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Lithium-ion batteries and the transition to electric vehicles: environmental challenges and opportunities from a life cycle perspective

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Citation

Xu, C. (2022, December 21). *Lithium-ion batteries and the transition to electric vehicles: environmental challenges and opportunities from a life cycle perspective*. Retrieved from <https://hdl.handle.net/1887/3503659>

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3 Future greenhouse gas emissions of automotive lithium-ion battery cell production^b

Abstract

Understanding the future environmental impacts of lithium-ion battery is crucial to enable a sustainable transition to electric vehicles. Here, we build a prospective life cycle assessment (pLCA) model for lithium-ion battery cells production for 8 battery chemistries and 3 production regions (China, US, and EU). The pLCA model includes scenarios for future life cycle inventory data for energy and key materials used in battery cell production. We find that greenhouse gas (GHG) emissions per kWh of lithium-ion battery cell production could be reduced from 41-89 kg CO₂-Eq in 2020 to 10-45 kg CO₂-Eq in 2050, mainly due to the effect of a low-carbon electricity transition. Cathode is the biggest contributor (33%-70%) of cell GHG emissions in the period between 2020-2050. In 2050, LiOH will be the main contributor to GHG emissions of LFP cathode, and Ni₂SO₄ for NCM/NCA cathodes. These results promote discussion on how to reduce battery GHG emissions.

3.1 Introduction

In the transportation sector, a global shift from internal combustion engine vehicles (ICEVs) to electric vehicles (EVs) has been widely recognized as one of the most effective ways to mitigate climate change^{57,151}. The International Energy Agency (IEA) expects the global light-duty EV fleet to grow from around 10 million in 2021 to 124-199 million EVs in 2030⁶. Due to recent policy incentives and ongoing innovations in battery technologies and business models, amongst others, it is expected the global light-duty EV fleet size will grow to 970-1940 million EVs by 2050⁷.

The transition to the use of EVs will impact the supply chain of the automotive industry¹⁵². One of the key changes exists in the production and use of batteries⁸⁹. Due to low cost and high performance, lithium-ion batteries dominate the current EV market and are expected to dominate in the next decade. The most important battery

^b Published as: Xu, C., Steubing, B., Hu, M., Harpprecht, C., van der Meide, M. & Tukker, A. Future greenhouse gas emissions of automotive lithium-ion battery cell production. *Resources, Conservation & Recycling* 187, 106606 (2022).

types include lithium nickel cobalt manganese oxide batteries (NCM), lithium nickel cobalt aluminum oxide batteries (NCA), and lithium iron phosphate batteries (LFP).

Although a lot of studies have found that EVs have environmental advantages over ICEVs³⁷⁻³⁹, the impacts of battery production are still rather uncertain⁴⁰⁻⁴². Current studies find quite diverging battery impacts⁴³⁻⁴⁵. This is due to the use of different data and assumptions on battery performance and compositions⁴⁶, battery production processes, geographical scope⁴⁷, and life cycle inventory (LCI) information^{48,49}, and environmental impact assessment methodologies⁵⁰, amongst others. All these factors can lead to questionable conclusions on the magnitude of environmental impacts of battery production. Moreover, changes in environmental impacts of battery production in the next decades are rarely estimated, due to the challenges in estimating futurized background LCI data and modeling future battery production processes.

In this paper, we aim to overcome most of the aforementioned knowledge gaps by building a prospective life cycle assessment (pLCA) model to estimate future GHG emissions of the battery cell production per kWh battery capacity. The pLCA model simulates the lithium-ion battery cell production for 8 types of battery chemistries in 3 production regions (China, US, and EU) for the period 2020-2050. The foreground system is complemented by prospective life cycle inventory (pLCI) of background data that considers i) future energy scenarios as modelled in the Integrated Assessment Model REMIND¹⁵³ for the Shared Socio-Economic Pathway 2 (SSP2)-Base (no climate policy) and the SSP2-PkBudg 1100 scenarios (with climate policies)¹⁵⁴ as well as ii) future supply chain of key battery metals including nickel, cobalt, copper, and others (see details in methods). In this way, this paper aims to contribute to a better understanding of the current and future GHG emissions of battery cell production and the discussion of how to minimize such impacts in the context of a mobility transition towards EVs.

The paper is structured as follows. In section 2 we discuss the approach to the pLCA, discerning the goal and scope definition, life cycle inventory, and life cycle impact assessment. Section 3 gives the results and interpretation. Section 4 ends with discussions and conclusions.

3.2 Methods

3.2.1 Goal and scope

The goal of our pLCA model is to evaluate GHG emissions per kWh of battery cell production in 2020, 2030, 2040, and 2050. The modeled battery cell is a lithium-ion battery cell used in battery electric vehicles. The modeled cell capacity is 0.275 kWh, the most common size of an EV battery cell. The functional unit is chosen as 1 kWh in terms of the nominal battery cell capacity. The study is an attributional LCA, with a contribution analysis to reveal the environmental hotspots of battery cell production. The results are intended to give prospective environmental information to battery technology developers and EV policy makers.

The pLCA model covers 8 different battery chemistries and 3 production regions:

I. Battery chemistries. Battery chemistry development will lead to differences in material compositions and production processes and corresponding environmental impacts. Here we explore chemistry-specific GHG emissions by distinguishing 8 chemistries: LFP-Graphite, NCA-Graphite, NCM111-Graphite, NCM523-Graphite, NCM622-Graphite, NCM622-Graphite (Si), NCM811-Graphite (Si), and NCM955-Graphite (Si) batteries. We include these 8 chemistries because they are currently seen as the most likely dominant battery chemistries in the future according to our previous study⁷.

II. Production regions. Battery production region determines where material and energy are supplied from, which significantly influences the associated environmental impacts. Here, we cover China, EU, and US as three main battery production regions in the world to explore region-specific GHG emissions.

Emissions of batteries in the use phase are negligible to zero. In the end-of-life phase, there may be benefits from 2nd uses or recycling of components or materials, but such scenarios and hence the environmental benefits of them are highly uncertain¹⁵⁵. Therefore, we apply cradle-to-gate system boundaries for this study which allocates all production impacts to the first use of the battery in an EV. We include the production of all battery cell components, *i.e.*, cathode, anode, electrolyte, separator, and cell container, as well as the electric energy used to assemble all components into a complete cell (Fig. 3.1). We do not account for the environmental impacts of processing

battery cells to battery modules and –packs, or other components such as battery management systems, as they are minor (less than 10%⁴⁰) compared to the battery cell production itself.

In the impact assessment, we focus on GHG emissions. We use the IPCC GWP 100 characterization method of 2013 that expresses GHG emissions in kg CO₂-Eq.¹⁵⁶. For the LCA implementation, we use the Activity Browser software¹⁵⁷ to calculate the life cycle impacts for all battery chemistries, production regions, temporal boundary, and background scenarios.

