follows: *Strategy_Scenario_location_Capacity strategy_Technology strategy_Vertical integration*. Thus strategy 1 is shortened as: *S1_X_USA_Lead_HEV_All* and strategy 2: *S2_X_CN_Follow_NoHEV_NoCell*.

The production strategies are tested under two alternative scenarios for the diffusion of EV and thus for the market demand for LiB: "Oil age", a rather pessimistic scenario (from the point of view of electric mobility) and "Electrical age", a quite optimistic one. The two scenarios differ in the number of potential customers for EV and the degree of diffusion (represented in the Bass diffusion model by the coefficient of innovation and imitation).

4.1 Results of the oil age scenario

Figure 4-1 shows the diffusion results for the different EV types on the left-hand side and the resulting orders on the right-hand side. It is apparent that the diffusion of the different types of EV takes place at different times and with different intensities.

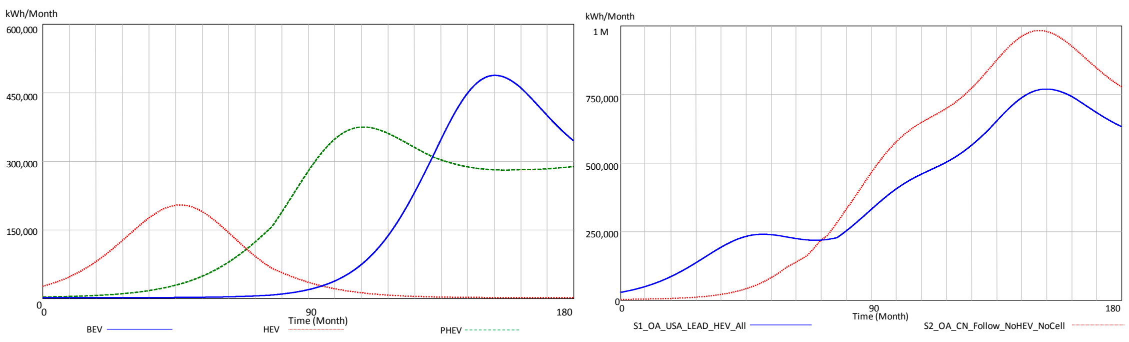

Figure 4-1: Diffusion of EV (left) and orders for LiB (right) in the oil age scenario

In the oil age scenario, the overall demand and thus the orders for LiB are rather small compared to the electrical age scenario depicted in Figure 4-3. In strategy 1, the effect of the additional production of HEV batteries is visible in the early increase in orders. But this effect is soon outpaced by the orders of strategy 2. The comparatively low unit costs of strategy 2 depicted in Figure 4-2 are the reason for this strong increase. The costs decrease rapidly so the produced LiB soon reach a competitive cost level. This makes it possible to increase the company's market share and thus the orders.

