Dynamic Life Cycle Assessment of Lithium-ion Batteries for Electric Vehicles

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Abstract

Demand for battery electric vehicles (BEVs) is growing as part of the drive to decarbonise transportation. This could in turn significantly increase demand for metals and other materials that are energy-intensive to produce (from mining to manufacturing). A sustainable low-carbon transition will require a comprehensive understanding of the current and future global environmental impacts of lithium-ion batteries. This thesis analyses the cradle-to-gate life cycle energy use and greenhouse gas (GHG) emissions of current nickel-manganese-cobalt and lithium-iron-phosphate battery technologies. We consider existing battery supply chains and future electricity grid decarbonisation prospects for specific countries involved in materials mining and battery production. Currently, around 60% of the total global GHG emissions associated with battery manufacturing are highly concentrated in three countries: China (37%), driven by battery assembly and material refining; Indonesia (13%) due to nickel production; and Australia (12%), due to lithium, nickel, and aluminium production. On a unit basis, projected electric grid decarbonisation could reduce GHG emissions of future battery production by up to 38% by 2050. An aggressive BEV uptake, as per the International Energy Agency's Sustainable Development Scenario (SDS), could result in cumulative GHG emissions of 8.2 $GtCO_2eq$ by 2050 due to the manufacturing of nickel-based chemistries. However, a switch to LFP-based chemistry could enable a GHG emission saving of about 1.5 $GtCO_2eq$. This study offers a solid basis for more detailed market-specific environmental assessments of battery supply chains. Secondary materials, via recycling, can help reduce primary supply requirements and alleviate the environmental burdens associated with the extraction and processing of materials from primary sources, where direct recycling offers the lowest impacts, followed by hydrometallurgical and pyrometallurgical, reducing GHG emissions by 61%, 51% and 17%, respectively, compared to primary production.

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Nomenclature

Name	**Abbreviation**
ANL	Argonne National Laboratory
BEV	Battery electric vehicle
BGS	British Geological Survey
BMS	Battery Management System
BOM	Bill-of-material
CH4	Methane
CO_2	Carbon dioxide
CO_2eq	Carbon dioxide equivalent
$CoSO_4$	Cobalt sulfate
EU	European Union
GHG	Greenhouse gases
GREET	Greenhouse gases, Regulated Emissions, and Energy use in Technologies
GWh	Gigawatt hour
H_3PO_4	Phosphoric Acid
ICEV	Internal combustion engine vehicle
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
kgCO_2eq	Kilograms of carbon dioxide equivalent
kWh	Kilowatt hour
LCA	Life cycle assessment

LCI	Life cycle inventory
LFP	Lithium iron phosphate
LIB	Lithium-ion battery
Li_2CO_3	Lithium carbonate
LiOH	Lithium hydroxide
$MnSO_4$	Manganese sulfate
MJ	Megajoule
$MtCO_2eq$	Million tonnes of carbon dioxide equivalent
N_2O	Nitrous oxide
NCA	Lithium nickel cobalt aluminium oxide
$NiSO_4$	Nickel sulfate
NMC	Lithium nickel manganese cobalt oxide
PED	Primary Energy Demand
SDG	Sustainable Development Goals
SDS	Sustainable Development Scenario
SPS	Stated Policies Scenario
T&D	Transmission and distribution
TWh	Terawatt hour
US	United States
USGS	United States Geological Survey
WEO	World energy Outlook

CHAPTER 1 Introduction

1.1 Background

To achieve a successful sustainable energy transition, the world will require significant volumes of metals and other materials produced using low-carbon technologies. The push to electrify transport and the rise of battery electric vehicles (BEVs) will be a key driving force behind this growing demand for low-carbon materials (Sovacool *et al.*, 2020). The global BEV fleet is expected to increase from 1.2 million in 2015 to 965 million in 2050, significantly boosting demand for critical raw materials and supply risk of these resources to the whole supply chain that entails the country-level concentration of primary raw materials for battery manufacturing (Berkeley *et al.*, 2017; IRENA, 2020). BEVs have zero tailpipe emissions, but they are not without environmental impact. Elsewhere in the global supply chain, greenhouse gas emissions are released, especially during the production of materials and battery manufacture. The mining and refining of materials, cell manufacturing, and battery assembly processes together account for 10-30% of the total life cycle emissions of a BEV (IEA, 2020b). These negative externalities (e.g., GHG emissions, resource availability concerns) could potentially offset the absolute benefit of using BEVs to replace internal combustion engine vehicles (ICEVs). This thesis develops dynamic methods to better understand the life cycle impacts of battery manufacture across the global value chain and their change over time to 2050. The following paragraphs introduce the importance of BEVs and the need to understanding their related sustainability concerns from a life cycle perspective: Lithium-ion batteries, life cycle assessment method, the role of electricity in battery production, battery supply chain, battery technology development, and battery end-of-life.