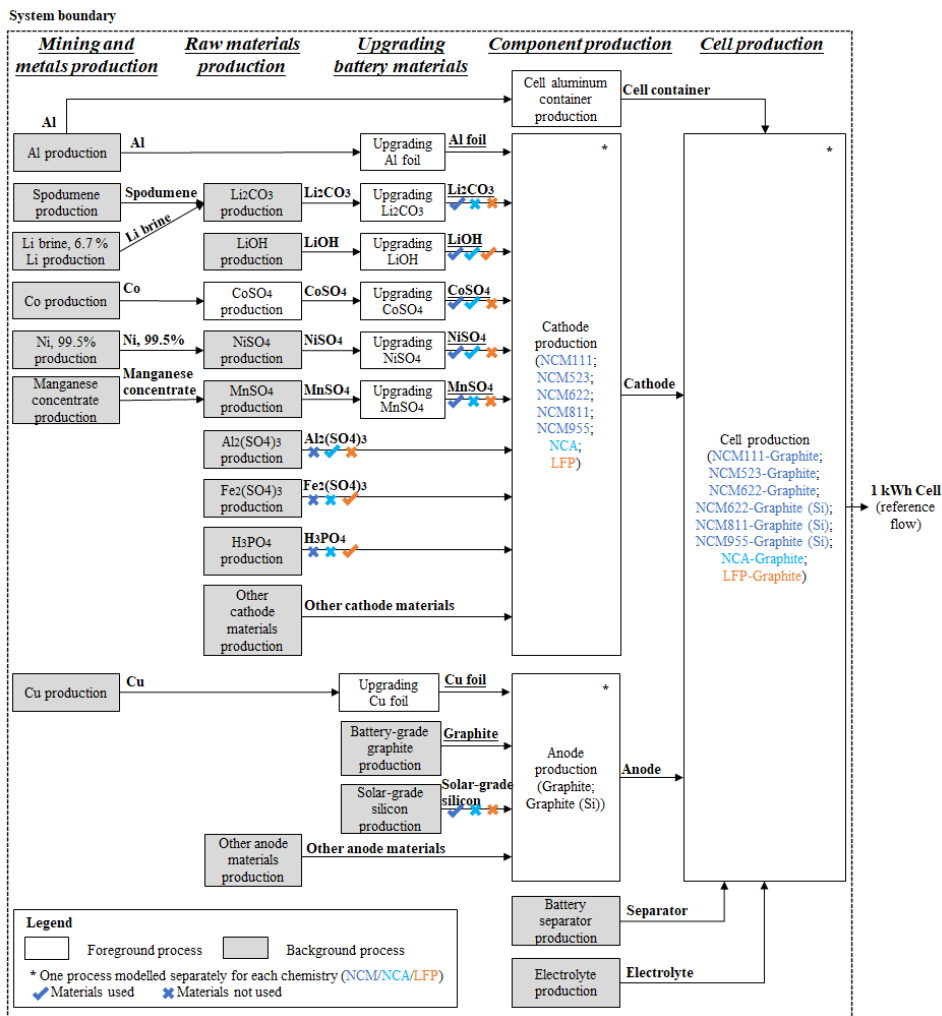


Fig. 3.1: Flow chart of the production of battery cells. Italicized underlined characters on top of the figure refer to life cycle stages. Materials with underlines indicate the quality of materials up to battery-grade, otherwise industry-grade.

3.2.2 Inventory analysis

Futurized background system

The futurized background system of our pLCA model is built based on the ecoinvent 3.6 database¹⁵⁸, considering future energy scenarios and supply chains of key battery

metals. Firstly, we use the premise²⁸ tool to build a futurized version of the ecoinvent 3.6 database¹⁵⁸ (cut-off system model). The tool systematically builds regional LCIs of future electricity production based on detailed regional energy scenarios from the Integrated Assessment Model REMIND¹⁵³. Secondly, we incorporate technology scenarios for the future supply of key battery metals into the futurized version of the ecoinvent 3.6 database. Via this approach, we created the futurized background system of our pLCA model as follows.

I. Processes obtained from ecoinvent 3.6. We used ecoinvent 3.6¹⁵⁸ as a basis to build futurized LCIs of battery raw materials. From ecoinvent 3.6, we included Li_2CO_3 , LiOH , CoSO_4 , NiSO_4 , MnSO_4 , Al , and other materials for the production of the cathode. For the anode, we included graphite, silicon, Cu , and other materials. We further included all relevant raw materials and processes leading to the production of the separator, electrolyte, and cell container.

II. REMIND energy scenarios. We use the REMIND model¹⁵³ with Shared Socioeconomic Pathway 2 (SSP2)¹⁵⁹, a “middle-of-the-road” scenario with regard to future population and GDP growth. Under this SSP2 pathway, we use two future regional energy scenarios from REMIND model¹⁵³ to distinguish the effect of climate policy on the decarbonization of the electricity system. One is the “SSP2-Base” scenario where no specific climate policies are implemented and thus the global temperature could increase by more than 3.5 degrees Celsius by 2100. In the SSP2-Base scenario, the share of renewable energy (wind, solar, and hydro) will increase from only 24% in 2020 to 45% in 2050 for China, from 26% in 2020 to 63% in 2050 for EU, and from 14% in 2020 to 54% in 2050 for US. The corresponding energy mix in 2050 will result in 0.4, 0.14, and 0.18 kg CO₂-Eq per kWh electricity for China, EU, and US, respectively, reducing from 0.72, 0.36, and 0.48 kg CO₂-Eq per kWh electricity in 2020. The second is the “SSP2-PkBudg1100” scenario, which has a goal to limit the cumulative global GHG emissions to 1,100 gigatons by 2100, thus limiting the global average temperature increase to well below 2 degrees Celsius by 2100. In the SSP2-PkBudg1100 scenario, the share of renewable energy (wind, solar, and hydro) will further increase to 68%, 92%, and 93% for China, EU, and US in 2050, which leads to 0.079, 0.029, and 0.033 kg CO₂-Eq per kWh electricity, respectively. Please see details in Supplementary Fig. 3.1 and Supplementary Fig. 3.2 for regional energy mix and GHG emissions per kWh electricity production in 2020, 2030, 2040, and 2050.

III. Future technology scenarios for the supply of key battery metals. We incorporated the future technology supply scenarios of key battery metals as modelled by *Harpprecht et al.*¹⁶⁰ and *van der Meide et al.*¹⁶¹ into the futurized version of the ecoinvent 3.6 database to create the background system. We consider future developments in the supply chains of the following key battery metals: copper¹⁶⁰, nickel¹⁶⁰, aluminum¹⁶², lithium^{163,164}, and cobalt¹⁶¹. These future supply chains use LCIs for the current situation as provided by ecoinvent 3.6 as a basis. For copper, we use the scenario developed by *Harpprecht et al.*¹⁶⁰ to model future changes in ore grades, energy efficiency improvements, and market shares of primary and secondary production as well as of primary production routes. For nickel, we consider future ore grades and increased secondary production. For lithium, an increase of future secondary production share is assumed based on the work of^{30,31}. For aluminum, an increase of future secondary production share is used based on the work of the International Aluminium Institute¹⁶². We use the future cobalt supply chain developed by *van der Meide et al.*¹⁶¹. This model takes into account cobalt ore grade development, changes in the market shares of primary cobalt production routes, and changes in the share of secondary cobalt production share.

Battery cell production stages

In relation to the futurized background system, this section describes the battery cell production stages and relevant modeling choices, data sources, and assumptions. Battery cell production is taking place in five life cycle stages, namely: mining, raw materials production, upgrading battery materials, component production, and cell production (Fig. 3.1).

I. Mining and metals production. This life cycle stage refers to the extraction and concentration, smelting, refining, and other necessary procedures to produce metals. This stage includes the production processes of Al, spodumene, Li brine, Co, Ni (99.5%), manganese concentrate, and Cu for NCM cathodes; Al, spodumene, Li brine, Co, Ni (99.5%), and Cu for NCA cathode; Al, spodumene, Li brine, and Cu for LFP cathode. The data source for this stage is the aforementioned futurized background system.

II. Raw materials production. Raw materials production refers to the production of raw materials from relevant metals, such as hydrometallurgical leaching of Ni to produce NiSO₄. At this stage, the processes for producing Li₂CO₃, LiOH, CoSO₄, NiSO₄,

MnSO₄, and other necessary battery raw materials are considered for NCM cathode; LiOH, CoSO₄, NiSO₄, Al₂(SO₄)₃, and other necessary battery raw materials for NCA cathode; LiOH, Fe₂(SO₄)₃, H₃PO₄, and other necessary battery raw materials for LFP cathode. The data source for raw materials production is the aforementioned futurized background system, except for CoSO₄. We compile the LCIs for producing CoSO₄ from Co using information from the China battery industry reports in the period 2020-2022¹⁶⁵.

