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Think global act local: The dependency of global lithium-ion battery emissions on production location and material sources

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ABSTRACT

The pursuit of low-carbon transport has significantly increased demand for lithium-ion batteries. However, the rapid increase in battery manufacturing, without adequate consideration of the carbon emissions associated with their production and material demands, poses the threat of shifting the bulk of emissions upstream. In this article, a life cycle assessment (LCA) model is developed to account for the cradle-to-gate carbon footprint of lithium-ion batteries across 26 Chinese provinces, 20 North American locations and 19 countries in Europe and Asia. Analysis of published LCA data reveals significant uncertainty associated with the carbon emissions of key battery materials; their overall contribution to the carbon footprint of a LIB varies by a factor of ca. 4 depending on production route and source. The links between production location and the gate-to-gate carbon footprint of battery manufacturing are explored, with predicted median values ranging between 0.1 and 69.5 kg CO_2-eq kWh^{-1}. Leading western-world battery manufacturing locations in the US and Europe, such as Kentucky and Poland are found to have comparable carbon emissions to Chinese rivals, even exceeding the carbon emissions of battery manufacturing in several Chinese provinces. Such resolution on material and energy contributions to the carbon footprint of LIBs is essential to inform policy- and decision-making to minimise the carbon emissions of the battery value chain. Given the current status quo, the global carbon footprint of the lithium-ion battery industry is projected to reach up to 1.0 Gt CO_2-eq per year within the next decade. With material supply chain decarbonisation and energy savings in battery manufacturing, a lower estimate of 0.5 Gt CO_2-eq per year is possible.

1. Introduction

1.1. Background

The shift towards electric vehicles (EVs) has generated an unprecedented demand for lithium-ion batteries (LIBs), which, in turn is causing a spike in the demand for critical raw materials such as lithium, nickel and cobalt. Regulatory shifts such as the European Battery Regulation and the Inflation Reduction Act have ranked the establishment of domestic LIB and battery material value chains high on the political agenda (Melin et al., 2021; Trost and Dunn, 2023). This is partly justified by a perceived potential for greenhouse gas (GHG) emission reductions by relocating the value chain from China to locations in Europe and North America (Kallitsis et al., 2022b; Linder et al., 2023). In addition, while EVs offer significant emission savings compared to competing technologies (Knobloch et al., 2020), it is now evident that unlocking the full climate benefit of electrification requires further decarbonisation of upstream LIB production (Milovanoff et al., 2020; Peiseler et al., 2022). Recently, the world's largest battery manufacturer unveiled their carbon reduction plan (CATL, 2023), identifying key links for action further supporting previously published evidence that has identified battery material production and large-scale LIB manufacturing as GHG emission hotspots in the battery life cycle (Chordia et al., 2021; Kallitsis, 2023; Peiseler et al., 2022). In a bid to reduce the carbon footprint (CF) of their

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products, certain battery manufacturers have pledged to sourcing 100% fossil-free energy for their factories (Northvolt, 2021; Tesla, 2022), although currently only a few locations source energy exclusively from renewable sources, others rely on the regionally-available electricity supply to power their operations. The electricity source is a strong link between the CF of a LIB and its production location (Kallitsis et al., 2020; Linder et al., 2023). In addition, since batteries demand substantial material input, a significant portion of their CF originates from upstream material mining and processing operations (Dai et al., 2019; Whattoff et al., 2021), with a recent policy insight emphasising the significance of accurately accounting for such emissions for European policymaking (Peiseler et al., 2022).

1.2. Literature gaps

Life cycle assessment (LCA) has become a prevalent method for quantifying GHG emissions associated with the cradle-to-gate battery production (Chordia et al., 2021; Ellingsen et al., 2014; Kallitsis et al., 2020; Nordelöf et al., 2014; Peters, 2023). The production CF of a LIB is primarily made up of energy contributions, traced to cathode active material production and cell manufacturing, and material contributions associated with upstream mining/refining of key battery materials (Chordia et al., 2021; Dai et al., 2019; Kallitsis et al., 2020). While the former has attracted increased attention (Degen et al., 2023; Jinasena et al., 2021; Kallitsis, 2022), LCA practitioners have primarily relied on secondary data from LCA databases to account for the CF of producing battery materials (Crenna et al., 2021; Peters et al., 2016). As new data emerges regarding the climate impact of producing key battery materials, such as lithium (Chordia et al., 2022; Schenker et al., 2022), cobalt (Cobalt Institute, 2019; Dai et al., 2018; Zhang et al., 2021), nickel (IEA, 2021; Nickel Institute, 2020), manganese (Winjobi and Kelly, 2021) and graphite (Engels et al., 2022; Surovtseva et al., 2022), it has become evident that their CF varies significantly depending on the type and ore grade at source and production location (Ali et al., 2023; Chordia et al., 2022). Such variability upstream of the battery value chain causes major uncertainties regarding the cradle-to-gate CF of LIBs, which remain to be understood in a high level of detail.

As discussed, production location plays an important role in the overall CF of a LIB, as the carbon intensity of the electricity supply can vary significantly. Previous research has shown that batteries produced in China come with 26 %–140 % higher CF compared to those produced in Europe or the United States (Kallitsis et al., 2022a; Kelly et al., 2020; Linder et al., 2023). This disparity has played at least some role in motivating these regions to develop their own battery value chains; in addition to the economic arguments, with regulatory initiatives such as the Inflation Reduction Act (Trost and Dunn, 2023). However, a significant oversight in forming such arguments is that of data resolution, i.e. several Chinese provinces generate lower-carbon electricity than specific US states or European countries which are active sites in LIB production. This information is lost when choosing country or continental averages for modelling electricity mixes. For example, the key battery-manufacturing Chinese province of Sichuan has a carbon intensity of 0.2 kg CO_2-eq kWh^{-1} for its electricity, which is comparable to Portugal, and Germany has a higher carbon intensity than the Yunnan province (0.37 vs 0.14 kg CO_2-eq kWh^{-1}) (Li et al., 2017). Even within provinces or countries, further regional variations are also possible. This necessitates a reassessment of battery CFs, accounting for the specifics of dominant battery production locations.

