The potential of reducing greenhouse gas emissions of lithium-ion battery production in different geographic scenarios

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ABSTRACT

Battery electric vehicles (BEVs) have emerged as a promising solution for the transition towards sustainable mobility, offering the potential to decrease greenhouse gas (GHG) emissions and reducing dependence on fossil fuels. However, while BEVs offer the potential for reduced emissions during operation, battery manufacturing processes are associated with considerable carbon footprints. Furthermore, the choice of cathode material significantly influences the environmental impact created by lithium-ion battery production. The current state-of-the-art route of production of lithium-ion batteries occurs mainly outside of Europe and to a large extent in countries owning a greenhouse gas-intensive electricity mix, resulting in a significant quantity of emissions generated. As the European Green Deal promotes sustainable production and use of batteries within the EU, this paper investigates GHG emissions generated by a hypothetical battery manufacturing scenario occurring in Europe, using the framework of Life-Cycle Assessment, and compares them to the conventional production route occurring globally and mainly in Asia. The results are retrieved for different battery types and for both, a hypothetical European Route and a Conventional Route, per 1 kWh of battery pack produced. The cathode chemistries under scope are NMC111, NCA and LFP, representing the state of the art of today's automotive battery technology. The outcomes of this paper highlight that the European production route shows a significant potential for greenhouse gas reduction (approximately 40 % for all

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battery chemistries) in comparison to the Conventional Route. Besides high-lighting the high relevance of local material sourcing and battery production, the results also outline the necessity of using renewable energy sources for the entire process of lithium-ion battery production. In this way, a holistic consideration of influencing factors supports a detailed discussion and derivation of recommendations with the target to make the production of lithium-ion batteries more sustainable.

1. INTRODUCTION

The transition towards sustainable mobility has gained increasing importance in recent years, driven by the urgent need to reduce greenhouse gas (GHG) emissions and mitigate climate change. Battery electric vehicles (BEVs) have emerged as a key solution in this transition, offering the potential to reduce emissions and decrease reliance on fossil fuels. However, while BEVs produce lower emissions during operation compared to internal combustion engine vehicles (ICEVs), the environmental impact of their production—particularly the manufacturing of lithium-ion batteries (LIBs)—remains a significant concern.

LIBs, essential for powering BEVs, are responsible for considerable GHG emissions during their production. Figure 1 illustrates this dynamic by comparing the lifecycle emissions of a BEV and an ICEV. To achieve an early break-even point in terms of emissions, both using a high share of renewable energy in the Use-Phase and employing a low-emission battery production process are crucial.

A key factor influencing the environmental impact of LIB production is the choice of cathode materials. Various cathode chemistries have been developed, each offering distinct advantages and disadvantages in terms of performance, cost, and sustainability. The material selection plays a critical role in determining the overall emissions associated with battery manufacturing.

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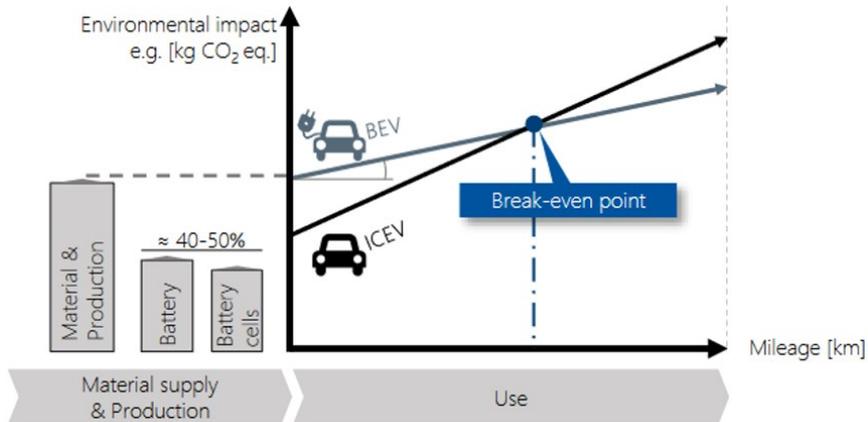

Figure 1: Comparison of generated GHG emissions over lifetime for a BEV and an ICEV. Adapted from [6].

Currently, most LIB production takes place outside of Europe, often in regions with carbon-intensive electricity grids, leading to significant emissions. Additionally, the reliance on global supply chains for critical raw materials – such as lithium, cobalt, and nickel – poses sustainability challenges, including ethical concerns related to mining practices and resource extraction. Addressing these issues requires a comprehensive approach that integrates environmental and social considerations into battery production and supply chain management.