III. Upgrading battery materials. The raw materials produced from the last life cycle stage are at the level of industry-grade, which is not suitable for battery production yet. In this stage, raw materials are upgraded to a battery-grade level with additional materials and energy inputs. For the NCM cathode, this includes the production of battery-grade Li₂CO₃, battery-grade LiOH, battery-grade CoSO₄, battery-grade NiSO₄, battery-grade MnSO₄, and battery-grade Al; for the NCA cathode, battery-grade Li₂CO₃, battery-grade LiOH, battery-grade CoSO₄, battery-grade NiSO₄, and battery-grade Al foil are required; and for the LFP cathode battery-grade LiOH is needed. For the anode production, we include the process for producing battery-grade Cu foil, battery-grade graphite, as well as solar-grade silicon if silicon is required for the anode (*i.e.*, Graphite (Si) anode).

The LCI data for upgrading industry-grade chemicals to battery-grade LiOH, battery-grade CoSO₄, and battery-grade NiSO₄ are based on the EverBatt model⁴⁸ developed by Argonne National Laboratory to assess the cost and environmental impacts during the battery life cycle. The LCIs of battery-grade Li₂CO₃, battery-grade MnSO₄, battery-grade Al foil, and battery-grade Cu foil are compiled using information from the China battery industry reports¹⁶⁵

IV. Component production. At the component production stage, the battery cell components, *i.e.*, cathode, anode, electrolyte, separator, and cell container, are produced from battery-grade materials. From the EverBatt model⁴⁸, we derive LCI data of cathode production from relevant battery-grade materials, including LFP, NCA, NCM111, NCM523, NCM622, and NCM811. These LCIs of cathode production are complemented by emissions inventory of nickel, cobalt, and manganese to air or water during cathode production (which is lost in the EverBatt model⁴⁸), using the information given in the China battery industry reports¹⁶⁵. In addition, we model the LCI of producing the NCM955 cathode based on that of NCM811 cathode, based on

their differences in material compositions.

V. Cell production. During this stage, all battery cell components are assembled into a complete cell. Our model for this stage considers material inputs and energy consumption. The material inputs are based on the composition of the battery cells as determined in previous work of the authors⁷. In cell production, electrical energy is used, and we need to account for the amount of electrical energy required to combine all battery components into a battery cell. There are only a few studies providing detailed energy consumption data for cell production, and they have large deviations¹⁶⁶. The total energy consumption per Wh cell production is highly influenced by production volumes, and could range from over 1000 Wh in the lab and pilot-scale to below 100 Wh on an industrial scale⁴⁰. Here, we use an average electricity consumption from 5 industrial-scale studies, *i.e.*, 74 Wh per Wh cell production¹⁶⁶.

3.3 Results and interpretation

3.3.1 GHG emissions

Fig. 3.2 shows the cradle-to-gate GHG emissions for producing 1 kWh of cell capacity in 2020 by type of battery chemistry and production region. From the figure, we find a significant variation in the cradle-to-gate GHG emissions per kWh of battery cell production in China, US, and EU in 2020. This is mainly due to a substantial difference in the share of renewable energy and resulting emission intensities for electricity used for battery cell production across the three regions. In 2020, the EU electricity mix has the lowest emission intensity (0.36 kg CO₂-Eq per kWh electricity), followed by the US (0.48 kg CO₂-Eq per kWh electricity) and China (0.72 kg CO₂-Eq per kWh electricity). As a consequence, the GHG emissions per kWh of battery cells produced in EU are 16%-18% lower than in the US, and 38%-41% lower than in China in 2020.

In addition to production regions, GHG emissions depend on battery chemistry as different materials and production processes are used. For instance, LFP does not require nickel, cobalt, and aluminum metals whose production is very energy-intensive and generates significant amounts of polluting emissions, while these metals are used for NCM and NCA cell production. For this reason, LFP cell production generates 20%-28% lower GHG emissions than NCA and NCM cells in terms of per kWh cell production, depending on the production region.

As a result, LFP cells produced in the EU can generate the lowest GHG emissions, while NCA and NCM cells produced in China can generate the highest emissions in 2020. There is a factor of ~2.2 between the lowest and highest GHG emissions per kWh of battery cell production in 2020.

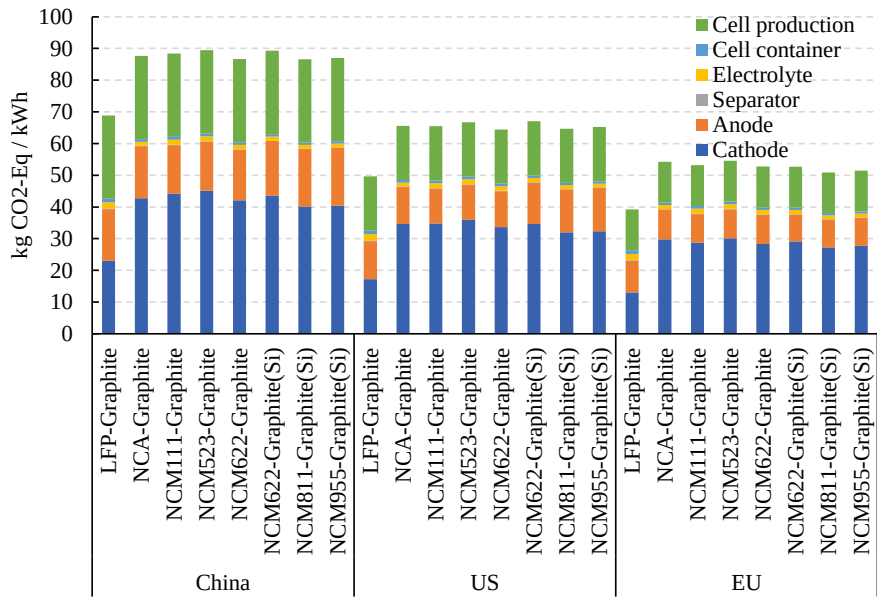


Fig. 3.2: Cradle-to-gate GHG emissions per kWh of cell production by battery chemistry and production region in 2020.

Future GHG emissions.

Given the similar GHG emissions of NCM and NCA chemistries, we show the future cradle-to-gate GHG emissions per kWh of battery cell production for two distinct chemistries in Fig. 3.3: LFP-Graphite cell and NCM622-Graphite cell (see results of other cell chemistries in Supplementary Fig. 3.3, Supplementary Fig. 3.4, and Supplementary Fig. 3.5). Mainly due to the development of renewable and low-carbon electricity used for cell production, the cradle-to-gate GHG emissions of cell production per 1 kWh capacity is significantly reduced significantly from 2020 to 2050. Depending on battery chemistry and production region, the GHG emissions could be reduced by 49%-52% under the SSP2-Base scenario in 2020-2050, and even 74%-81% under the SSP2-PkBudg 1100 scenario during the same period.

In addition, the absolute variation in GHG emissions between production region and battery chemistry is expected to decline between 2020 to 2050. In 2020, the cradle-to-gate GHG emissions range from 41 to 89 (difference of 48) kg CO₂-Eq per kWh battery cell capacity. In 2050, the cradle-to-gate GHG emissions range from 21 to 45 (difference of 24) kg CO₂-Eq per kWh battery cell capacity in the SSP2-Base scenario and from 10 to 17 (difference of 7) kg CO₂-Eq in SSP2-PkBudg 1100 scenario. Depending on energy scenarios, the corresponding absolute variation for GHG emissions in 2050 is 2-6.5 times lower than that in 2020.