Lithium-ion batteries. Lithium-ion batteries (LIBs) are currently the leading energy storage systems in BEVs and are projected to grow significantly in the foreseeable future. They are composed of a cathode, usually containing a mix of lithium, nickel, cobalt, and manganese; an anode, made of graphite; a liquid electrolyte, comprised of lithium salts, and a separator. Aluminium and copper are also major materials present in the pack components. LIBs are commonly labelled by their cathode chemistry where the most popular types are lithium cobalt oxide (LCO), lithium manganese oxide (LMO), lithium iron phosphate (LFP), lithium nickel cobalt aluminium (NCA) and lithium nickel manganese cobalt (NMC) (Miao *et al.*, 2019b).

The European Commission produced the European Union (EU) list of Critical Raw Materials that contains a total of 30 materials that are important to the EU's economic growth and have a concerning supply risk. This list includes key battery materials including cobalt, graphite, phosphate rock, and lithium.(European Commission, 2020c). Manufacturers have been transitioning towards high-nickel cathodes and lower cobalt content to handle risks associated with its complex supply chain due to elevated prices and concerns about inappropriate mining practices. The rapid surge of battery production capacity has attracted attention in the whole battery supply chain stages: from raw material mining, processing and refining, cell component production, battery assembly, and recycling and re-use of critical materials (IEA, 2022c). Therefore, this thesis presents a modelling framework to evaluate the life-cycle environmental impacts (mainly primary energy demand and GHG emissions) associated with LIB manufacturing of different chemistries, to detect the more impactful materials and activities.

Life Cycle Assessment (LCA). LCA is a standardised method to identify and quantify the potential environmental impacts (e.g., resource use, energy flows and associated emissions released) of a product or a system for all life cycle phases from initial resource extraction, raw material processing, manufacture, use of the product, and end-of-life (ISO, 2006). LCA offers the need for a more holistic perspective to support comprehensive and robust tools that assist decision-makers identify the solutions that best support a sustainable battery production (Hasuchild, Rosenbaum and Olsen, 2018). At its core, LCA has been carried out for measuring the environmental impacts of batteries for electric vehicles and to identify key drivers in their production. Impacts are commonly compared on the basis of a functional unit (e.g., one kWh of battery or one kg of battery material). However, benchmarking LCA results for batteries is challenging due to the lack of primary data and ambiguous methodological preferences (e.g., wide range of system boundaries, functional units, primary data, etc.) leading to difficulties when cross-comparing results (Kim *et al.*, 2016; Dai, Kelly, *et al.*, 2019b; Porzio and Scown, 2021). The reported GHG emissions greatly differ in the range of 39-487 kgCO_2eq/kWh battery (Notter *et al.*, 2010; Majeau-Bettez, Hawkins and StrØmman, 2011; Dunn *et al.*, 2012; Ellingsen *et al.*, 2014; Peters *et al.*, 2017). These differences vary mainly in the assumed regional acquisition of raw materials, the regional production stages and the electricity mix in these regions. Therefore, LCA's are evolving and the need for a consensus in the battery LCA field is required to allow for meaningful interpretations respecting the boundaries of the scope, e.g., geographical, temporal, or technological assumptions.

