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Designing robust transformation toward a sustainable circular battery production

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Abstract

To achieve CO_2 neutrality in 2050, internal combustion engine vehicles will be gradually substituted by electric vehicles since they enable an emission-free use phase if powered with renewable energy. However, producing lithium-ion batteries for electric vehicles is associated with high environmental impacts and economic challenge such as supply bottlenecks. Seeking to tackle these challenges by integrating recovery activities, car and battery manufacturers are increasingly transforming their production systems to circular production. Yet, transforming the entire production system poses several risks and uncertainties, e.g., technological developments and regional political instabilities. Therefore, a robust transformation toward a sustainable circular battery production is needed. Using a scenario design approach, we envision sustainable circular battery production in 2050 and the correlating transformation with minimum total CO_2 emissions throughout the transformation process. To consider the potential enablers, inhibitors, and feasible (counter)measures, we conducted a workshop with experts from life cycle engineering, mechanical engineering, and business economics. Based on the results, both technological enablers and fundamental challenges of sustainable circular battery production were derived, which have to be addressed in the context of life cycle engineering.

Keywords: lithium-ion battery; fault tree analysis; closed-loop supply chain; circular production; transformation; sustainability

1. Introduction

To achieve the goal of the Paris Agreement of limiting global warming to 1.5°C above pre-industrial levels, CO_2 neutrality must be reached by 2050 [1]. Furthermore, CO_2 emissions must be minimized along the way. Passenger cars account for 39% of the global CO_2 emissions caused by the transportation sector in 2022, according to IEA's Sustainable Development Scenario [2]. Hence, to achieve net-zero CO_2 emissions in this sector is a mandatory step to limit the impacts of global warming. Although electric vehicles enable an emission-free use phase, the production of electric vehicles, particularly the traction battery, leads to high emissions. According to Thies et al., the energy demand related to cell production and material extraction is the hotspot, accounting for 61% and 33% of the CO_2-eq emissions in battery production, respectively [3].

To overcome the challenges of problem shifting from the use to the production phase, new strategies for reducing emissions in the production phase are needed. First, integrating recovery options such as reuse, repurposing, and recycling enables an extension of the product lifetime and a reduction of the demand for new products and materials. Second, powering the production processes with renewable energy improves their CO_2 footprint. While these strategies promote a sustainable circular battery production, several risks and uncertainties,

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such as supply chain disruptions and technological developments, threaten a successful transformation from a linear toward a sustainable circular battery production.

Therefore, we aim to design a robust transformation that achieves the goals concerning sustainability even in the presence of potential risks. For this purpose, inhibitors of a successful transformation need to be identified to develop countermeasures. Also, enablers that promote a successful transformation should be determined to evaluate measures of the stakeholders. Consequently, cause-effect relations between the enablers and inhibitors are identified. For this purpose, we propose a method based on workshop-based backcasting with an adapted fault tree analysis.

The remainder of the paper is structured as follows. In Section 2, existing literature for designing transformation is analyzed. In Section 3, we describe the proposed method and its execution. In Section 4, the results are described with deep dives in three exemplary clusters. Finally, a conclusion is given in Section 5.

2. Literature overview

The following section gives an overview of studies addressing the transformation of production systems and supply chains toward sustainable practices.

General studies on the transformation toward circular systems can be found in [4,5]. Scheel et al. developed a methodology for transforming linear production chains into circular value-extended systems based on interviews [4]. In particular, they expand a conventional business model framework by adding three customers (society, environment, and companies) according to the triple bottom line. In this context, they identify "gain creators" and "pain relievers" for each customer. They evaluate their approach using the case of mining industry in Bartica, British Guyana. Asgari & Asgari considered the circular ecosystem in their study on transforming business models through circular economy by conducting literature reviews and interviews [5].

To integrate digitization into the transformation process was extensively studied in recent years, e.g., [6,7]. A resource-based study on how digitization can support the transformation toward net-zero manufacturing and circular economy is given by Okorie et al. [7]. They analyze which competitive advantage the transformation can achieve based on workshops with industry managers. Kurniawan et al. studied digital technologies for waste recycling in Indonesia [6]. In this context, they analyzed the use of online applications for waste selling from customers to businesses in a real-life case.

Also, the transformation toward sustainable and resilient cities has gained importance in recent years. For example, Mendizabal et al. included a vulnerability analysis to identify the critical aspects of the transformation [8]. Kishita et al. proposed a computer-aided scenario design method that they applied to the transformation toward sustainable cities in Japan [9]. Considering the emission of buildings, Shooshtarian et al. analyzed the transformation of the construction and demolition waste system toward circular economy in Australia based on literature analysis [10]. They focused on improvements in the production, transportation, and recycling phase by identifying issues, strategies, and stockholders.