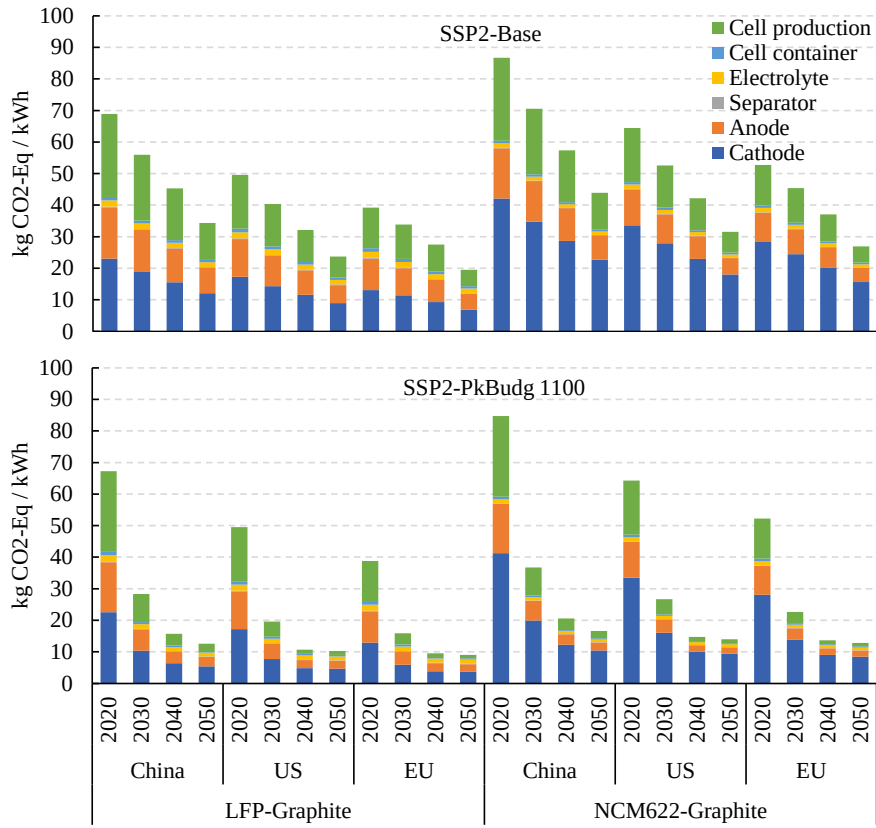


Fig. 3.3: Future GHG emissions per kWh of cell production for LFP-Graphite and NCM622-Graphite in China, EU, and US. Please see results for other cell chemistries in Supplementary Fig. 3.3, Supplementary Fig. 3.4, and Supplementary Fig. 3.5.

3.3.2 Contribution analysis of battery cell

Fig. 3.2 and Fig. 3.3 also present the contribution of different cell components to GHG emissions results. The cathode, anode, and cell production are the three most important contributors to GHG emissions. The relative contribution of the cathode for NCM/NCA cells is higher than that of LFP cells, while the relative contribution of the anode and cell production for LFP cells is higher than that of NCM/NCA cells. These are mainly due to different material compositions between NCM/NCA cells and LFP cells.

The NCM/NCA cathode is, with 46%-55% depending on battery chemistry and production region, the biggest contributor to GHG emissions in 2020, which is more than the total contributions from all other components. This is because NCM/NCA cathodes make up around 53%-59% of the weight of battery cells and also its production relates to the majority of metals contained in a battery cell which require GHG-intensive mining and refining processes (such as lithium, nickel, cobalt, and others). The NCM/NCA cathode is expected to remain the primary contributor to cradle-to-gate GHG emissions until 2050 (Fig. 3.3). Yet, its relative contribution is expected to increase to 49%-60% in the SSP2-Base scenario and 60%-70% in SSP2-PkBudg 1100 scenario during 2020-2050, depending on battery chemistry and production region.

Fig. 3.4 provides a relative contribution analysis by battery production life cycle stage. In 2020, the two most important life cycle stages from a GHG emissions perspective are "component production" followed by "cell production". They together account for 74%-83% of GHG emissions for LFP cells and 54%-69% for NCM/NCA cells, depending on production region/cell chemistry. These numbers could decrease to 39%-76% for LFP cells and 23%-61% for NCM/NCA cells depending on energy scenarios, due to the stronger effects of low-carbon energy development on life cycle stages of "cell production" and component production" rather than other life cycle stages.

"Mining and metals production" could become a significant life cycle stage for NCM/NCA cells in the future, especially when considering a stronger low-carbon energy development scenario. The SSP2-PkBudg 1100 scenario could result in "mining and metals production" as the primary life cycle stage to GHG emissions, accounting for 33%-42% of NCA cells and 24%-47% of NCM cells in 2050. Note that for NCM cells,

the future transition from NCM111 chemistry to NCM955 chemistry will improve the contribution of “mining and metals production” to GHG emissions. This transition increases the content of Ni with relatively high GHG emissions (7 kg CO₂-Eq in 2020 and 3-4.7 kg CO₂-Eq in 2050 per kg NiSO₄ globally) and decreases the content of Co with relatively low GHG emissions (2.7 kg CO₂-Eq in 2020 and 1.2-1.7 kg CO₂-Eq in 2050 per kg CoSO₄ globally) for NCM cells, resulting in an overall increase in GHG emission during the life cycle stage of “mining and metals production”.

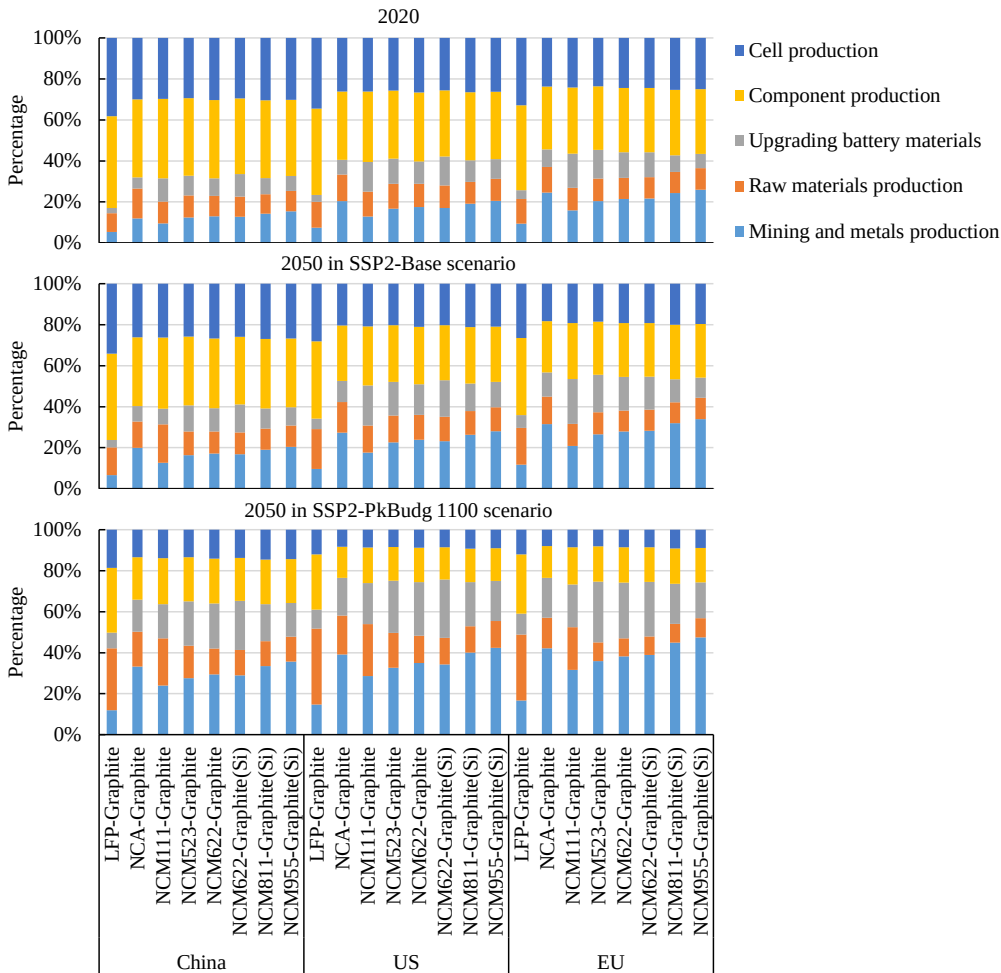


Fig. 3.4: GHG emission contributions by life cycle stage for different battery cell chemistries and production regions in 2020 and 2050.