Recognizing these challenges, the European Union has introduced regulatory measures aimed at promoting sustainable and responsible battery production. Initiatives such as the Circular Economy Action Plan - one of the main building blocks of the European Green Deal, seek to establish a circular economy, reduce carbon emissions, and enhance the sustainability of LIB manufacturing within Europe [4].

Against this backdrop, this study assesses the greenhouse gas emissions generated during lithium-ion battery production in Europe, using a Life Cycle Assessment (LCA) framework, per 1 kWh of battery pack produced. The results are then compared to the conventional global production route. Given

the diversity of LIB chemistries available, the study focuses on three common cathode types: NMC111, NCA, and LFP.

2. METHODOLOGY

Life Cycle Assessment is the methodology applied in this study, based on DIN EN ISO 14040/44, which can be used to evaluate the environmental impacts and resource consumption associated with a product's entire life cycle, from raw material extraction through production, use, and waste management. An LCA study consists of the following four phases: Goal and Scope Definition, Life Cycle Inventory Analysis (LCI), Life Cycle Impact Assessment (LCIA), and Interpretation [5].

The goal and scope of this study is assessing and comparing the amount of greenhouse gases generated by the production of 1 kWh energy storage capacity of an NMC111-type, an NCA-type and an LFP-type lithium-ion battery pack, taking place in two different production routes. The first route involves the conventional production process, wherein all materials incorporated in the battery pack and the battery pack itself are manufactured in locations that represent the state of the art (e.g., China, Australia, Congo, etc.). The second route involves the production of materials included in the battery pack and the battery pack itself in a hypothetical "European Route", with the majority of production occurring in Europe. The emissions generated by transportation processes occurring in the production of the Cathode Active Materials (CAMs) are determined as well for both routes.

The system boundary is limited to the production of the battery pack, which encompasses the sourcing of raw materials, processing and refining to form materials, and battery manufacturing. This system boundary represents a cradle-to-gate approach and is employed to facilitate a comparative analysis of the NMC111-, NCA- and LFP-type batteries. The assumed energy densities for the battery packs are 158 Wh/kg for NMC111, 170 Wh/kg for NCA and 133 Wh/kg for LFP [2]. The production stages of the following constituents are included: NMC111-CAM, NCA-CAM, LFP-CAM, synthetic graphite, natural graphite, electrolyte, current collectors, constituents made of copper and aluminum, separator, constituents made of polymers, constituents made of steel and stainless steel, binder, thermal insulation, coolant, battery management system (BMS), NMP, aluminum oxide and the battery assembly process. Furthermore, the transport processes occurring in the cathode active material are considered.

All data for the LCI was collected from the GREET 2022 model [8], reports/publications from Argonne National Laboratory and other scientific literature sources. All assumptions and their respective sources used in order to produce a functioning LCA model can be found in detail in [2]. The information used for creating the modelling the European Route primarily stems from [3]. The GREET model (Greenhouse gases, Regulated Emissions, and Energy use in Technologies) is used as an LCA tool, for modelling of both scenarios. It was developed by the Argonne National Laboratory, designed to evaluate energy and environmental effects (emissions of greenhouse gases, water consumption, emissions of air pollutants) of transportation fuels, vehicle technologies, energy systems and other end-use sectors [1].