Such lack of resolution regarding the contribution of materials and production location to the CF of LIBs currently hinders our in-depth understanding of carbon emissions arising upstream of the battery value chain with broader implications for policy- and decision-making. The CF of LIBs depends not only on the source of battery materials and the location where battery manufacturing takes place, but also on the battery chemistry, as different types of materials and energy densities affect the material demand to produce LIBs. Studies by Kelly et al. (2020) and Winjobi et al. (2022) have explored regional variations on the CF of LIBs based on market-dominant battery manufacturing supply chains. However, both studies have relied on a single database, the Greenhouse Gases, Regulated Emissions, and Energy Use in Transport (GREET) model, and focused on a single chemistry, lithium nickel manganese cobalt oxide (NMC) and its variations. The former fails to capture the effect of up-to-date LCA datasets on dominant production routes for key battery materials and the latter neglects market-dominant battery chemistries, lithium nickel cobalt aluminium oxide (NCA) and lithium iron phosphate (LFP) coming with a fundamentally different material demand. In addition, both studies have represented China as a single entity which does not capture province-level variations within the world's largest battery manufacturing country. The same is true for North America, as specific states within the United States and Canada have fundamentally different carbon intensities of their regional energy supply which has a direct effect on the CF of battery production.

1.3. Research approach and contributions to literature

This study aims to fill two major research gaps associated with the carbon emissions of LIB production globally by (a) quantifying variations on the CF of key battery materials traced to different production routes based on a wide body of literature, industry reports and LCA databases and (b) exploring the links between production location and the CF of LIBs in a high level of detail to reveal variations at province-level in China, state-level in North America and country-level in Europe. LIB production locations are considered based on the projected Gigafactory pipeline in 2035 to include regions that might not be producing batteries yet but are expected to have a significant role in the future. Both contributions and their effect to the cradle-to-gate CF of LIBs are quantified through a Monte Carlo simulation, encompassing market-dominant battery chemistries. Therefore, this comprehensive analysis not only provides an in-depth understanding on the comparative importance of material sources and production location to the CF of LIBs, but also offers valuable insights into future trends and regional impacts in the evolving battery industry.

First, the methodological setup of the study is discussed in the context of the LCA ISO standards (ISO, 2014, 2006) and the contribution of materials and energy to the cradle-to-gate CF of LIBs is presented. Next, 53 data sources are analysed to quantify and explain variations on the CF of key battery materials, including lithium carbonate (Li_2CO_3), lithium hydroxide (LiOH), cobalt sulphate ($CoSO_4$), manganese sulphate ($MnSO_4$), nickel sulphate ($NiSO_4$), iron sulphate ($FeSO_4$), phosphoric acid (H_3PO_4), graphite (Gr), aluminium (Al) and copper (Cu). The gate-to-gate CF of battery manufacturing is evaluated in the world's current and future dominant battery production locations based on projections from the battery industry, encompassing 26 Chinese provinces and 4 other countries in Asia, 20 locations across North America and 15 countries in Europe. Statistically derived battery material footprints are integrated with location-specific energy footprints of battery manufacturing to determine the cradle-to-gate CF of dominant NMC, NCA and LFP batteries, accounting for uncertainty. Further, Gigafactory pipeline projections are combined to extrapolate the carbon emissions of the global battery industry to 2035. By quantifying uncertainty upstream of the battery value chain and examining location-specific details on the CF of battery manufacturing, this study presents a framework to quantify the CF of LIBs to inform strategic decision-making to minimise the current and future carbon footprint of LIB production and its value chain.

2. Methods

The aim of the study is to explore key sources of variability associated with the CF of market-dominant LIB chemistries and highlight the importance of taking a global perspective on LIB production and its supply chain. First, a wide body of literature is analysed in order to quantify variability around the CF of key battery materials. Next, a streamlined LCA model is developed to account for material and energy contributions to the CF of LIBs and a Monte Carlo simulation is performed to quantify uncertainties. Finally, the cradle-to-gate CF of LIBs is combined with projections of the battery market to quantify GHG emissions arising from LIB manufacturing on a global scale.

2.1. LCA goal and scope

The LCA principles and framework (ISO, 2014, 2006) are followed to construct a model capable of predicting the CF of commonly used battery chemistries in electric vehicles. The functional unit is set as one kWh of battery cell capacity produced. The system boundary is set as cradle-to-gate, i.e., includes mining and production of battery materials, cell production and final assembly. Specifically, the foreground system includes cathode active material preparation, electrode preparation, cell production, assembly and conditioning. The background system includes the production processes for battery materials and the sources of energy used for cell production. The battery use phase and end-of-life are important steps in the battery life cycle (Gutsch and Leker, 2024; Lander et al., 2021), however their assessment is beyond the scope of this study.

The geographical boundary is set as global, as the objective of the study is to assess the carbon emissions arising from the globally-distributed battery value chain. The LCA model is streamlined by neglecting any facility and equipment requirements. The impact assessment is only focused on the CF, which is used here to represent the 100-year Global Warming Potential (GWP) (IPCC, 2023). The analysis accounts for geographical variations in battery material production and cell manufacturing, with the two contributions presented separately as shown below.

2.2. Material contributions to the carbon footprint

The technological focus of the study includes LIB technologies which are representative of the current electric vehicle market, including $LiNi_{1/3}Co_{1/3}Mn_{1/3}O_2$ (NMC111), $LiNi_{0.6}Co_{0.2}Mn_{0.2}O_2$ (NMC622), $LiNi_{0.8}Co_{0.1}Mn_{0.1}O_2$ (NMC811), $LiNi_{0.8}Co_{0.15}Al_{0.05}O_2$ (NCA) and $LiFePO_4$ (LFP) cathode chemistries combined with graphite in the anode. The material demand to produce such battery cells in kg kWh^{-1} is illustrated in Fig. 1. The material demand was calculated based on Winjobi et al. (2020) and is representative for the bills of materials included in the GREET model, with cell level energy densities ranging from 213 Wh kg^{-1} for LFP to 316 Wh kg^{-1} for NCA. The full set of material demand to produce battery cells is shown in the supplementary tables (ST), with other materials that are used in significantly lower amounts in LIB manufacturing being excluded here by applying a 2 % cut-off rule. This led to the exclusion of materials such as carbon black, PVDF and other polymers. NCA active material preparation typically utilises alumina sulphate, which is quantified here as Al metal demand, due to data scarcity on the specific CF of alumina sulphate. Various studies have presented bills-of-materials for a range of battery chemistries (Chordia et al., 2021; Ellingsen et al., 2014; Kallitsis et al., 2020), the sole reliance on the study of Winjobi et al. (2020) is that it includes bills-of-materials for a wide range of battery chemistries which are inherently consistent, i.e. they are calculated based on the BatPac tool for all chemistries (Ahmed et al., 2016).