3.3.3 Contribution analysis of cathode

Given the substantial contribution of the cathode in the battery GHG emissions, we perform an absolute contribution analysis for cathode disaggregated by life cycle stage, with each stage divided into energy and materials input. Fig. 3.5 presents the results for LFP and NCM622 cathodes produced in China in 2020 and 2050 (please see the results of US and EU in Supplementary Fig. 3.6 and Supplementary Fig. 3.7). The contribution analysis results differ a lot between LFP and NCM622 cathodes. For battery cells produced in China in 2020, the life cycle stage of “mining and metals production” and “cathode production” contributes to around 22% and 44% for NCM622 cathode respectively, while these numbers are 2% and 71% for LFP cathode.

In addition, the energy input dominates (around 78%) the cradle-to-gate GHG emissions of the LFP cathode, while the energy input and materials have almost equal contributions to GHG emissions for the NCM622 cathode in 2020. In the future, input materials, rather than input energy, will become more important contributors to GHG emissions due to the decarbonization of the electricity system. Input materials will even become the major source of cradle-to-gate GHG emissions for cathodes in 2050, with a relative contribution of up to 34%-81% for LFP cathodes and 52%-71% for NCM/NCA cathodes depending on energy scenarios/production regions/cell chemistries.

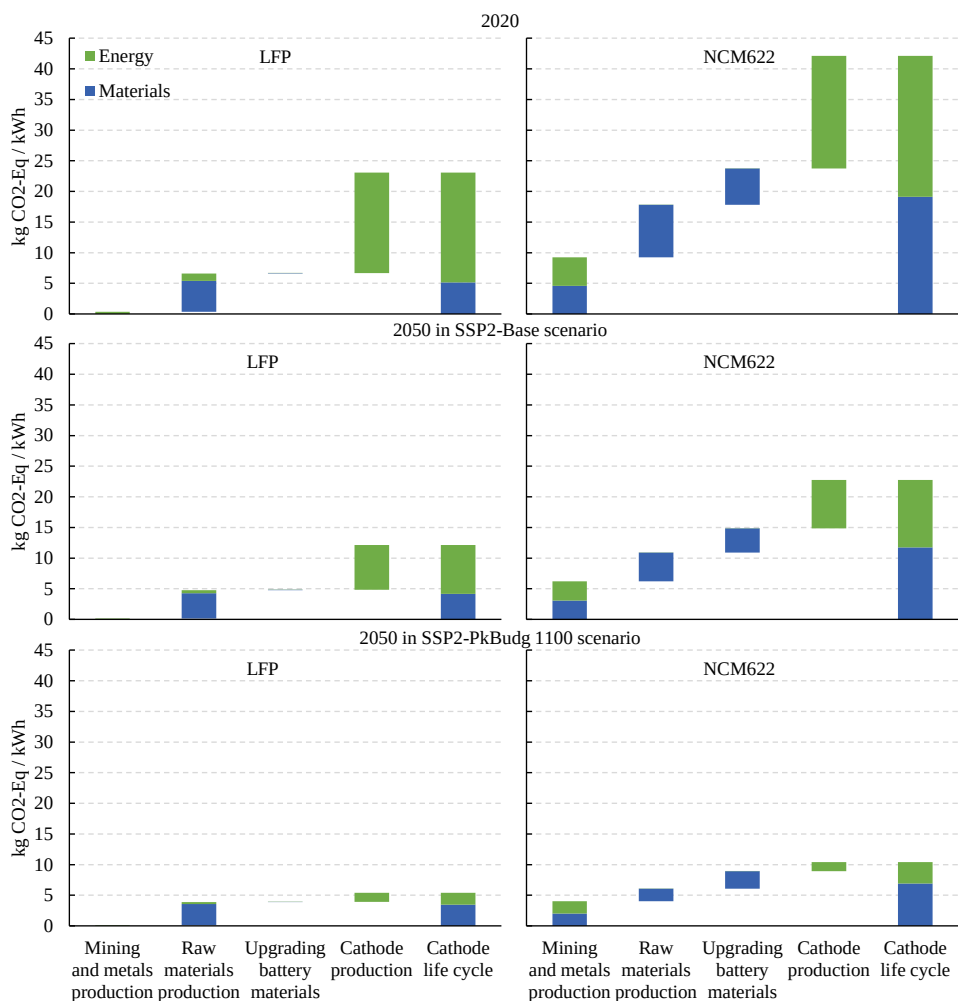


Fig. 3.5: Absolute contribution analysis of cradle-to-gate GHG emission of the cathode production for 1 kWh battery cell capacity by life cycle stages, divided by input energy and input materials, for LFP and NCM622-Graphite in China in 2020 and 2050. Please see results of US and EU in Supplementary Fig. 3.6 and Supplementary Fig. 3.7.

Fig. 3.6 further illustrates which specific materials and energy sources account for the GHG emissions for LFP and NCM622 cathodes. LiOH and electricity are key contributors to GHG emission of LFP cathodes. They together account for 82-86% in 2020 and 64%-82% in 2050 of GHG emissions for LFP cathodes, depending on the

production region. Taking the perspective of the production of the whole LFP cell, LiOH and electricity together contribute to 27%-29% in 2020 and 28%-35% in 2050 of GHG emissions for the production of LFP cells.

Looking at the cradle-to-gate GHG emissions of NCM622 cathode production, NiSO₄ and Li₂CO₃ materials, rather than CoSO₄ and other cathode materials, are important contributors. NiSO₄ and Li₂CO₃ can contribute to 18%-30% and 6%-11% of GHG emissions of NCM622 cathode in 2020 respectively. These numbers change to 25%-46% and 8%-21% in 2050, depending on the production region and energy scenarios. In other words, NiSO₄ and Li₂CO₃ can account for 16%-31% and 5%-14% of GHG emissions of NCM622 cells in 2050.

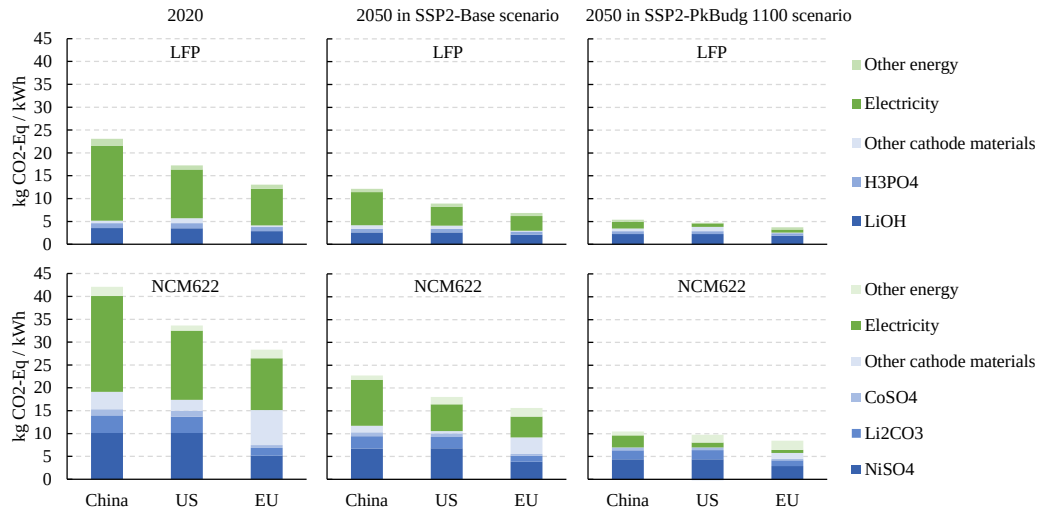


Fig. 3.6: Absolute contribution analysis of GHG emissions of the cathode production split by materials and energy, in terms of 1 kWh battery cell capacity.