A visual representation of production locations and transportation routes occurring in the production of the CAMs, for the conventional and the hypothetical European Route, is given below in figure 2 and figure 3. Country-specific electricity mixes are used for each production activity in the respective location, except for some specific components in the European Route for which the European average electricity mix is used.
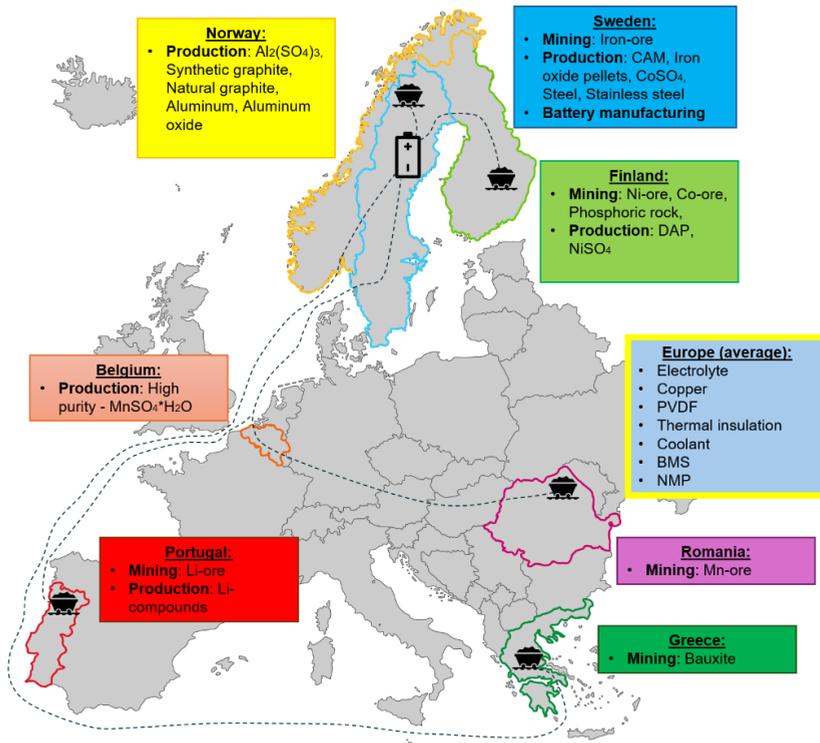
Figure 2: Visual representation of potential production locations and transportation routes occurring in the production of the CAMs, for the European Route.
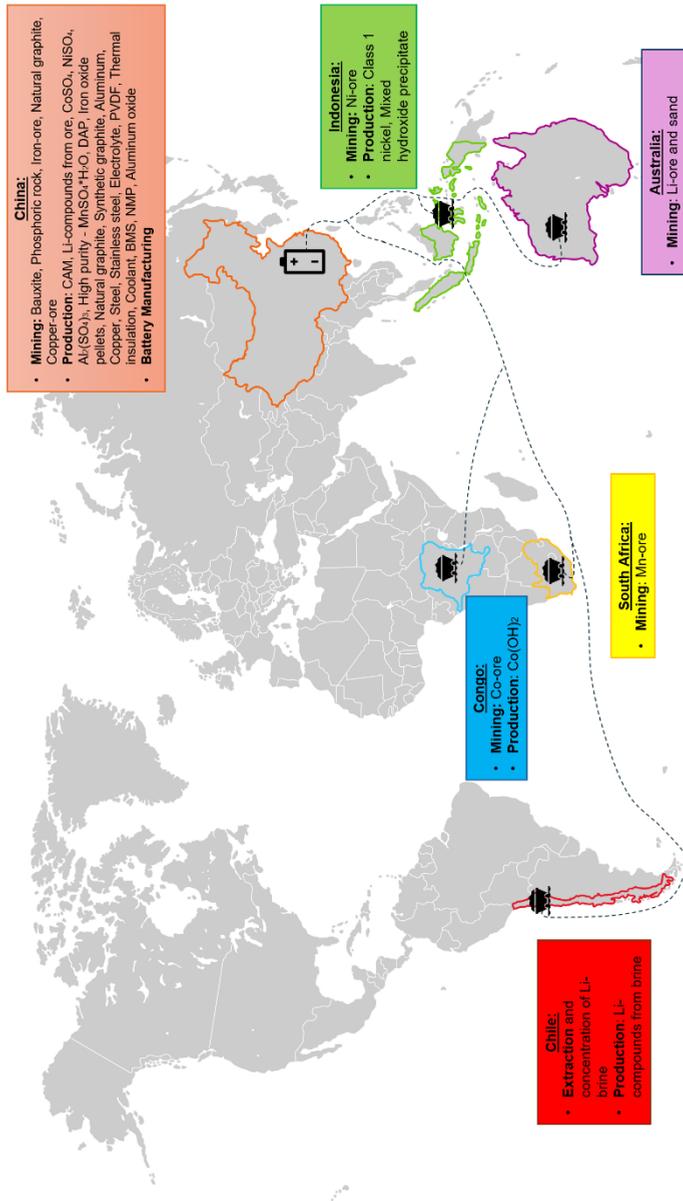
Figure 3: Visual representation of production locations and transportation routes occurring in the production of the CAMs, for the Conventional Route.