To calculate the battery material contribution to the CF for each battery chemistry, the CF of material production (in kg CO_2-eq kg^{-1}) was multiplied by the kg kWh^{-1} material requirement to produce battery cells. The former was calculated based on a wide range of literature sources, industry reports and LCA databases as shown in Table S1 of the ST. Data shown in Table S1 refer to the CF of key battery materials, as shown in Fig. 1. Due to the utilisation of various sources, it is acknowledged that reported CFs are calculated based on different impact assessment methods which exhibit methodological variations and would lead to slightly different estimations for the CF.

2.3. Energy contributions to the carbon footprint

NMC, LFP and NCA battery manufacturing has been reported to consume approximately 30–50 kWh kWh$_{cell}^{-1}$ for the cell manufacturing process (Jinasena et al., 2021; Kallitsis, 2022). A more recent study by Degen et al. (2023) predicted energy consumption values for cell manufacturing in 2040 ranging from 20 to 40 kWh kWh$_{cell}^{-1}$. However, such values exclude the cathode active material preparation step, which is known to consume an additional, and slightly higher amount, (Kallitsis, 2022). A recent study reported that cathode active material

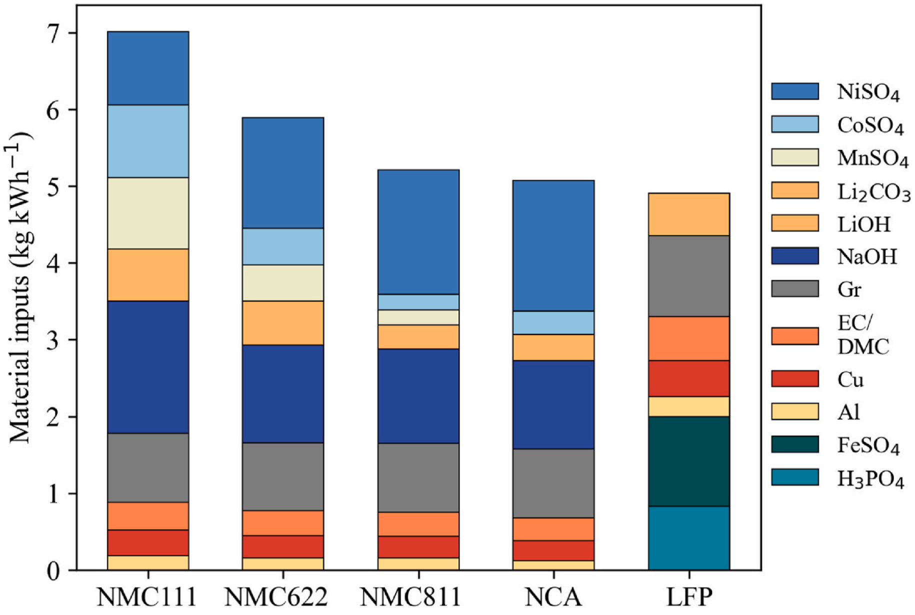

Fig. 1. Combined material demand in kg kWh^{-1} of battery cells corresponding to cathode active material preparation, electrode production and cell manufacturing for NMC111 (267 Wh kg^{-1}), NMC622 (299 Wh kg^{-1}), NMC811 (311 Wh kg^{-1}), NCA (316 Wh kg^{-1}) and LFP (212.7 Wh kg^{-1}) chemistries. NMC111 and NMC622 use lithium carbonate and the rest use lithium hydroxide.

synthesis accounts for more than 50% of production costs, CF and environmental impacts (Gutsch and Leker, 2024). According to GREET producing NMC, NCA and LFP cathode precursor requires 20 to 30 kWh kWh_{cell}^{-1}. Therefore, the gate-to-gate energy demand for a battery Gigafactory, including the cathode and cell production stages was assumed to vary between 40 and 80 kWh of energy kWh^{-1} cell produced, assuming a uniform distribution for the Monte Carlo simulation. This range of values is assumed to be representative for all battery chemistries, as there is currently no specific trend regarding the comparative energy consumption of competing chemistries, as highlighted by Bouter and Guichet (2022). All energy requirement is represented as electricity values, although it includes heating and cooling. This is an accepted assumption across literature studies but might slightly underestimate the CF (Jinasena et al., 2021).

The gate-to-gate CF of battery production in kg CO_2-eq kWh^{-1} was derived by multiplying the energy demand for cell manufacturing with the carbon intensity of electricity in each of the locations considered. 26 Chinese provinces, 20 North American locations and 19 countries in Europe and Asia were selected as key battery manufacturing locations, based on a mix of market reports detailed in the ST. The projected capacity to go online before 2035 in each location is shown in Table S3. The carbon intensity of electricity in Chinese provinces, US states and the remaining countries in Europe, North America and Asia is presented in Table S4 based on online resources and the study of Li et al. (2017).

2.4. Cradle-to-gate and global carbon footprint of LIBs

To calculate the cradle-to-gate carbon footprint of LIBs under uncertainty, material and energy contributions were combined, neglecting any facility or transport requirements. The latter has been found to contribute around 5% to the overall CF of LIBs (Linder et al., 2023), therefore not expected to lead to significant differences across scenarios. Material contributions to the CF of LIB manufacturing in each location were assumed to remain unchanged. In other words, it is assumed that the variation in the carbon emissions of each key LIB material is independent of where battery manufacturing takes place. This assumption is backed by the fact that materials supply chains are globally distributed. Therefore, the cradle-to-gate CF of LIBs in each location varies in line with different gate-to-gate contributions from battery manufacturing, which are traced to the local carbon intensity of electricity.

3. Results

3.1. Carbon footprint of battery materials

Fig. 2 illustrates the CF (in kg CO_2-eq kg^{-1}) of battery materials reported across literature studies, LCA databases and industry reports. Key materials with significant CF uncertainties include $NiSO_4$, $CoSO_4$, Li_2CO_3, LiOH, and Gr. These materials are extensively utilised throughout the battery production chain, underscoring the importance of assessing the CF of LIBs with consideration for such uncertainties, especially as new CF rules were recently announced by the European Commission.

Lithium is the most studied material, with recent reviews covering the production and conversion of Li_2CO_3 and LiOH through brine and spodumene resources (Chordia et al., 2022; Schenker et al., 2022). The CF for LiOH varies between 5.5 and 19.2 kg CO_2-eq kg^{-1} and that of Li_2CO_3 between 2.1 and 33 kg CO_2-eq kg^{-1}. While spodumene-based pathways tend to be more GHG intensive due to their energy and carbon intensity, producing lithium products from low grade brines can reach similar climate impacts (Chordia et al., 2022).