The role of electricity in battery production. Given the rapid-growing penetration of BEVs, the electricity sector will play a major role on the transport sector in the upcoming years, not only for the BEV use phase but for the key battery materials production processes (i.e., mining and refining) and battery manufacturing processes, which are known to be energy intensive. Consequently, the GHG emissions associated with these activities are highly likely to be driven by the energy inputs, electricity in particular, which accounts for a substantial share of life cycle GHG emissions (Dai, Kelly, *et al.*, 2019b). Meaning that efforts to decarbonise the electricity sector can highly contribute to reducing the overall life cycle GHG emissions from BEVs in the future. The electricity mix varies across geographic regions, and although average global carbon intensity for electricity generation can provide an estimate, a better understating of the implications of region or country-specific electricity carbon intensity is necessary to inform decision-makers in the importance of electricity in the battery systems. Location (regional grid mix) and time (future decarbonisation) will impact the GHG emissions of producing materials, components, and batteries. In that regard, this thesis lays out how the GHG emissions associated with LIB material mining and refining activities are sensitive to differences in the electricity mix across geographic regions, and the expected GHG emission reductions towards 2050 by anticipated decarbonisation of the electricity sector.

Supply chain of batteries. Supply chains of LIB materials are characterised by highly global trade, with energy-intensive activities related to ore extraction, processing, and refining taking place across a wide range of locations globally (IEA, 2019, 2022c). This complex supply chain creates uncertainty in the LCA analyses due to the high variability between different production routes. Key materials used in a LIB include nickel, cobalt, manganese, graphite, and lithium. These materials are produced and refined in different parts of the world where the clarity and resolution of understanding the LIB's life cycle production impacts will differ depending on the location. However, the geographical distribution of key battery materials is sufficiently diverse to require detailed consideration of the multiple locations where each material is mined and processed throughout the supply chain to derive global-average climate change impact of LIBs. Global-average impacts are important because they reveal the current state of LIBs manufacturing, whilst keeping consistency with previous studies. However, detailed emission factors for specific supply chains become more important because they allow quantification of current and future energy and GHG emissions of battery manufacturing. Toward this goal, this thesis develops analytical methods to improve awareness of the impacts of battery production considering specific spatial distribution of battery materials by acknowledging where the emissions are occurring across the supply chain, based on the upstream material mining and refining activities and on the electricity mix used, and opportunities to alleviate the emissions by considering the least impactful geographic regions.

Battery technology development. The battery chemistry defines the performance, specific energy (Wh/kg), the material requirements, and the cost of a battery. Various battery chemistries are of current relevance including lithium nickel manganese cobalt (NMC), nickel cobalt aluminium (NCA), and lithium iron phosphate (LFP) (Miao *et al.*, 2019b). As of 2021, NMC and NCA chemistries were dominating the BEV market, given their high energy density provided by the high nickel content (IEA, 2022b). However, due to the increasing metal prices coupled with battery producers moving away on cobalt due to supply issues, LFP has reappeared on the battery roadmap as a potential candidate to gain fleet size in the future BEV market (Ryu *et al.*, 2021; IEA, 2022c). Whilst LFP batteries have lower energy density compared to nickel-based batteries, LFP offers cost advantages. Thus, to evaluate the potential impacts and challenges of future BEV market, the mix of different battery chemistries that are expected to become dominant in different points in time are taken into account. In this regard, this thesis models the dynamic battery manufacturing system considering projected technology uptake of competing battery chemistries and market shares in the future.

End-of-life of batteries. Recycling poses a great potential by recovering valuable battery materials to supply secondary materials and incorporate them into the battery supply chain (i.e., closed-loop recycling) (Harper *et al.*, 2019). Secondary supply, via recycling from end-of-life (EoL) batteries, can help reduce primary supply requirements and alleviate the environmental burdens associated with the mining and refining of materials from primary sources. However, although recycling offers useful complementary resources, it can only provide a smallish fraction of demand, meaning that recycling will not be able to cope the expanding demand (Bloodworth, 2014). The technical limitations of recycling are susceptible to the battery chemistry and the various recycling methods, which recover different materials at different rates and efficiencies (Dai *et al.*, 2019; Harper *et al.*, 2019). This thesis, lays into context the potential GHG emissions reductions of battery manufacturing using secondary materials.