3. LCIA-RESULTS AND INTERPRETATION

Since lithium compounds are needed to produce the cathode active materials, GHG emissions generated by their production are calculated and presented in figure 4, for the Conventional Route and the European Route. For CAMs with high nickel concentrations, such as NMC811 and NCA, typically LiOH·H$_2$O is used as a lithium compound for its production. In contrast, CAMs without or with low nickel concentrations, like NMC111 and LFP, use Li$_2$CO$_3$ [7]. Li$_2$CO$_3$ and LiOH·H$_2$O can both be produced either from lithium-rich brine or lithium-containing ores, such as spodumene.
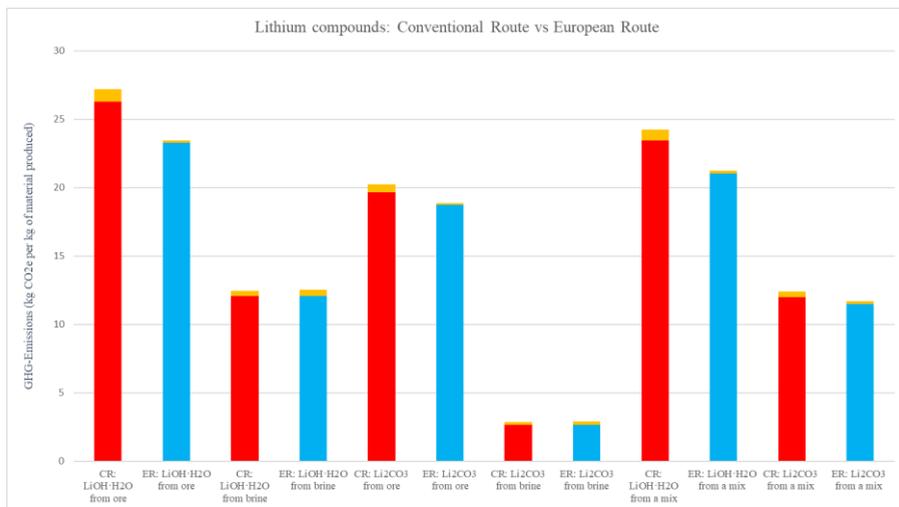

Figure 4: GHG emissions generated by the production of 1kg of lithium compound from different Li-feedstocks and a Li-feedstock mix, represented for the Conventional Route (CR) and the European Route (ER). Red/blue bars: GHG emissions from material production; Orange bars: GHG emissions from transport

Figure 4 illustrates that LiOH·H2O production from ore has the highest global warming potential, followed by Li2CO3 from ore, then LiOH·H2O from brine, and finally Li2CO3 from brine. A reduction in GHG emissions of approximately 14% can be observed in the European production route of lithium hydroxide from ore in comparison to the Conventional Route, which is attributed to the less GHG-intensive electricity mix in the European Route. Additionally, shorter distances for transportation are utilized. The same appears for Li$_2$CO$_3$ production from ore, although the reduction is less significant. The GHG emissions generated due to the production of the lithium

compounds made of brine are marginally higher for the European Route. This is due to the fact that the road transport distance for trucks is greater for the European Route. LiOH·H2O and Li2CO3 made from brine are already produced in Chile for both routes, thus their production cannot benefit from the electricity mix in Portugal. The production of lithium compounds from a lithium-feedstock mix, representing the production of lithium compounds the best, exhibits a reduction in GHG-emissions of approximately 12% for LiOH·H2O and 6% for Li2CO3, when comparing the European Route to the Conventional Route.