The CFs of the remaining cathode materials, including $NiSO_4$, $MnSO_4$ and $CoSO_4$ have been less studied. $NiSO_4$ can be produced from sulphide and laterite ores, with the lower bound (1.8 kg CO_2-eq kg^{-1}) corresponding to production in Russia from sulphide ores (Norilsk Nickel, 2022) and the upper bound (22.4 kg CO_2-eq kg^{-1}) providing an estimate for the conversion of nickel pig iron to matte, which could be further processed to $NiSO_4$ (IEA, 2021). Generally, producing nickel from sulphide ores comes with a lower CO_2 intensity compared to laterite ores. This comes from a combination of lower energy intensity and low-carbon energy sources utilised in sulphide mining and processing. Specifically, nickel laterites need to either be smelted completely or be hydrometallurgically processed resulting in increased process complexity and energy intensity (Schmidt et al., 2016). In addition,

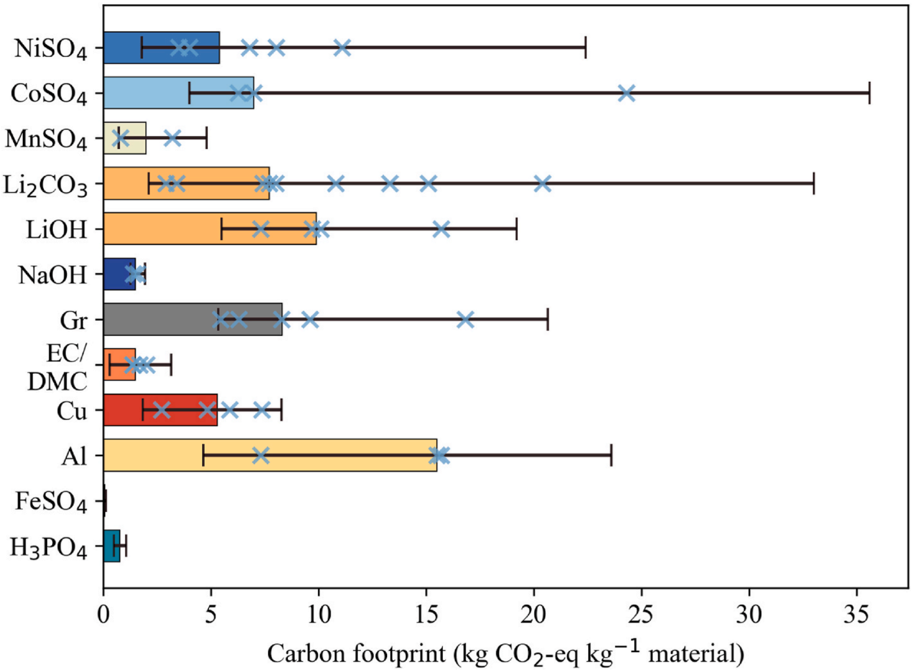

Fig. 2. Carbon footprint of key battery materials in kg CO_2-eq kg^{-1} across literature studies, life cycle assessment databases and industry reports. Bars indicate median values, positive and negative errors show the minimum and maximum value and any reported values in-between are shown as a scatter. The median CF for $FeSO_4$ is 0.76 with minimum and maximum values of 0.5 and 1.0 kg CO_2-eq kg^{-1}, respectively. The full set of data is shown in Table S1 of the ST.

sulphide ore is mined in locations with lower carbon intensity energy, such as Canada and Russia, in contrast with Indonesia, New Caledonia and the Philippines being the dominant laterite mining countries, heavily relying on coal. Cobalt is mainly mined in the Democratic Republic of Congo (DRC), which is further processed to $CoSO_4$ in China. A comprehensive data collection effort on the dominant supply chain of cobalt has revealed a carbon footprint for $CoSO_4$ of 6.9–9.7 kg CO_2-eq kg^{-1}, depending on the allocation method as it is almost always a co-product in other mineral systems (Dai et al., 2018). However, the values in Fig. 2 range from 4 to 35.6 kg CO_2-eq kg^{-1}, with the lower bound corresponding to a market-average from the Cobalt Institute (Cobalt Institute, 2019) and the upper bound being representative of both mining and refining processes taking place in China (Zhang et al., 2021). Cobalt mining in the DRC heavily relies on hydroelectric power, resulting in a low carbon intensity, with the carbon emissions of cobalt being traced to the refining step, usually performed in China. The values for $MnSO_4$ are bounded between 0.7 and 4.8 kg CO_2-eq kg^{-1}, with the ones included in the Ecoinvent and GREET databases falling towards the lower end of the spectrum. The carbon intensity of energy sourced in $MnSO_4$ production is the main source of such variability, as production in Botswana, Czech Republic, North America and a global average are considered herein, coming with significantly different emission profiles. Aluminium sulphate is extensively utilised in NCA precursor production, quantified as primary Al demand herein, known to come with significant geographical variations, with production in China associated with a carbon intensity three-times higher than that of Europe. Key cathode materials used in LFP battery manufacturing, $FeSO_4$ and H_3PO_4, come with significantly lower CFs and are included here for completeness based on data from GREET and Ecoinvent.

On the anode side, graphite has been reported as a "hidden impact" in battery manufacturing due to the underestimation of its CF in commercial LCA databases (Whattoff et al., 2021). Recent LCAs for natural and synthetic graphite reported values of 9.6 (Engels et al., 2022) and 20.6 (Surovtseva et al., 2022) kg CO_2-eq kg^{-1}, respectively, which are much higher than earlier-reported numbers. Graphite mining and surface modification are the main energy demand drivers for natural graphite, while the graphitization stage is the main energy requirement in the production of synthetic graphite. Both products result in a high energy intensity, making their CF sensitive to regional electricity mixes, with the CF for natural graphite production predicted to be almost three times lower in North America, compared to China. Materials used in the electrolyte and current collectors, such as Cu, ethylene carbonate (EC) and dimethyl carbonate (DMC), and sodium hydroxide (NaOH) are consumed in large amounts in battery manufacturing and are included for completeness.