1.2 Aims and Objectives

To fulfil the aforementioned research gaps, the aim of this thesis is to investigate the life cycle environmental impacts of the LIB manufacturing process for different battery chemistries to detect environmental hotspots (i.e., activities and materials largest overall contributors) throughout their life cycle, emphasizing spatial and temporal resolution (i.e., geographically-specific emissions of current and future processes) due to anticipated uptake of competing battery chemistries and decarbonisation of the electricity sector; and the environmental benefits of recycling using secondary materials for spent LIBs. The framework aims to address the following research questions:

1. Which battery chemistry provides the least GHG emissions and which materials contribute the highest GHG emissions to the overall cradle-to-gate manufacturing process?
2. In which geographical locations are these emissions expected to occur for different battery chemistries?
3. How are the future global GHG emissions expected to change towards 2050 by decarbonising the electricity sector and considering various battery technology scenarios?
4. What are the GHG emissions reductions of battery manufacture using secondary materials via different recycling technologies?

These research questions are addressed by investigating the likely contribution of battery-related emissions in the future, drivers of these emissions, and possible methods for mitigation.

The implications of decarbonising the electricity sector over time are explored looking at different battery market shares to 2050 and looking at the variability of GHG emissions impact depending on source across the supply chain. Finally, the emissions from primary and secondary battery manufacturing are compared, using different recycling methods and their implications of decarbonising the electricity sector in the future.

The thesis has four objectives:

i. Develop geographically explicit life cycle assessment model of lithium-ion battery manufacturing supply chain for different chemistries.
ii. Develop dynamic, forward-looking life cycle assessment models of battery manufacturing considering decarbonisation of the electricity sector to 2050.
iii. Incorporate anticipated battery chemistry market shares in life cycle assessment model to 2050.
iv. Develop current and future life cycle assessment of closed-loop recycling and battery manufacture using secondary materials considering decarbonisation of the electricity sector to 2050.

1.3 Journal Papers

- Llamas-Orozco, J.A., Meng, F., Walker, G.S., Adbul-Manan, A.F.N., MacLean, H.L., Posen, D., McKechnie, J. “Estimating the environmental impacts of lithium-ion battery supply chain: a temporal, geographical, and technological perspective”. *Pending review*, 2023.

1.4 Attended Conferences

- University Consortium on Engineering Education and Research 2022 (UCEER)- A global PhD Conference. Virtual Conference, oral presentation. Llamas-Orozco, J.A., McKechnie, J., Meng, F. “Life Cycle Assessment of lithium-ion for Electric Vehicles” 12-14 April 2022.
- Smart Energy and Decarbonisation Summer School. Organised by Decarbon8 through the Engineering and Physical Sciences Research Council (EPSRC). 7-8 June 2022, Durham and Newcastle, UK.
- UK Energy Research Centre (UKERC). In-person, poster presentation. Llamas-Orozco, J.A., McKechnie, J., Meng, F., Walker, G.S., “Supply chain environmental impacts of lithium-ion batteries production and future emissions” 13 June 2022, Manchester, UK.
- Visit to University of Toronto as visiting researchers as part of the Electrification of the UK light duty vehicle fleet project. 14-17 June 2022.
- International Symposium on Sustainability Systems and Technologies (ISSST). In-person, oral presentation. Llamas-Orozco, J.A., McKechnie, J., Meng, F., Walker, G.S., “Global Supply chain emissions of lithium-ion batteries production”. Pittsburgh, Pennsylvania, USA. 21-23 June 2022. Dr. Ben Davies presented on my behalf because of US visa issues.
- 3rd Life Cycle Innovation Conference (LCIC). In-person, oral presentation. Llamas-Orozco, J.A., McKechnie, J., Meng, F., Walker, G.S., “Estimating the environmental impacts of lithium-ion battery supply chain: a temporal, geographical, and technological perspective”. Berlin, Germany. 29 June - 1 July 2022.

- Accelerating the Decarbonisation of Mobility: Working Across Boundaries Summer School. 27-29 September 2022. York, UK. Organised by Decarbon8 through the Engineering and Physical Sciences Research Council (EPSRC).

1.5 Outline of thesis

A total of 6 chapters are included in this thesis, with regard to the research questions mentioned previously.

Chapter 1 lays out the introduction to the general topic of the thesis including description of aim and objectives and research questions.