Studies regarding the energy sector can be found in [11–13]. Kishita et al. employ a narrative story using backcasting and fault tree analysis to develop a resilient energy system for Suita City in Japan [11]. In this case, fault tree analysis allowed to identify critical risks and countermeasures, which can be used in backcasting to derive resilient pathways originating from the collapse future. Supapo et al. conducted a study using backcasting to analyze the transition of off-grid islands toward 100% renewable energy production [12]. Additionally, they simulated the qualitative scenarios to validate and quantify them. Furthermore, the International Energy Agency developed scenarios for the energy sector and electromobility, including scenarios on how to reach net-zero emissions by 2050 [13]. Within the net-zero scenario, time and intensity to decrease or increase each energy source are determined. They further include a population growth and energy consumption forecast and describe ways needed investments are obtained from private sources through public policies. They also describe pathways for each sector including the transportation sector. Concerning the battery industry, they identified the advancement of battery technology regarding energy density, fast charging ability, and costs as key drivers.

Furthermore, Tao et al. used life cycle simulation to describe scenarios to design circulation systems for second-life traction batteries [14]. Levänen et al. analyze the institutional influence on circular business models within the battery recycling [15]. In particular, they derived voids and enablers for circular business models based on two companies in Finland and Chile. Wrålsen et al. extend the viewpoint by incorporating both recycling and second use options in their study [16]. For this purpose, they used Delphi method with participants from industry and research. They identified circular business models and corresponding drivers, barriers, and stakeholders. In this study, the financial situation is the most critical barrier, and governments as well as car manufacturers are the most important stakeholders. Last, Islam and Iyer-Raniga conducted a literature review on lithium-ion battery recycling [17].

In conclusion, many studies have focused on the transformation toward sustainable circular systems or general developments in circular battery production. However, an extensive study on robust transformation toward sustainable circular battery production is missing. Regarding the methodology, among others scenario design has proven to be an appropriate method since it allows to analyze complex interrelations within the transformation process.

3. Methodology

We took a workshop-based scenario design approach to develop a robust transformation for sustainable circular battery production by 2050 using the example of Japan. In particular, we combined backcasting and fault tree analysis to visualize experts' views, through which transformation scenarios are developed. The proposed methodology is presented in Figure 1.

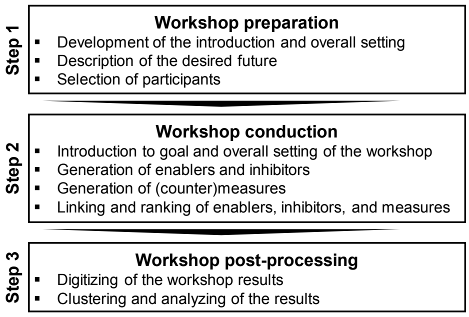

Figure 1: Flow chart of the proposed methodology

In Step 1, the moderators prepared the introduction and overall setting of the workshop. Here, it is important to create a common understanding of the initial situation of the system, i.e., the current share of electric vehicles and relevant legal boundaries, as well as potential key performance indicators of a successful transformation, i.e., net-zero emissions. Furthermore, the desired future was described and participants were selected. Step 2 starts with the moderators presenting the results of Step 1 to the participants. Then the participants brainstormed and discussed enablers and inhibitors of the described goal. To do this, the conventional fault tree analysis was adjusted. Usually it contains goals, risk factors, and countermeasures [11]. However, since the discussion originates from the desired future rather than the collapse future, enablers and inhibitors are addressed instead of risks. Afterward, measures were determined to achieve the enablers or counter the inhibitors. Furthermore, the participants described the interconnections and ranked the critical aspects of the workshop. The discussion itself was held by six researchers (see Table 1). The moderators did not interact in the brainstorming and discussion section to prevent the results from being influenced by the moderators. Finally, in Step 3, the moderators post-processed the findings by digitizing, clustering, and analyzing the results.

Table 1: Research fields and topics of the workshop participants

	Research field	Research topic
1	business economics	lithium-ion batteries
2	mechanical engineering	electronics
3	mechanical engineering	remanufacturing, adaptive manufacturing, electronics, automotive
4	service engineering	general circular economy
5	life cycle engineering	electronics, electromobility, lithium-ion and future batteries
6	life cycle engineering	lithium-ion and future batteries

4. Results

In the following section, the overall setting of the workshop as well as the general findings are shown. Afterward, three exemplary clusters are analyzed in detail. Finally, we formulate the methodological contributions of this paper.