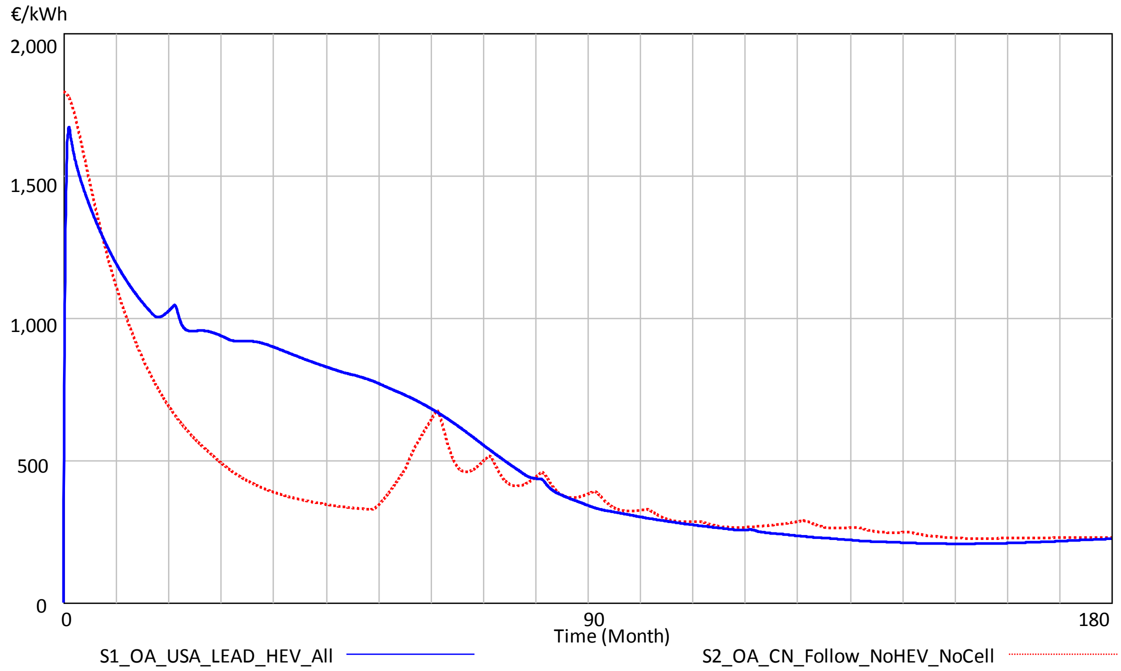

Figure 4-2: Unit costs per kWh in the oil age scenario

In strategy 1, the unit costs do not decrease as rapidly. This is because production capacities have to be established to meet the increasing demand for high power batteries (see Figure 4-1). Therefore investments in the production system are necessary so depreciation increases as do the unit costs. The decrease in unit costs in strategy 2 continues until around month sixty, when the demand for PHEV and BEV begins to take off so that new production systems have to be implemented. This leads to the peak in the unit costs. This effect is enhanced by the defensive follow-capacity strategy. Because of the lack of sufficient production capacity, penalty payments have to be made which raise unit costs even more. In the long term, however, both strategies show a comparable cost level.

4.2 Results for the electrical age scenario

In the electrical age scenario, the demand for LiB and therefore the orders are approximately ten times higher than in the oil age scenario. The development of orders for strategy 1 and strategy 2 follow the same pattern as in the oil age scenario. Strategy 1 has a higher number of orders at the beginning due to the HEV-batteries and is soon outpaced by strategy 2.

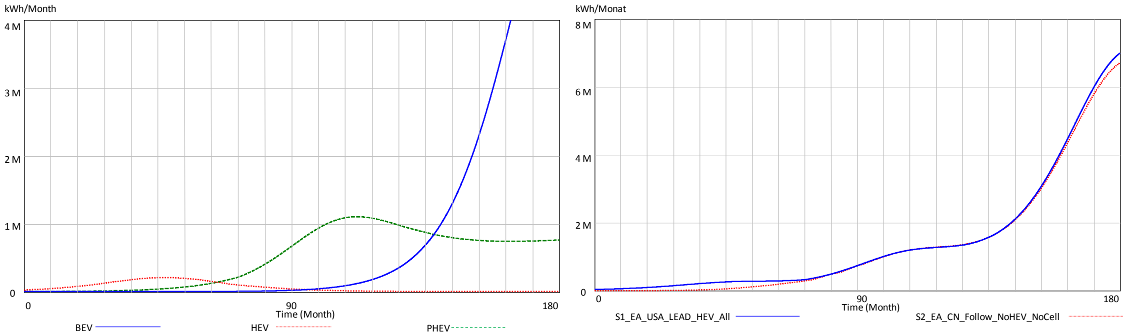

Figure 4-3: Diffusion of EV (left) and orders for LiB (right) in the electrical age scenario

With regard to the unit costs depicted in Figure 4-4, both strategies show the same pattern as in the oil age scenario at the beginning. But in contrast to the oil age scenario, the effect of missing production capacities in strategy 2 around month sixty is much greater due to the stronger rise in market demand.