The material contribution to the cradle-to-gate CF of NMC, NCA and LFP LIBs is illustrated in Fig. 3, through a Monte Carlo simulation generating an array of 100,000 random numbers from a uniform distribution of the CF of each material, with boundary values corresponding to the minimum and maximum numbers shown in Fig. 2. This visualization showcases the effect of uncertain battery material footprints. The median values for NMC111, NMC622, NMC811, NCA and LFP are 64.3, 56.1, 47.4, 47.8 and 28.3 kg CO_2-eq kWh^{-1} for a cell of given capacity. The notably lower values for LFP are attributed to the fact that LFP cathode precursor manufacturing requires significantly lower amounts of materials (Fig. 1), while key cathode materials $FeSO_4$ and H_3PO_4, come with significantly lower CFs (Fig. 2). An arithmetic average for all LIB chemistries is also calculated with a median of 48.8 kg CO_2-eq kWh^{-1} and whisker values ranging from 22 to 75.3 kg CO_2-eq kWh^{-1}. This further highlights the uncertainty associated with the carbon emissions of key battery materials as shown in Fig. 2, which is transferred to the cradle-to-gate CF of LIBs.

3.2. Carbon footprint of battery manufacturing

The location-specific CF of battery production, associated with its energy demand for active material and cell manufacturing, and neglecting the contribution of materials (gate-to-gate), is shown in Fig. 4. The boxplots account for the fact that energy demand for cell manufacturing can vary between 40 and 80 kWh of energy kWh^{-1} cell produced as discussed in section 2.3. Depending on the carbon intensity of electricity grid mixes in each location as defined by the proportion of renewable energy versus fossil fuels, the contribution to the overall CF of a LIB can vary by an order of magnitude. In Europe, producing batteries in Sweden and Norway can come with a low median CF of 2.8 and 1.6 kg CO_2-eq kWh^{-1}, respectively. Meanwhile, Poland and Germany lead the way in terms of projected battery production capacity but use carbon-intensive electricity mixes leading to a much higher median gate-to-gate carbon footprint of 39.6 and 21.9 kg CO_2-eq kWh^{-1}, respectively. The Chinese province of Sichuan is expected to produce the same amount of LIBs in 2035 as Germany and Poland combined, with a median gate-to-gate CF of 12.0 kg CO_2-eq kWh^{-1}. In addition, Kentucky is leading the way in North America in terms of projected pipeline capacity, with the median gate-to-gate CF estimated as 47.2 kg CO_2-eq kWh^{-1} which is quantitatively similar to that of Zhejiang, with the latter expected to produce 563 GWh of LIBs by 2035. Such evidence challenges the notion that merely establishing a European or North American battery value chain provides sufficient means to decarbonise LIBs.

By observing the findings of Fig. 4, it becomes evident that the majority of the battery industry has optimised Gigafactory locations for costs, neglecting carbon emissions. The combined projected capacity of low-carbon manufacturing locations of Quebec, Ontario, Sweden, Switzerland and Norway does not exceed the expected LIB production capacity of Germany. Such evidence provides an additional variable to be taken into account when selecting Gigafactory locations and provides robust quantitative evidence to inform policy making towards incentivising low-carbon battery manufacturing in the face of EU regulations. It would be possible to solve this problem, without moving already built or planned Gigafactories, if new renewable energy generation is built alongside these plants, that otherwise would not have been built.

A significant variation is observed between Chinese provinces, with gate-to-gate CF median values ranging from 8.7 kg CO_2-eq kWh^{-1} in Yunnan to 69.5 kg CO_2-eq kWh^{-1} in Tianjin. In addition, LIBs produced in the province of Jiangsu, speculated to produce more batteries than the rest of the world combined (Benchmark, 2022), are found to come with a median gate-to-gate CF of 59.9 kg CO_2-eq kWh^{-1}. Oversimplified

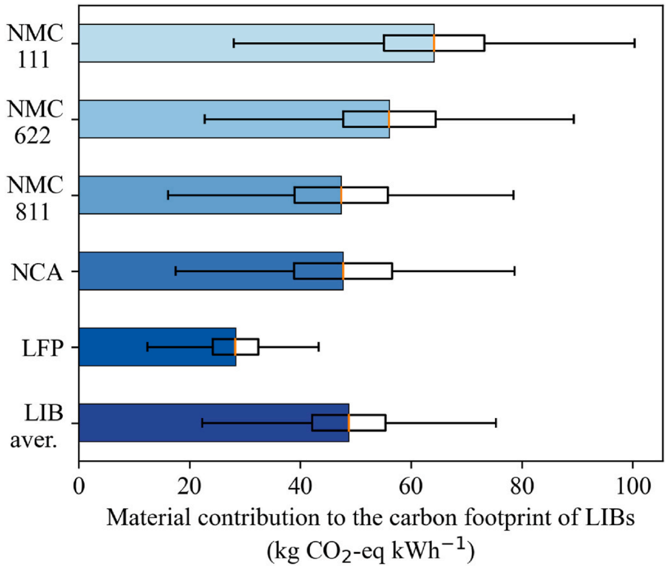

Fig. 3. Material contribution to the carbon footprint of lithium-ion batteries in kg CO_2-eq kWh^{-1} for NMC111, NMC622, NMC811, NCA, LFP and an arithmetic average for the five chemistries (LIB average).