3.4 Discussion

In this study, we build a prospective LCA model to quantify future cradle-to-gate GHG emissions per kWh battery cell production for 8 types of cell chemistries and 3 production regions until 2050. According to the pLCA model, our results for GHG emissions per kWh battery cell production (53-85 kg CO₂-Eq per kWh in 2020 and 10-45 kg CO₂-Eq per kWh in 2050) lie in the lower end of the range of earlier studies found in literature^{44,49,167} (28-356 kg CO₂-Eq per kWh). However, our results

compare well with the findings from the International Council of Clean Transportation ¹⁶⁸ (34-77 kg CO₂-Eq per kWh in 2021). There are various explanations for this. First, existing literature uses dated LCI data for battery cell production. Our modeling uses up-to-date LCI data based on the EverBatt model¹⁴⁸ and China battery industry reports in the period 2020-2022¹⁶⁵, which takes changes in battery chemistry next to cell production into account. Second, we take into account the effects of the low-carbon energy transition on battery production based on integrated assessment model REMIND. Results are intended to give reliable insights into future cradle-to-gate GHG emissions from battery cell production, which can form a basis for doing suggestions to further reduce impacts from this production.

Since LFP battery is expected to generate less GHG emissions than NCM/NCA batteries until 2050, one option is to support LFP battery deployment. The somewhat lower technical performance of LFP batteries compared to NCM/NCA batteries, in terms of specific energy (Wh/kg), may however be an obstacle for the large-scale deployment of LFP batteries. At the same time, advantages of LFP batteries are their relatively long useful lifetimes and low materials cost of LFP battery. Battery producers can take advantage of this, and at the same time invest in improving LFP battery performance. One example is that several battery producers started to improve the mass and space utilization of battery pack by removing modules and directly assembling cells into a pack (the LFP blade battery created by BYD can reach the specific energy of 140 Wh/kg at the pack level, which is higher than that of a standard NMC622 prismatic battery)¹⁶⁹.

Choosing battery production regions, which determine the electricity mix used to produce batteries, could be another important factor to consider for battery producers to reduce GHG emissions. China dominates the battery production market and is expected to continue so in the next decade. Reducing the emissions of China's electricity supply is key for achieving a lower GHG impact. EU and US provide greener electricity supply than China, and in theory, they are ideal regions for producing batteries with the lowest GHG emissions. However, it may not be possible to put a complete battery production supply chain in EU and US in the short term due to an uneven geographical distribution of extraction locations for primary materials required for batteries. Putting some part of the battery production life cycle stages in EU or US, rather than China, can be a pathway to start to reduce impacts of battery production.

This could be particularly considered for energy-intensive production stages such as cell production which uses electric energy to assemble all battery components into a complete cell.

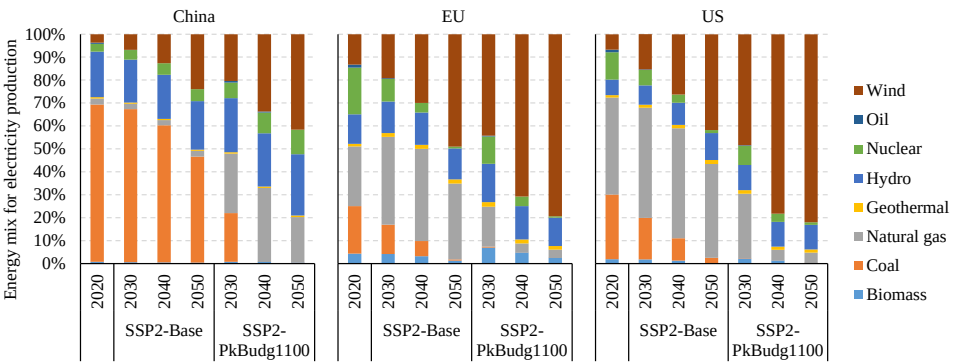
We must emphasize the crucial role of a low-carbon electricity transition for reducing GHG emissions of battery production, reflected by the results of SSP2-PkBudg 1100 scenario. The energy supply for battery production should be as carbon-neutral as possible. For instance, Tesla's announced Giga watt-hour battery production factory is planned to be built together with a solar energy supply facility¹⁷⁰. In this case, a 100% supply of solar power for battery production is ensured, which can lead to extremely low GHG emissions.

Given the major contribution of the use of NiSO_4 and Li_2CO_3 to the GHG emissions of the production of NCM/NCA batteries and of the use of LiOH to the production of LFP batteries, reduction of GHG emissions along the supply chain of Ni and Li metals is relevant too. Replacing fossil fuels with renewable electricity, improving energy efficiency, as well as controlling and capturing the GHG emissions during nickel mining and refining can be effective approaches to reduce impacts of NiSO_4 production. We can apply similar approaches to Li. Moreover, Li_2CO_3 produced from the leaching of spodumene with sulfuric acid can generate less GHG emission as when it is produced from concentrated brine¹⁷¹. The spodumene leaching pathway has currently still a minor market share of the Li_2CO_3 production market. Promoting this pathway is another option to reduce GHG emissions related to LFP battery production.

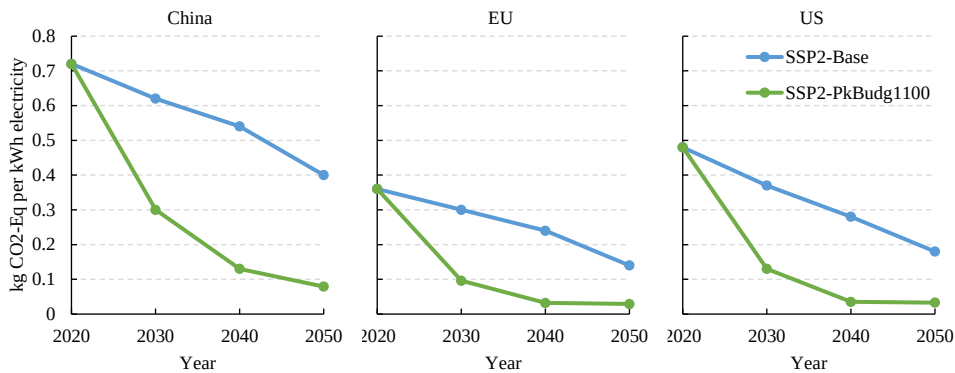
There are some future developments, which we did not consider in this study. Firstly, although we included a wide range of scenarios for battery chemistries, metal production, and energy generation, other scenarios may play out in the future (*e.g.*, lower or deeper decarbonisation of the energy system, or low-impact production processes for certain materials, such as the application of inert anodes in the Hall-Herault process for aluminum production¹⁷²). Secondly, it is possible that the expected fast scaling up to high-volume production of the batteries considered in this study leads to considerable learning effects. This can result in significant efficiency improvements and lower costs and impacts, for instance by using automated manufacturing technologies using robots¹⁷³. Thirdly, the development of new breakthrough battery technologies, such as solid-state Lithium-Sulphur and Lithium-

Air batteries ¹⁷⁴, Na-ion¹⁷⁵, etc., may create radical changes in battery production processes and relevant materials supply chains. It is currently unclear if such technologies indeed will break through. There is further insufficient experience with such novel battery technologies to make a reliable quantitative estimate of life cycle inventory data, while also little is known about the impacts of such novel battery technologies once they have been scaled up from lab or pilot scale to full production plants.