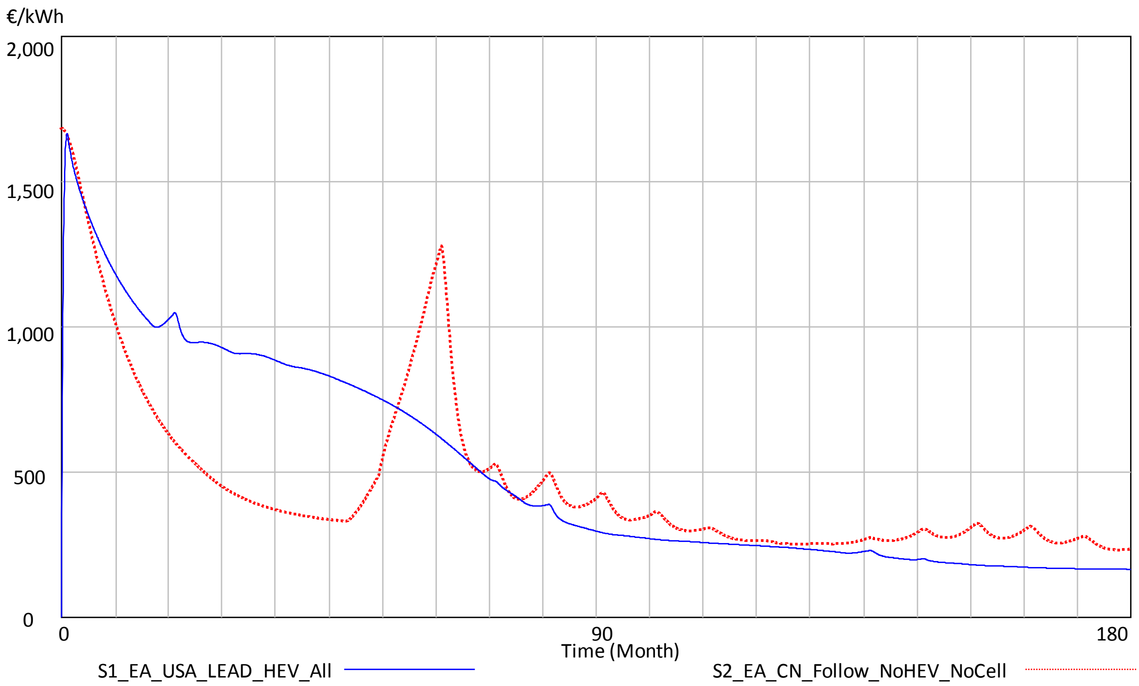

Figure 4-4: Unit costs per kWh in the electrical age scenario

Additionally in this scenario, which is characterized by strong and rapid diffusion of EV, the effect of the vertical integration strategy becomes obvious: While the unit costs under strategy 1 decline continuously, the unit costs under strategy 2 stay more or less on the same level (in the long term). A major reason for this (besides the penalty payments) is that, for each battery system sold, the supplier margin for cells has to be considered. Thus strategy 1 becomes more and more favorable with an increasing number of orders.

5 Conclusions and outlook

This paper presents a system dynamic model to simulate and analyze the impact of different production strategies on the unit costs of a lithium-ion battery system. Two different strategies were examined under a rather pessimistic and an optimistic scenario. The model can capture the interactions between market development, the influence of the different strategies and the performance of the production system in the form of the resulting unit costs.

It becomes obvious in both scenarios that a technology strategy including the production of high power batteries results in comparatively higher unit costs to start with. Furthermore, it can be stated that a defensive capacity strategy is not recommendable, because the savings due to avoided overcapacities are more than compensated by penalty payments for late or non-delivery. With regard to the strategy of vertical integration, buying the cells from a supplier offers an advantage when the market is still young, because no investments have to be made. But in the long term, especially under strong market growth, this strategy does not permit cost reductions below a certain level, because the supplier’s margin has to be factored in.

This study provides a first insight into the complex interactions between the decision to pursue a particular production strategy and the resulting performance of a company’s production system. Obviously, under real life conditions, the interactions are much more complex and the decision for or against a specific production strategy is not purely an economic one but also takes soft criteria into account (e.g. protection of intellectual property,..). Furthermore, the impact of a production strategy on the other two strategic production targets of time and quality has to be considered. These aspects should be the subject of further investigation when trying to improve the methodology.

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