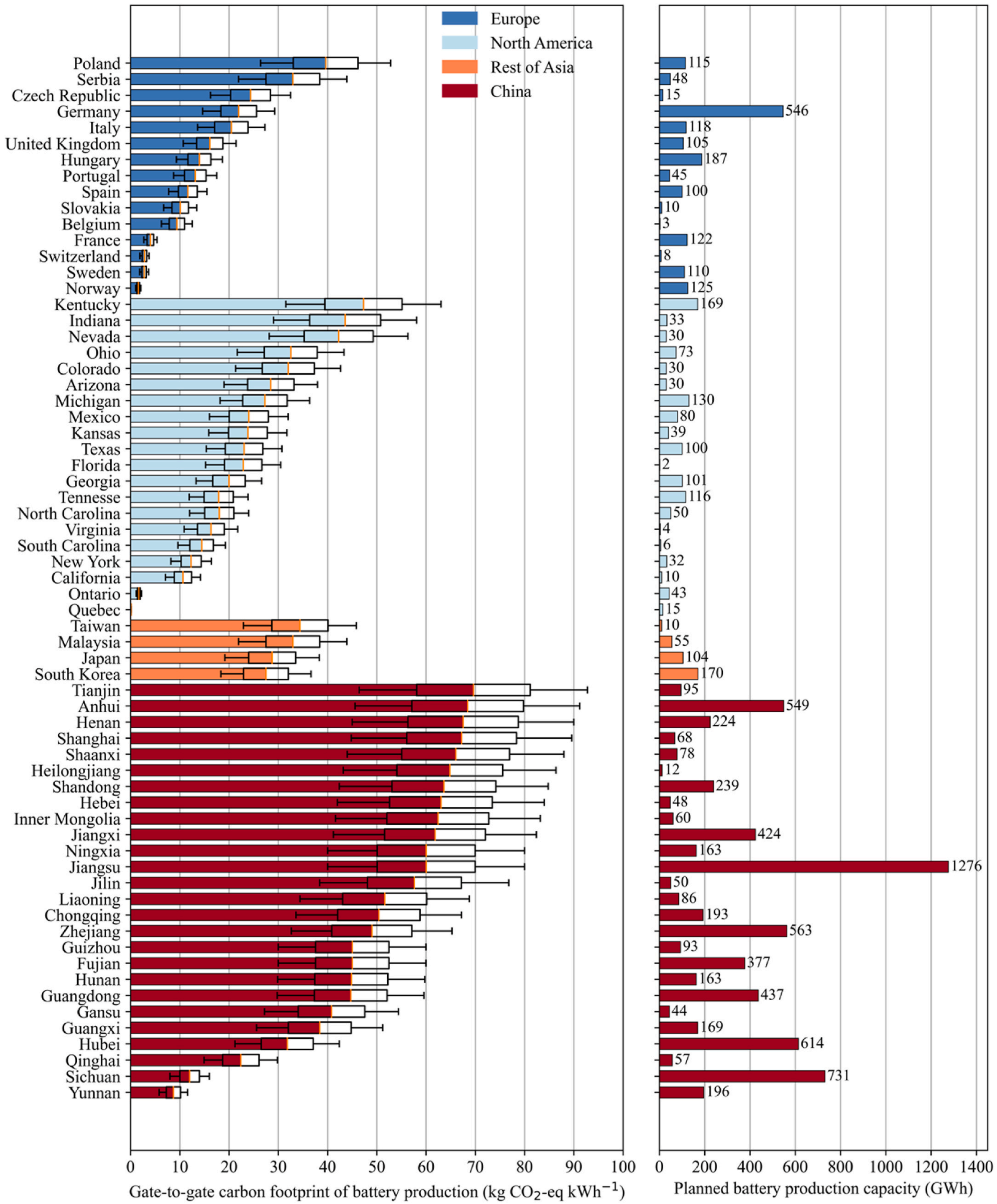

Fig. 4. Gate-to-gate carbon footprint of battery production in kg CO_2-eq kWh^{-1} and planned GWh battery production capacity by 2035, across 26 Chinese provinces and 4 countries in the rest of Asia, 20 North American locations and 15 countries in Europe.

assumptions to represent the leading battery manufacturing country as a single entity in LCA studies have led to a skewed picture regarding the carbon emissions of battery manufacturing globally. Fig. 4 highlights the links between the CF of LIBs and production location or energy sources, emphasizing the importance of considering regional electricity grids and carbon intensity when establishing manufacturing facilities to effectively decarbonise LIBs.

3.3. Cradle-to-gate carbon footprint of LIBs

The cradle-to-gate CF of LIBs is presented in Fig. 5, accounting for both material and energy contributions. Depending on production location and the source of materials, median LIB carbon footprints of 57.5–118.4 kg CO_2-eq kWh^{-1} are observed in Chinese provinces, 48.9–96.0 kg CO_2-eq kWh^{-1} across North America and 50.4–88.4 kg CO_2-eq kWh^{-1} in European battery manufacturing countries. This is in line with published literature claiming that, on average, batteries manufactured in Europe or North America have a lower CF than those manufactured in China (Kallitsis et al., 2020; Kelly et al., 2020; Linder et al., 2023). However, and as a result of providing increased resolution when looking at the specifics of each manufacturing location, several Chinese provinces can compete with western locations in terms of CF. The projected battery manufacturing capacity of Yunnan, Sichuan, Qinghai and Hubei in 2035 is quantitatively similar to the combined capacity for all European countries, with the median CF of the former ranging from 57.5 to 80.6 kg CO_2-eq kWh^{-1}. Commonly quoted LIB CFs for European and North American locations portray best-case scenarios for locations such as Sweden or California (Linder et al., 2023). From an industrialist point of view, this underlines the fact that merely establishing a European or North American battery value chain might not inherently bring significant carbon emission savings, underscoring the importance of sourcing low-carbon materials and energy for battery manufacturing.

From a policymaking viewpoint, Fig. 5 provides a framework to assess the reported CF of LIBs, which is timely given the fact that the European Commission will require CF disclosures for any battery placed on the market from 2024 (Peiseler et al., 2022). This becomes evident by comparing literature findings to the location-specific ranges reported herein. For example, Chordia et al. (2021) reported a cradle-to-gate CF of 104 kg CO_2-eq kWh^{-1} for an NMC811 battery produced in South Korea, which falls towards the upper whisker values reported in Fig. 5. In addition, Dai et al. (2019) reported a 72.9 kg CO_2-eq kWh^{-1} for an NMC111 battery produced in the United States, falling within the lower whisker values reported for North America in Fig. 5. Results falling outside of the whisker values of Fig. 5, such as 53 (Yu et al., 2018) or 20 (Xiong et al., 2019) kg CO_2-eq kWh^{-1} for LIBs produced in China, have been reported to exhibit life cycle inventory inconsistencies (Kallitsis et al., 2020). Significantly higher CF values reported by Kallitsis et al. (2020) and Ellingsen et al. (2014), than the range of 46.3–106.1 kg CO_2-eq kWh^{-1} reported here for South Korea, have been traced to the fact that they refer to pilot-scale facilities rather than Giga-scale factories considered herein, with the former resulting in almost three-times higher energy demand for cell manufacturing (Kallitsis, 2022).

4. Discussion

4.1. The role of production location and material sources

From the perspective of an LCA practitioner, this study uncovers a significant level of uncertainty surrounding the CF of LIBs as a result of the highly variable CFs for the upstream production of key battery materials, an aspect that has often been inadequately addressed in previous research. While this study presented a first effort to analyse the CF of these materials, the current inventories and emission factors available are limited. It is expected that more comprehensive and up-to-date datasets will reveal higher variations in the CF for each material.