Chapter 2 contains the literature review of lithium-ion battery technologies for electric vehicles, existing life cycle assessment studies on batteries, battery supply chain issues, the role of the electricity carbon intensity, and recycling technologies.

Chapter 3 presents the methods and the modelling framework for the evaluation of current and future environmental impacts of battery manufacture and battery recycling. Life cycle inventories for LIB materials and manufacturing activities are coupled with data on the location of activities and location-specific emissions factors for energy and material inputs to assess the global GHG emissions implications of battery manufacture. A forward-looking analysis considers how the mix of LIB chemistries and background energy systems will drive future GHG emissions trends.

Chapter 4 describes the life cycle assessment of several LIB technologies providing spatial and temporal resolution to quantify where in the global supply chain materials and manufacturing processes take place, the environmental impacts associated with these activities, and how these emissions are expected to vary over time due to anticipated uptake of competing battery chemistries and decarbonisation of the electricity sector to 2050.

Chapter 5 describes the environmental impacts of secondary battery material from the recycling processes of LIBs with different battery chemistries. In addition, a GHG emission comparison from the different recycling processes, and two distinct scenarios to evaluate the environmental benefits of secondary battery materials are carried out.

Chapter 6 discusses the general conclusions and the main take-home points of the research.

CHAPTER 2 LITERATURE REVIEW

2.1 Introduction

This chapter provides background information on the state-of-the-art of lithium-ion batteries for electric vehicles, literature reviews related to life cycle assessment (LCA), material supply chain of batteries, electricity generation and their carbon intensity, and the role of battery recycling.

2.2 Battery Electric Vehicles Technology State of the Art

2.2.1 Electric Vehicles

In 2021, the transport sector accounted for 37% of global carbon dioxide (CO_2), ~7.7 Gt CO_2, from main energy end-use sectors. Road vehicles, accounted for 76.6% of the total transport emissions, where passenger vehicles (e.g., cars, buses, motorcycles) contributed 46.4% and freight vehicles (e.g., trucks, lorries) 30.2%.(IEA, 2022d). The expanding transport sector requires excessive energy requirements, which mostly relies on petroleum. Hence, the main challenge the world seeks is to satisfy the transport demand while ensuring energy security and minimise the urgent damage to the environment caused by fossil fuel burning. Electric vehicles (EVs), including battery electric vehicles (BEVs) and plug-in hybrid electric vehicle (PHEVs), have been hailed as a suitable solution to decarbonise and revolutionise the transport sector since they can alleviate the energy consumption and environmental impacts, particularly when the electricity used to charge the BEV comes from low-emission renewable energy sources (Notter *et al.*, 2010; Faria *et al.*, 2013; Hawkins *et al.*, 2013; Bauer *et al.*, 2015).

The global BEV fleet is expected to increase from 1.2 million in 2015 to 965 million in 2050, significantly boosting material demand for battery manufacturing (IRENA, 2020). In 2021, 6.6

million electric vehicles (EV) were sold, this is twice as many compared to 2020, accounting for almost 10% of global vehicle sales. China and Europe combined reported over 85% of global EV sales, while North America accounted for 10% (IEA, 2022b). Governments around the world have announced to completely phase out the sales or registrations of new internal combustion engine (ICE) vehicles in the next years (ICCT, 2021) . Thus, pushing towards the electrification of their vehicle fleet. For example, the UK has pledged to ban new sales of ICE petrol and diesel cars by 2030 (BEIS, 2020), same as Iceland, Ireland, Sweden and the Netherlands (ICCT, 2021). Norway holds the most ambitious target, demanding new vehicles to be fully zero emission at the tailpipe by 2025 (ICCT, 2021). Given the projected size of the global EV market, massive expansion of battery manufacturing and charging infrastructure will be a crucial driver towards a sustainable and zero emission mobility sector. At the moment, these strategies do not mention raw materials security and supply, and does not take into account the whole life-cycle of a vehicle and their associated environmental impacts.

The race to net-zero and the increasing need for global rapid shift towards BEVs to decarbonise the transport sector will concentrate around the resource security on critical materials and their associated environmental impacts.