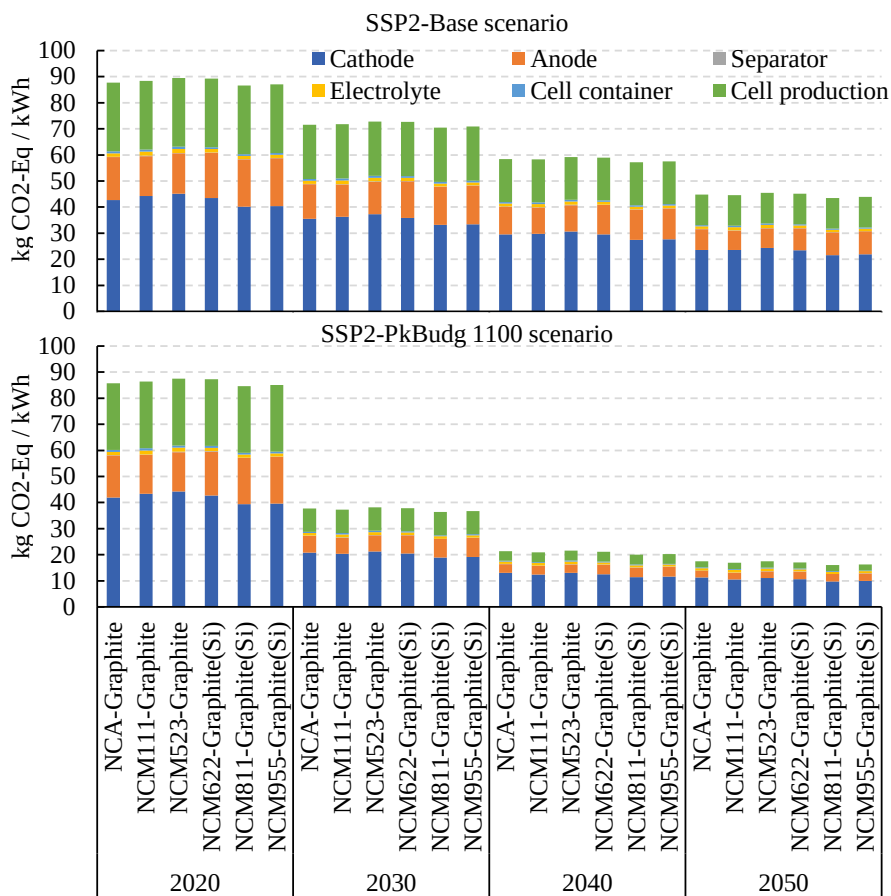
3.5 Supplementary information



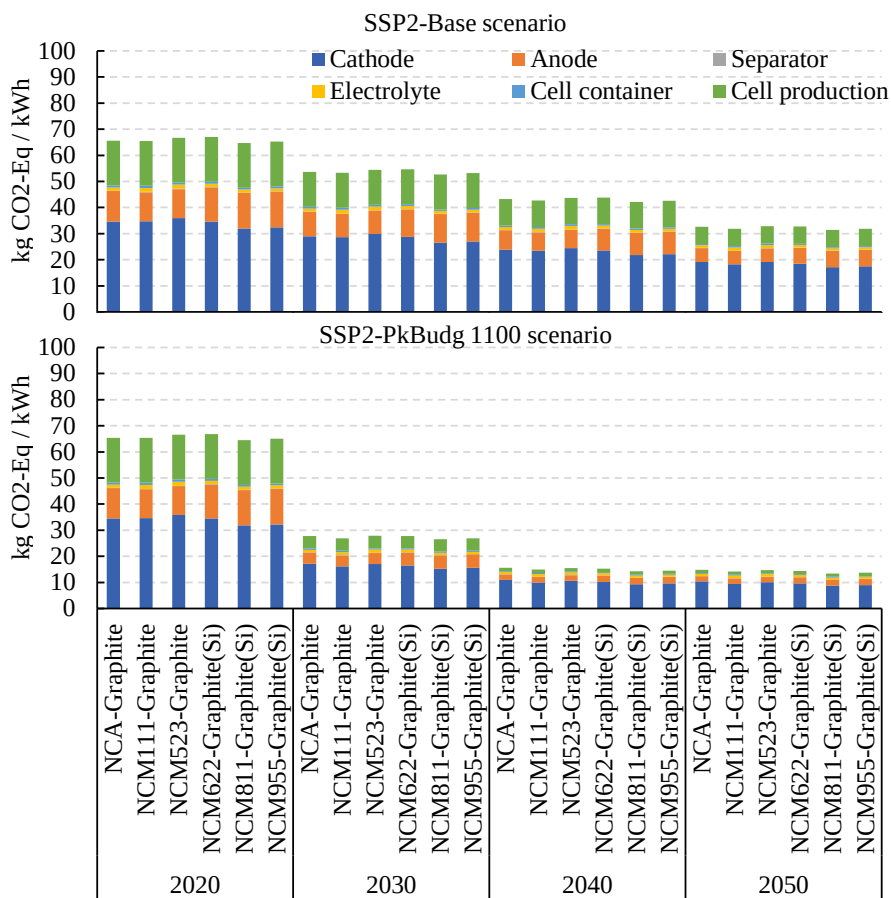
Supplementary Fig. 3.1: Regional energy mix for electricity production in SSP2-Base and SSP2-PkBudg1100 scenarios.



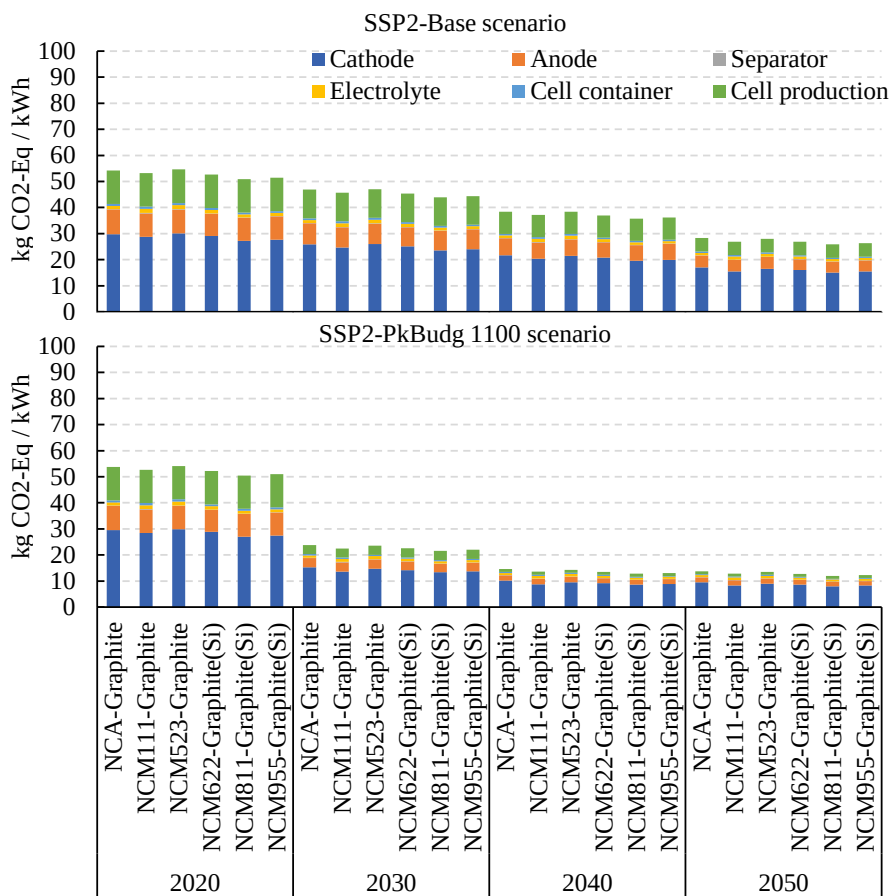
Supplementary Fig. 3.2: Regional GHG emissions per kWh electricity production in SSP2-Base and SSP2-PkBudg1100 scenarios.