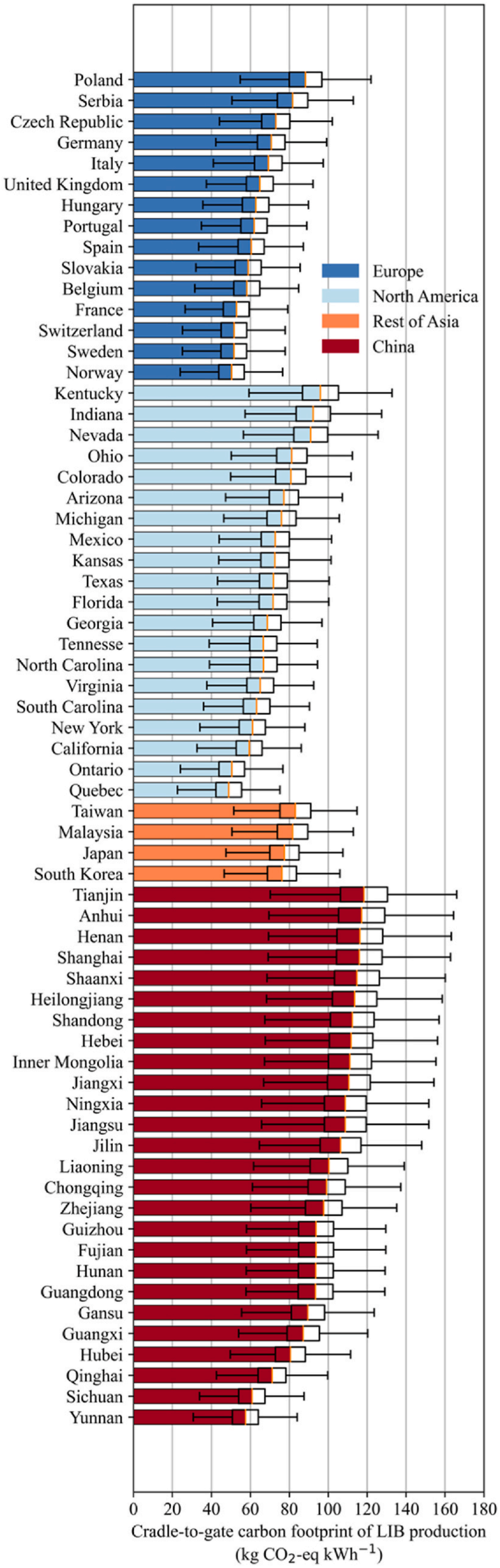

Fig. 5. Cradle-to-gate carbon footprint of battery cell production in kg CO_2-eq kWh^{-1}, accounting for both material and energy contributions, across 26 Chinese provinces and 4 countries in the rest of Asia, 20 North American locations and 15 countries in Europe.

The CFs of accurately mapped supply chains could also increase in the future due to lowering of ore grades at the currently operating mining sites (Chordia et al., 2022). This uncertainty is particularly apparent when examining the CF values of graphite as shown in Fig. 2. Prior to 2022, widely-used LCA databases like GREET and Ecoinvent reported CFs of 8.27 and 5.44 kg CO_2-eq kg^{-1} for graphite. In contrast, more recent studies by Engels et al. (2022) and Surovtseva et al. (2022) reported CFs of 9.6 and 20.6 kg CO_2-eq kg^{-1} for natural and synthetic graphite, respectively. It is important to note that the datasets analysed in this study might under-represent some prevalent supply routes, such as lithium production in Australia or nickel mining in Indonesia, due to limited data availability. These routes depend heavily on coal consumption, which is likely to further increase the CFs of the materials involved. Such gaps emphasise the urgent need for further research, practical applications of LCA and data collection efforts to prioritize the investigation of upstream mining and processing for key battery materials.

The interplay between energy and material contributions to the CF of LIBs has broader implications for stakeholders involved in the LIB value chain. First, taking North America as an example, sourcing low carbon materials will have a fundamentally different effect for a battery manufacturer located in Ontario compared to Kentucky. For the former, given the low carbon intensity of their gate-to-gate operations via the utilisation of renewables-based regional energy, effectively reducing the cradle-to-gate footprint of their LIBs comes down to sourcing low carbon materials. The latter should prioritise decarbonisation of their energy supply before addressing the important raw materials. This extends to the environmental effectiveness of LIB recycling, which can effectively reduce the material contribution to the LIB CF (Baars et al., 2021; Ciez and Whitacre, 2019; Kallitsis et al., 2022a). As battery value chains are being developed in the Western world, results shown in Fig. 5 quantify the opportunity of sourcing low carbon materials and energy to decarbonise the LIB value chain, and perform well-informed policy- and decision-making.

4.2. Global emissions of LIBs

Results presented in this work are used to project the carbon emissions of the LIB industry globally, as shown in Fig. 6., accounting for both battery manufacturing and material supply chain contributions. These are combined with the pipeline capacity presented in Fig. 4., assuming a staged approach to reach 10 TWh battery manufacturing capacity in 2035. The battery manufacturing capacity in 2020, 2025 and 2030 was 0.95, 4.1 and 7.7 TWh, respectively. Such projection assumes that all planned battery manufacturing capacity will materialise. In addition, Fig. 6 should be seen as a worst-case scenario, as it extrapolates today's technologies to 2035, not accounting for further improvements in battery manufacturing and LIB technology. A recent study found that Gigafactory energy consumption could be reduced up to 66% by 2040 by switching to post-LIB chemistries and improving production technologies, which would have an important effect on the CF (Degen et al., 2023). Decarbonisation pathways for power production were taken into account by following a staged approach, reducing the carbon intensity of electricity by ca. 30% in 2035 compared to 2020 levels (IEA, 2018). Finally, in performing such projections, attribution of specific plants to a specific battery chemistry was not performed, assuming that the range of CF values reported herein is representative of all battery chemistries.

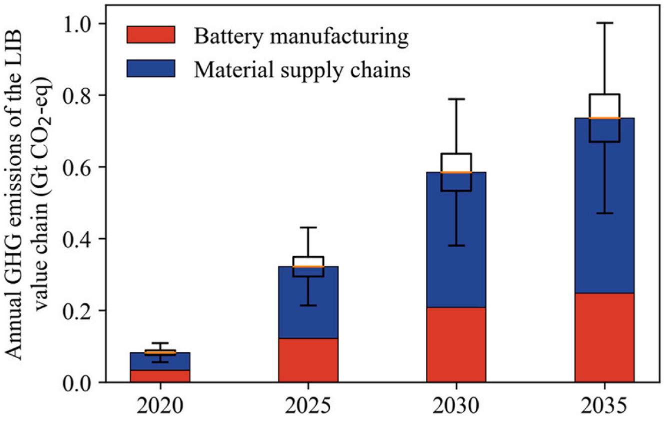

Fig. 6. Extrapolation of carbon emissions of the lithium-ion battery value chain to 2035, including the contribution of battery manufacturing and material supply chains.