2.2.2 Outline of Lithium-ion Batteries

Due to the massive use of laptops and mobile phones, lithium-ion batteries (LIBs) have become one of the most popular batteries in world. However, they are relatively new compared to conventional batteries such as lead-acid batteries that have been manufactured for one and a half centuries (Rand, Woods and Dell, 1998). In the early 1990s, LIBs started to gain acceptance and popularity and consequently first commercialised in Japan (LeVine, 2015).

In essence, a LIB is defined as a rechargeable energy storage device that uses lithium ions acting as charge carriers through intercalation and insertion reactions from a positive and a negative electrode (Horiba, 2014). During discharge process, the electrons move from the negative electrode (anode) to a current collector to the load, and then via a second current collector the positive electrode (cathode). Simultaneously, the anode releases Li-ions through the electrolyte to the cathode in order to preserve electroneutrality. Similarly, during charge process, the electron current and Li-ion flow is inverted. These events are referred to as insertion and extraction reactions (Miao *et al.*, 2019b).

The main components of a LIB are positive electrode (cathode), negative electrode (anode), electrolyte and separator. The cathode contains key materials including lithium, nickel, manganese, and cobalt. The anode is commonly formed from carbon materials such as graphite, although some batteries have used metal oxides such as lithium titanate (LTO) (Horiba, 2014). There are some ongoing research in anode novel materials such as lithium-air, lithium-silicon, lithium-metal, lithium-sulfur, batteries which are expected to be commercialized and enter the BEV market in the next decade (Benveniste *et al.*, 2018; Imanishi and Yamamoto, 2019; Wang *et al.*, 2019, 2020; Xu *et al.*, 2020). The electrolyte provides the channel for the ions transfer that generates energy (Keshan, Thornburg and Ustun, 2016). An electrolyte is generally integrated of a mixture of lithium salts (e.g., LiPF6) and organic solvents (e.g., ethyl and propylene carbonate). Besides, under use conditions the electrolyte must offer the maximum lithium ion transfer, e.g., LIB to +60ºC heated when a combination of heat generated by charging and environmental conditions, or -30ºC to a parked EV in severe cold (Miao *et al.*, 2019b). The separator is usually a separating membrane that allows the transfer of Li-ions between the electrodes, thus preventing the contact between them and avoiding an internal short circuit (Hannan *et al.*, 2018; Miao *et al.*, 2019b).

Although there is still a lot of room for improvement, lithium-ion batteries (LIB) have become an established and reliable technology that allows to store energy in the short-term and to utilise it on demand (Bobba *et al.*, 2020; Schill, 2020). The price of an electric vehicle (EV) is affected by the price of the battery, which make up 40%, and cathode materials account for about a quarter of the battery total cost. This implies that the supply and availability of key materials for battery production becomes essential for the global sustainable energy transition (IEA, 2022c).

The three main LIB cathode chemistries used in current BEVs are lithium-nickel-manganese-cobalt-oxide (NMC), lithium-nickel-cobalt-aluminium (NCA), and lithium-iron-phosphate (LFP). The most commonly-used LIB today is NMC (International Energy Agency, 2018), a leading technology used in many BEVs such as the Nissan Leaf, Chevy Volt and BMW i3, accounting for 71% of global battery sales (Dai, Kelly, *et al.*, 2019b; International Energy Agency, 2021). NMC batteries are favoured for their relatively high specific energy: nickel improves the specific energy of NMC but at the expense of the battery’s stability; on the other hand, manganese delivers good stability while compromising its specific energy (Hannan *et al.*, 2018). LIB manufacturers are transitioning towards lower-cobalt cathodes, which has led to an evolution from NMC111 to NMC523, NMC622, NMC811, and, lately, NMC955 which is estimated to be ready for commercialisation by 2030 (The Investor, 2020; U.S. DOE, 2020). The three different numbers -111, 622 and 811 indicate the ratio of nickel, manganese, and cobalt, respectively. There is a trend towards cathodes with higher nickel content as battery producers increasingly thrift on cobalt due to supply issues (Miao *et al.*, 2019b). The nickel-cobalt-aluminium (NCA) cathode is commonly used in Tesla vehicles, while Volkswagen typically favours NMCs.