Figure 5 presents a comparison of cathode active materials production for both routes. Here, NCA is responsible for the greatest quantity of GHG emissions. This is due to the fact that lithium hydroxide is employed in the manufacturing process, which is more emission-intensive than lithium carbonate, which is utilized in the production of the CAMs NMC111 and LFP. Furthermore, NCA exhibits the highest nickel-ratio among the other CAMs, indicating that a high quantity of nickel sulfate is utilized in its synthesis. Nickel sulfate and cobalt sulfate are the most GHG-intensive precursor chemicals per kg of product, among all batteries under scope (for both routes) [2]. Both chemicals are necessary for the synthesis of NCA and NMC111. Additionally, aluminum sulfate is needed for the synthesis of NCA and manganese sulfate for NMC111 – being, together with iron oxide and diammonium phosphate (DAP), the least GHG intensive precursor chemicals for both routes of CAMs [2].
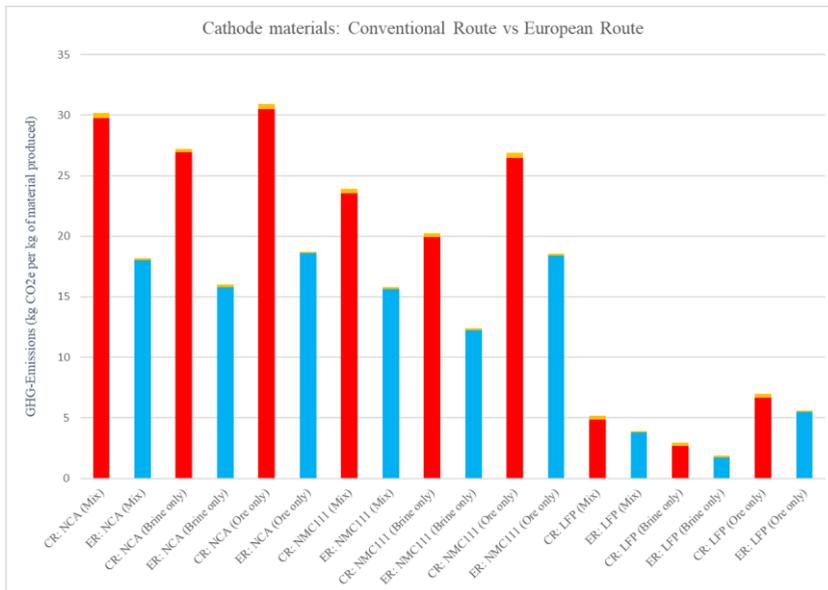
Figure 5: GHG emissions generated by the production of 1kg of CAM from different Li-feedstocks and a Li-feedstock mix, represented for the Conventional Route (CR) and the European Route (ER). Red/blue bars: GHG-emissions from material production; Orange bars: GHG emissions from transport

NMC111 exhibits a lower nickel ratio, which means a lower quantity of nickel sulfate and a higher quantity of cobalt sulfate and manganese sulfate are used in its synthesis than for NCA. Furthermore, lithium carbonate is used in its production instead of lithium hydroxide. These facts result in a lower global warming potential for NMC111 compared to NCA.

LFP employs iron oxide, DAP and lithium carbonate in its synthesis, which accounts for the CAM´s superior performance in terms of low GHG-emissions (approximately six times less GHG intensive than the NCA CAM). Nevertheless, it is not the case that the LFP battery pack causes also six times less GHG than the NCA battery (see figure 6). This is because the specific energy density of LFP batteries is lower than that of NCA batteries, which means that a greater amount of CAM is required to reach the same energy capacity.

For NCA and NMC111, the transport emissions account for approximately 1% of the total emissions, due to their emission-intensive production. In contrast, for LFP, the transport emissions represent approximately 10% of the

total emissions, given that its production is less emission-intensive than that of the other CAMs.

Figure 6 illustrates an overview of the differences in GHG-emissions generated in the production of the battery types under scope, for the Conventional and the European Route. It can be seen that the NCA and NMC111 - type batteries show approximately the same quantity of GHG-emissions per kWh (1,8% lower emissions for NMC in the CR compared to NCA; 2,1% lower emissions for NCA in the ER compared to NMC111), despite the fact that NMC111 uses less intensive CAM upstream materials than NCA. The reason for that is the lower energy density provided by the NMC-battery, which leads to a higher amount of material in the battery. Thus, energy density is an important parameter, significantly influencing the resulting GHG-emission intensity of batteries.
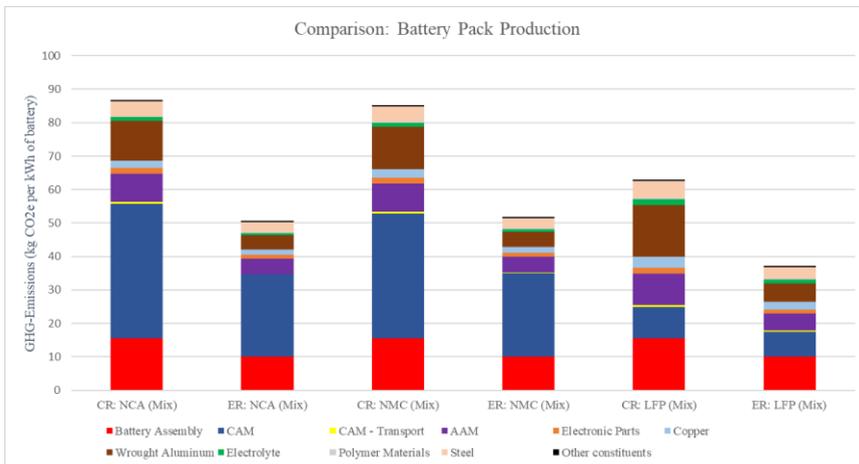

Figure 6: Comparison of results of all battery types, for the Conventional Route (CR) and the European Route (ER) in the Li-feedstock mix scenario.