4.1. Overall setting

According to the Japanese Ministry of Economy, Trade and Industry, Japanese battery manufacturers currently lose market shares to Chinese and Korean manufacturers [18]. To counteract this, the Japanese government set the goal to increase domestic battery cell production to 150 GWh and the global production volume of Japanese manufacturers to 600 GWh in 2030. However, Japan is highly dependent on the import of raw materials. This becomes problematic since battery raw materials are not equally distributed worldwide, leading to high dependencies on few countries [18,19]. Besides the material industry, challenges arise concerning the supply of renewable energy. In 2020, only 11% of the Japanese total energy supply was renewable [20].

4.2. General findings

In total, 20 enablers, 26 inhibitors, and 19 (counter)measures were found (see Supplementary material [21]). The results are clustered into seven groups: (1) decarbonization of the energy sector, (2) costs of recovery options, (3) data availability, (4) securing raw materials supply for production, (5) sustainable allocation of the limited spent batteries to recovery options, (6) design of long-life and sustainable batteries and, (7) extended use of batteries.

In all cases, financial advantage is a necessary condition. The profitability is crucial for different business models. Especially regarding the end-of-life processes, the participants find that profitability is still insufficient. Big investments are needed in all groups, e.g., for technology development or capacity buildup. However, the budgets of the companies are limited, necessitating governmental subsidies, funding, or tax reductions. Furthermore, joint actions of companies are often prevented due to fear of losing their competitive advantage and, hence, profitability, Second, technological advancements are needed in all cases considering the production, recovery, and information technology. Third, acceptance from customers and companies are critical to achieve the best outcome systemwide. For example, customer acceptance for used products needs to be increased to enable an extended lifetime. Hence, it contributes to groups (2), (4), (5), (6), and (7). The participants identified groups (1-3) as most important due to their relevance to the overall goal or the necessity to develop measures since they will not be met (in time) without additional efforts. In the following, these groups are discussed in detail (see Figure 2).

4.3. Exemplary detailed results

Decarbonization of the energy sector

Since energy consumption within the production accounts for 61% of the global warming potential of a battery cell, and 11-17% in battery recycling [3,22], to achieve 100% renewable energy along the entire life cycle is critical. In this context, extensive technological improvements have been achieved in the last years, leading to decreasing needed investments [23].