However, LFP batteries are also being considered favourably for BEVs given their relatively low material cost and high abundance, e.g. Tesla, recently announced the use of LFP batteries in its Model 3 (CNBC, 2021). With the expiry of the LFP patent in 2022 (TechCrunch, 2021), major automotive manufacturers outside of China are showing interest in LFP batteries, particularly for entry-level high-volume BEVs, given their cost advantages (CNBC, 2021)

(Insights, 2021)**.** LFP batteries are mostly used in BEVs in China, but battery productions in Europe and North America are likely to shift to LFP to meet projected demand growth. Whilst LFP batteries have lower energy density than BEVs with nickel-based LIB chemistry, interest in LFPs is growing, mainly driven by their cost advantage. LFP is still exposed to rising lithium prices, but it does not contain nickel and cobalt, thus avoiding price and market volatilities typically associated with these commodities (IEA, 2022c). Moreover, the latest cell-to-pack technology innovation could reportedly increase the energy density of an LFP to about 85% of that of an NMC811 battery (Green Car Reports, 2022). The future market share of BEVs chemistries will vary depending on the on the technological breakthroughs and on the raw material availability. This study assesses the variations over time of cathode technologies only, and does not consider anode and electrolyte potential future technologies.

2.3 Life Cycle Assessment studies

In the last decade, many life cycle assessment studies have been conducted to assess the cradle-to-gate environmental impacts of existing LIB technologies. The reported GHG emissions greatly differ in the range of 39-487 kgCO_2eq/kWh battery, as shown in **Table 1**. These variations are due to uncertainties in many factors including battery specifications and different technologies, geographical locations, life cycle material and energy inventory data, secondary data from estimates and approximations, processes emission factors, etc; leading to a challenging comparison of results. (Kim *et al.*, 2016; Peters *et al.*, 2017; Dai, Kelly, *et al.*, 2019b). (Peters *et al.*, 2017) analysed 36 LCA studies on LIB manufacturing, NMC, LFP and LMO; the main variations in the results were in the approach considered for manufacturing estimates: top-down or bottom-up (top-down produced higher impacts). The average GHG emissions for battery production for all chemistries are found to be 110 kgCO_2eq/kWh battery, whereas the total average GHG emissions for the NMC production of 1 kWh are 149 kgCO_2eq.

Regarding NMC batteries, Ellingsen *et al.* (2014) and Majeau-Bettez, Hawkins and StrØmman (2011) used industrial production data for battery manufacturing and reported GHG emissions of 172 and 196 kgCO_2eq/kWh battery, respectively. These findings resulted in the higher GHG emission estimates of all the findings studied. Dai *et al.* (2019a) collected inventory data from a leading Chinese battery manufacturer, indicating lower emissions for LIB production (73 kgCO_2eq/kWh). Sun *et al.* (2020) compiled data for a NMC622 LIB from 2017 to 2019 from two leading cathode material producers in China (124.5 kgCO_2eq/kWh). In comparison, the latest version of the Greenhouse gases, Regulated Emissions, and Energy use in Technologies model (GREET) reported GHG emissions of ~50 kgCO_2eq/kWh for NMC622 LIB (ANL, 2020a). These earlier LCA studies, due to varying life cycle inventory data, show significant uncertainty about battery production impacts that point to important research gaps. This thesis goes beyond by developing comprehensive battery production impacts and providing insights for various battery chemistries under a variety of scenarios.

Existing studies also widely report that electricity use accounts for the largest contribution to life cycle GHG emissions from LIBs manufacturing (~30%) (Dai *et al.*, 2019a). The emissions from electricity generation vary considerably amongst regions, therefore, the country-level electricity mix is a critical factor when assessing the energy and GHG emissions of LIB production (Romare and Dahllöf, 2017; Dai, Kelly, *et al.*, 2019a). A few studies have focused on country-specific electricity mix for their assessment. For example, the GHG emission findings of Dai, Kelly, *et al.*, (2019a) are based on the U.S. national average electricity, while Kim *et al.*, (2016) and Sun *et al.*, (2020) are based on the average mixes in South Korea and China, respectively. Whilst their findings are insightful, they may not be representative of LIB manufacturing elsewhere in the world. In the coming decades, this sector is likely to shift to more renewables, meaning a lower unit CO_2 per kWh of electricity generated and reduced GHG emissions associated with LIB production. Therefore, efforts to accurately estimate future battery production emissions must take into account the anticipated changes in the electricity sector.