The LFP-type battery exhibits a reduction in GHG emissions of 27.6% in comparison to NCA and 26.3% in comparison to NMC111, when utilizing the Conventional Route. With regard to the European Route, LFP is observed to result in a reduction in GHG emissions of 26.6% in comparison to NCA and 28.2% in comparison to NMC111. Consequently, the low emission level generated by the production of its upstream materials outperforms the lower energy density of LFP. However, LFP can be produced through either the hydrothermal or solid-state synthesis method. The solid-state synthesis route, which is employed in the model, is considerably less energy-intensive in its

production, resulting in relatively low GHG emissions for the LFP battery. In other life cycle assessment studies, LFP has been found to exhibit a global warming potential that is comparable to that of NMC and NCA. This observation can be attributed to the fact that LFP is produced using the hydrothermal synthesis route in those studies. However, solid-state synthesis is the well-established route for producing LFP commercially [1] and therefore considered in the present investigation.

4. CONCLUSION

It is possible to reduce the GHG emissions generated by LIB battery production by approximately 40% for all battery chemistries, by employing production in Europe. In addition, the applied lithium feedstock in CAM manufacturing has a relevant impact. If lithium brine is applied for manufacturing of lithium compounds, the emissions are significantly lower compared to production from lithium ore. Additionally, it has been found that producing Li_2CO_3 is less GHG intensive than $LiOH \cdot H_2O$, if the same type of feedstock is used for its production. Nevertheless, this does not necessarily imply that Li_2CO_3 should be employed in preference to $LiOH \cdot H_2O$, given that $LiOH \cdot H_2O$ is typically utilized in cathode chemistries that provide a high energy density, which subsequently also reduces the total GHG emissions of battery production, related to the energy storage capacity. The CAM pre-chain materials exhibit varying levels of generated GHG emissions. The pre-chain materials of LFP typically demonstrate significantly lower emissions than the pre-chain materials of NMC111 and NCA. For NMC and NCA, the highest carbon footprint is attributed to $NiSO_4$ and $CoSO_4$. Transport emissions generated by the production of the CAMs are negligible in comparison to the production processes occurring in CAM production, despite the transportation distances being very high for the conventional route.

The study shows that the most GHG emission-intensive processes are CAM production, battery manufacturing, AAM production and aluminum production (the sequence depends on the investigated battery-type). The LFP-type battery pack generates the least quantity of GHG emissions for both routes. The NCA- and the NMC111-type battery show similar results for both the conventional and the European route.

In conclusion can be stated, that if LIBs for BEVs shall generate low levels of GHG emissions during production, lithium brine should be used as a feedstock (regardless of whether Li_2CO_3 or $LiOH \cdot H_2O$ is produced). In addition, LFP should be chosen as a CAM and produced by solid-state synthesis, and

finally, all processing steps should be executed at locations with low GHG emission - electricity mixes. Even if a production in the Europe-only Route may not be entirely realistic, the paper demonstrates the potential for climate change mitigation of a hypothetical production scenario of LIBs in Europe. Furthermore, for production of next generation batteries, such as solid-state batteries or sodium ion batteries, the above-described findings can potentially be valid, too.

Not considered in the study, but also of relevance are strategic and economic factors. Automotive battery production in Europe not only has potential to lower the GHG emissions, but also represents a relevant factor for the local industry. In this context it is important to expand the European battery production with the target to intensify the involvement of local supplier industry, engineering services and research institutions. Considering the global market situation of battery production today, the Europe-only route would not be capable of delivering 100% supply of raw materials and production capacity for the European demand within competitive economic boundary conditions. Nevertheless, an increase of European contribution to automotive battery production can support both, reduction of greenhouse gas emissions and transferring relevant shares of value creation into the European market.

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