The emissions from upstream material processing and battery manufacturing in 2035 are estimated to range between 0.5 and 1.0 Gt CO_2-eq, with the upper bound being comparable to the annual GHG emissions of Japan. However, assuming that producing an average gasoline-powered car emits 5t CO_2-eq (Buberger et al., 2022; Gifford, 2021), this upper bound is quantitatively similar to the production GHG emissions of 220 million internal combustion engine cars. For reference, 278 million personal and commercial vehicles were registered in the US in 2021 (Tilford and Megna, 2023). The GHG footprint of material supply chains is shown to dominate the GHG emissions of the battery value chain, highlighting the importance of decarbonising mining and processing operations to mitigate the climate impact of the global battery ecosystem.

4.3. Limitations and future perspectives

One of the goals of this study is to increase caution regarding the importance of background battery material production datasets in battery LCAs. A significant level of variation associated with the contribution of materials to the cradle-to-gate CF of a LIB was uncovered as a direct consequence of the expanded background dataset utilised herein. Such analysis is performed under the assumption that the CF of material production varies according to a uniform distribution. This is a realistic assumption when accounting for the fact that practically, producing each battery chemistry can be performed by utilising any of the background datasets of Fig. 2. However, the probability to utilise some material supply routes might be higher compared to others. Improving the analysis would require building distributions based on the market share for each material supply route. Currently, this is not possible due to scarce information regarding the GHG emissions associated with key battery material production processes/pathways. For example, allocating a specific market share for Li chemicals for spodumene versus brine pathways would not be correct under the current literature landscape, as most data for spodumene-based routes present estimations based on secondary data (Chordia et al., 2022). The same is true for laterite-based pathways for nickel production, as no primary data are currently available in the literature.

In addition, production location was found to be a determinant factor for the gate-to-gate CF of LIBs, uncovering significant variations within the same country/continent. Even within the same region, positioning a Gigafactory in different areas might come with different carbon profiles arising from the carbon intensity of the local grid. However, accounting for such variations, e.g. state-level assessment in Germany, would significantly expand the scope of the study. It is also acknowledged that certain locations might decarbonise at a much faster pace, which would result in a lower carbon intensity of battery manufacturing as shown in Fig. 4. Accounting for the effect of regional policies in power decarbonisation was challenging given the high spatial resolution shown in Fig. 4. Therefore, the figure portrays emissions in 2021 in conjuction with the locations where battery Gigafactories will be built to increase caution regarding such issues and inform future battery LCAs on specific battery production routes. Finally, within this work emission factors for electricity generation were based on administrative boundaries, assuming that a Gigafactory positioned at a specific location will source electricity from the local grid. Practically, balancing authorities span several states in the US or provinces in China and some Gigafactories might be exclusively powered by renewable energy, which would change the location-specific emission profile.

The issues highlighted above uncover a significant omission in current battery LCA studies in the literature hindering our ability to perform accurate assessments, with high relevance to the EU battery regulation. Defining only the chemistry and geometry of a battery cell, without discussing manufacturer-specific information does not allow to trace the specifics of the battery cell manufacturing location. In addition, it is even harder to trace the origin of key battery materials, which are a determinant factor to the overall environmental impact of a battery. Kelly et al. (2020) tried to tackle such issue by building hypothetical scenarios on specific supply chains without defining a specific manufacturer for each battery cell. As CF assessments are adopted by industry, with disclosures being mandatory in EU by 2024, the goal and scope definition of the LCA process should clearly define the manufacturer and supply routes for key battery materials and the associated background datasets. Emerging blockchain-based solutions such as the battery passport might prove to be highly useful in this direction, as they contain a series of data attributes that would allow for more accurate quantifications of the carbon footprint (Berger et al., 2022; Nuttah et al., 2023). However, widespread adoption of the battery passport is expected from 2027 onwards, when the EU Battery Regulation will mandate its implementation.

5. Conclusions

This study uncovered a significant level of variation associated with the contribution of materials to the CF of market-dominant LIB chemistries. The Monte Carlo simulation demonstrated that, on average, the material contribution to the CF of a LIB can vary by approximately a factor of 4, depending on the type and source of battery materials. The latter should be clearly defined in future LCAs of LIBs, with a comprehensive dataset to account for the CF of key battery materials being provided herein. The gate-to-gate contribution of battery manufacturing to the CF of LIBs exhibits a clear correlation to production location. The level of detail employed herein uncovers significant variations within Chinese provinces, with low carbon manufacturing location being able to compete with European or North American location in terms of GHG emissions. In addition, it is shown that key battery manufacturing locations in Europe and North America do not favour GHG reduction, an aspect that should be accounted for in strategic decision-making, together with geopolitical factors. Overall, cradle-to-gate CF of LIB production varies widely based on location, energy sources, and material procurement, emphasising the need for a holistic approach to reduce emissions across the entire value chain. The median cradle-to-gate CF varies between 60 and 120 kg CO_2-eq kWh^{-1} as shown in Fig. 5., with the latter providing a significant level of detail for policymakers to assess the CF of batteries in various locations, ensuring accurate disclosures and promoting sustainable battery production. Given that performing a study with such a broad scope comes with a large set of assumptions, our results should be seen as indicative rather than definitive, providing a useful reference for further investigation and discussion in this rapidly evolving field.

The uncertainties in current datasets, particularly for key battery materials, highlight the need for further research and comprehensive LCA evaluations to better inform decision-making. Given the importance of battery materials to reduce carbon emissions, policy initiatives such as the European Critical Raw Materials Act should set specific decarbonisation targets for battery-related materials. By understanding the interplay between energy and material contributions, stakeholders can prioritize effective measures for decarbonising battery production, recycling, and material sourcing. Acknowledging the projected carbon emissions of the LIB value chain in 2035, it is crucial to develop and implement sustainable solutions today to minimise the environmental impact of our pursuit for clean energy.

CRediT authorship contribution statement

Evangelos Kallitsis: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Investigation, Data curation, Conceptualization. **Jordan J. Lindsay:** Writing – review & editing, Data curation. **Mudit Chordia:** Writing – review & editing, Data curation. **Billy Wu:** Writing – review & editing, Data curation. **Gregory J. Offer:** Writing – review & editing, Supervision, Funding acquisition. **Jacqueline S. Edge:** Writing – review & editing, Supervision, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2024.141725.

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