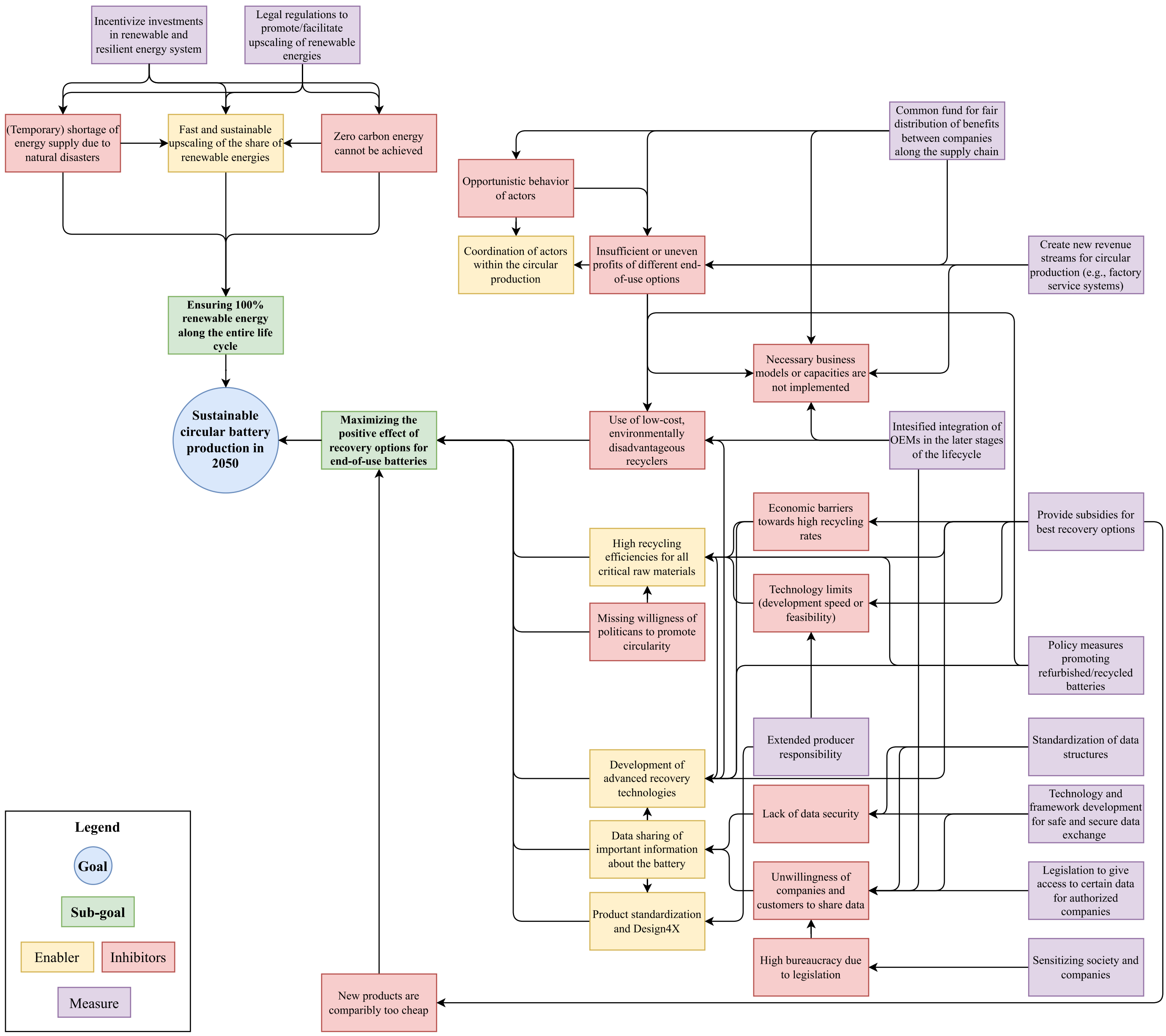

Figure 2: Sub-goals, enablers, inhibitors, and related (counter)measures to reach a sustainable circular battery production for the three main groups

Hence, renewable energies have become the preferred option for a cheap energy production. Therefore, the main challenge is to achieve fast and sustainable upscaling.

An early upscaling of renewable energy production has multiple advantages. On the one hand, it reduces emissions not only at the end but throughout the entire transformation process. On the other hand, an early and fast upscaling enables more flexibility to possible challenges. In case the upscaling is set to later phases of the transformation process, challenges cannot be met in time, making the transformation less robust.

Possible inhibitors correspond to the availability of energy as well as emissions. First, energy shortages might occur due to natural disasters. Since renewable energy production often cannot be increased in the short term, fossil energy might be used more extensively (see, for example, the increase of coal use due to missing Russian gas [24]). Second, the implemented energy supplies do not reach zero emissions. This could have many reasons, e.g., renewable energy is not equal to net-zero emissions, or fossil energy is considered renewable by the governments.

Hence, a government should implement rules to obligate the increase of renewable energy. However, this can encourage companies to outsource their production to avoid restrictions. Therefore, politicians need to decide if to incentivize investments is the preferred option. Governmental subsidies to build up renewable and resilient energy systems can support upscaling and prevent shortages. This is the case since renewable energy is often decentralized, which makes it less prone to disruptions.

Costs of recovery options

According to various studies, longer lifetimes through refurbishment and repurposing as well as reductions of primary materials use through recycling are necessary steps toward sustainable battery production and secure material supply [25]. However, the implementation of high-quality recovery processes necessitate economic benefits. Hence, low costs must be achieved for refurbishment and repurposing since they need to be competitive with cheap new batteries. For recycling, low costs need to be achieved since batteries recently have decreasing material values, e.g., low-cobalt content or lithium iron phosphate batteries. Hence, cost reductions must be achieved in all recovery options.

In this context, a variety of inhibitors exist. First, the insufficient or uneven distribution of profits may imply two problems. On the one hand, it could give preference to recyclers with environmentally disadvantageous but low-cost processes, such as pyrometallurgy at early stages leading to organic compounds loss [22]. On the other hand, missing profits could lead to an insufficient implementation of specific processes and business models. Second, technological challenges, such as automation in disassembly, hinder upscaling and advancement of recovery options from being implemented.

The existing inhibitors have opposing enablers. Advanced technologies can enable extensive reuse and recycling by increasing profits, e.g., increasing revenue by recovering new, high-value materials, such as lithium. Furthermore, a holistic coordination of all participants along the lifecycle enables compensation even if the profits are insufficiently distributed. Especially in the case of necessary but unprofitable business models and processes such mechanisms are crucial.