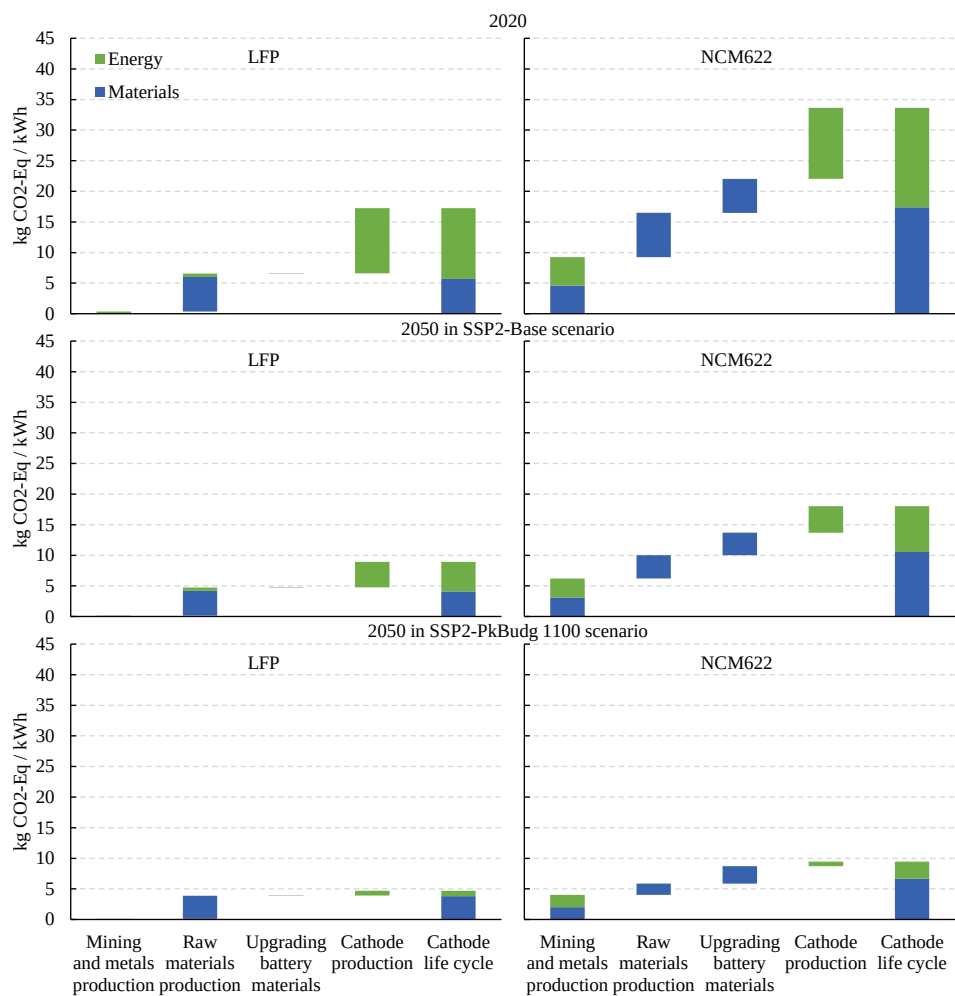
Supplementary Fig. 3.3: Future GHG emissions per kWh of cell production by different cell chemistries in China.



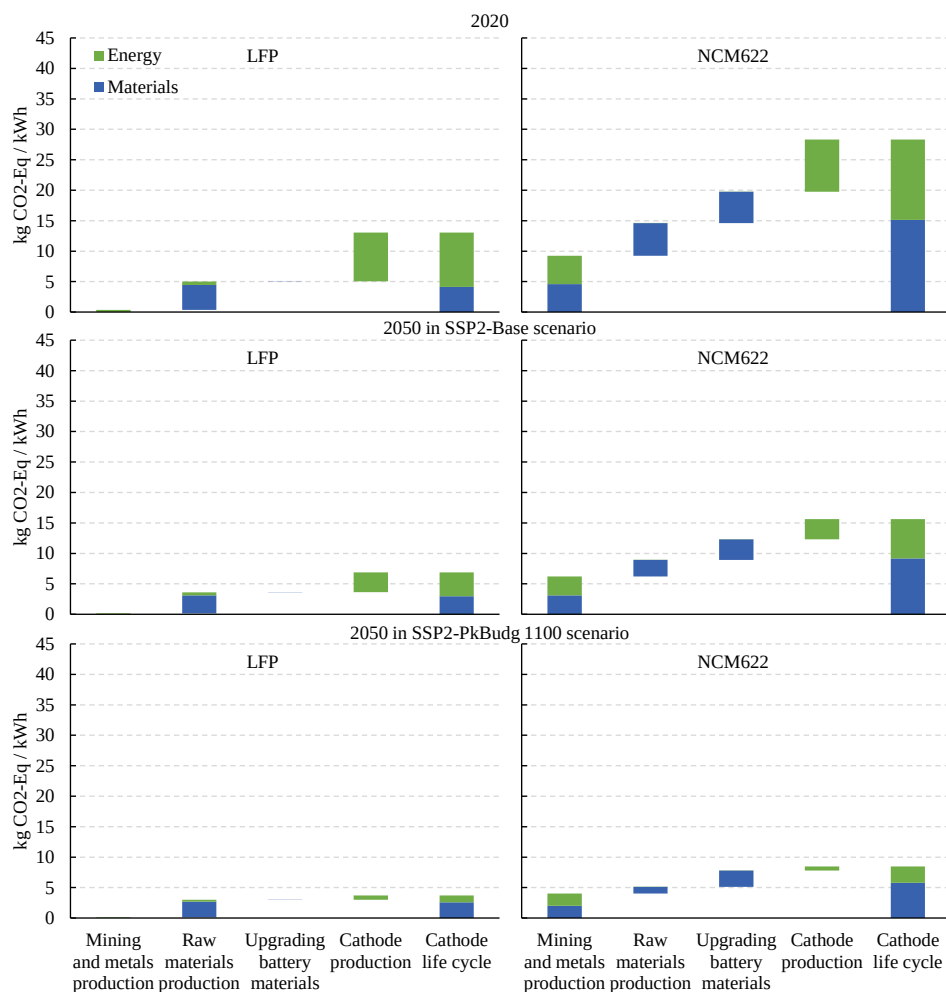
Supplementary Fig. 3.4: Future GHG emissions per kWh of cell production by different cell chemistries in US.



Supplementary Fig. 3.5: Future GHG emissions per kWh of cell production by different cell chemistries in EU.



Supplementary Fig. 3.6: Absolute contribution analysis of cradle-to-gate GHG emission of the cathode production for 1 kWh battery cell capacity by life cycle stages, divided by input energy and input materials, for LFP and NCM622-Graphite in US in 2020 and 2050.



Supplementary Fig. 3.7: Absolute contribution analysis of cradle-to-gate GHG emission of the cathode production for 1 kWh battery cell capacity by life cycle stages, divided by input energy and input materials, for LFP and NCM622-Graphite in EU in 2020 and 2050.