To achieve cost reduction, measures can be taken by the original equipment manufacturer (OEM), service suppliers, and politicians. OEMs can effectively decrease costs by intensifying their efforts in the end-of-use. In this case, supplying data, addressing problems in the product design, and using economies of scale through increasing the quantities are positive measures. Furthermore, this could also be partially achieved by extending the producer responsibility with a similar approach to the newly proposed European battery directive [26]. Besides, politicians should promote recovery options by either implementing subsidies for technological development, or economic incentives for environmentally preferable options, e.g., tax reduction for refurbished batteries. Furthermore, new revenue streams could be generated through product/process-as-a-service models, for example, for machinery and factories. By this business model capacities at the service provider are increased to larger scales, which results in lower costs and reduced entry hurdle for startups.

Data availability

For the development of recovery processes as well as the conduction of these processes, data availability is critical [27]. For example, information about driving patterns, state of health, state of charge, and many more can be used in the refurbishment processes. This allows an early indicator of the current performance of the battery and, hence, reduces unnecessary performance measures, improves the quality of the assessment process and its costs. Furthermore, information about the production process can give insights into potential problematic battery cells and modules. Data availability is key to achieve higher repurposing targets. However, the related data are often highly confidential.

Therefore, production companies show an unwillingness to share related data. A high bureaucratic involvement increases this problem since personal data are needed and various laws must be considered in an international context. Finally, even if there is a willingness to share data, data security might hinder the processes, especially regarding sharing confidential data, such as product design.

To overcome the unwillingness to share data, intrinsic and extrinsic measures exist. Suppose an OEM intensifies its integration into the later stages of the lifecycle. In that case, problems regarding data sharing decrease because they either carry out the recovery processes themselves, as is Volkswagen, or they build close cooperations, e.g., Nissan and 4R Energy. If the OEMs do not interact in the end-of-use, legislation should force OEMs to share needed data. Furthermore, the standardization of data structures could simplify data exchange and increase data security through advanced and secure interfaces.

4.4. Methodological contributions

From a methodological viewpoint, the proposed method enables to graphically visualize the relationship between enablers, inhibitors, and possible measures to achieve robust transformation for sustainable circular battery production. This visualization is useful to encourage scientific dialogues between researchers and stakeholders, thereby helping to specify the domains to be addressed (i.e., seven clusters as mentioned in section 4.2) as well as to identify “hot spots” and “trade-offs” for achieving robust transformation. In addition, the method is helpful to produce internally-consistent narrative scenarios because fault tree analysis inherently involves cause-effect relations.

5. Conclusion

As shown, to achieve a sustainable circular battery production poses challenges in the entire lifecycle, including energy and material supply, battery production, and end-of-use. Since the transformation of the energy sector has been widely studied, we refer to the scenarios of the International Energy Agency [13]. However, it should be noted that capacities for renewable energy should be drastically increased as soon as possible to be able to overcome the challenges.

The OEMs should focus on developing and producing new batteries with longer lifetimes and less critical raw materials. Many potential battery types have already been developed but need further research, such as lithium-sulfur batteries. Since these batteries will be first available in the 2030s [28], advancing current cell chemistries by substituting critical materials will be needed. For example, lithium iron phosphate batteries are a valid option for cheaper vehicles.

Recycling and reuse should be integrated into the production as soon as possible. This allows the technologies to gain a high readiness level before quantities of spent batteries drastically increase between 2030 and 2040 [25]. Furthermore, the variety of cell chemistries and battery types necessitate flexible reuse and recycling processes that can cope with all kinds of batteries. At the same time, high recovery rates in recycling must be met. Therefore, process development needs to focus on recovering the (formerly) less valuable materials, such as lithium and graphite. Politicians should start to subsidize and promote the research and development of flexible and high-quality processes at early stages. Furthermore, capacities for recovery processes should be increased to benefit from economies of scale. In this case, centralization can be beneficial until the quantities of spent batteries increase.

OEMs play a key role in the transformation because they can shape the product, have access to product, production, and use phase data, and are powerful within the system. Therefore, it is key to integrate the OEMs either through their own decision or through legal obligations and extended producer responsibility. Hence, politicians need to develop obligations where needed and incentives to facilitate the development, upscaling, and use of advanced technologies.

For future research, technology roadmapping [29,30] will provide a more detailed insight into the development regarding product design, production processes, and recovery processes. Consequently, simulation approaches should be used to quantify the impacts of the different enablers, inhibitors, and measures. This allows for assessing the robustness of different transformation paths. There are further research issues regarding the methodological contribution yet to be addressed. Examples include prioritization among enablers and inhibitors using, e.g., multi-criteria assessment, and a quantitative assessment of the results.

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