Most of the current battery LCA studies evaluated either the battery manufacture phase (cradle-to-gate) or the extraction of raw materials to disposal (cradle-to-grave). Due to lack of information about the LIB recycling process, few studies have concentrated on the LCA of battery remanufacturing, which involves reusing recycled or secondary materials from waste batteries. Compared to manufacturing a battery from primary materials, secondary materials from recycling is less GHG emission intensity (Dunn *et al.*, 2015; Richa, Babbitt and Gaustad, 2017; Ciez and Whitacre, 2019; Mohr *et al.*, 2020). Current most common recycling technologies are: pyrometallurgical, hydrometallurgical and direct recycling. Generally, hydrometallurgical, and direct recycling recover more materials, consequently producing less GHG emissions than pyrometallurgical, and relying less in primary materials when remanufacturing a battery. For example, Dunn *et al.* (2012) found emissions reductions of approximately 54% on a cradle-to-gate using direct recycling method, while Hendrickson *et al.* (2015) revealed GHG emission reductions of 23% from pyrometallurgy. Chen *et al.* (2022) used a cradle-to-cradle LCA approach to evaluate the environmental impacts of a remanufactured NMC811 battery in China, resulting in GHG emissions reductions of 5% for pyrometallurgical, 33% for hydrometallurgical and 52% for direct recycling, compared to primary production.

Table 1. Review of cradle-to-gate for NMC, NCA and LFP lithium-ion batteries including the electricity mix used and environmental impacts such as PED and GHG

Author, Year	**Battery Chemistry**	**Electricity mix**	**PED MJ/kWh**	**GHG $kgCO_2eq/kWh$**
(Ellingsen *et al.*, 2014)	NMC111	Own mix, average value of electricity (similar to US-avg)	2318	487
(Ellingsen *et al.*, 2014)	NMC111	Own mix, asymptotic value of electricity (similar to US-avg)	960	240
(Majeau-Bettez, Hawkins and StrØmman, 2011)	NMC111	EU (2004)	1870	196
(Hawkins *et al.*, 2013)	NMC	EU		190
(Ellingsen *et al.*, 2014)	NMC111	Own mix, lower value of electricity (similar to US-avg)	586	172
(Kim *et al.*, 2016)	NMC	S. Korea, cells US. Battery pack		141
(Sun *et al.*, 2020)	NMC622	China	1235	124.5
(Amarakoon, Smith and Segal, 2013)	NMC	US (2010)	1960	121
(Ellingsen, Singh and Strømman, 2016)	NMC	EU		119
(Yang *et al.*, 2022)	NMC	China		113
(Peters *et al.*, 2017)	NMC111	EU (2012)	1182	110
(Lastoskie and Dai, 2015)	NMC	US (2014)	1500	87
(Dai, Kelly, *et al.*, 2019b)	NMC111	US	1126	72.9
(Wang *et al.*, 2017)	NMC111	China	991	68.1
(Lu *et al.*, 2016)	NMC	China (2012)	682	50.6
(ANL, 2021)	NMC622	US	785	50.1
(Ambrose and Kendall, 2016)	NMC	US		34.8

(Dunn, Gaines and Sullivan, 2014)	NMC	US, Chile (2009)	940	
(Dunn *et al.*, 2015)	NMC	US	741	
(Simon and Weil, 2013)	NMC	n/a	665	
(Aguirre *et al.*, 2012)	NCA	US-Calif. (2007)	2141	170
(Samaras and Meisterling, 2008)	NCA	US (2004)	1700	120
(Sullivan, Burnham and Wang, 2010)	NCA	US (n/a)	910	72
(Lastoskie and Dai, 2015)	NCA	US (2014)	860	50
(Ambrose and Kendall, 2016)	NCA	US		42.9
(Gaines *et al.*, 2011)	NCA	US (n/a)	1600	
(Majeau-Bettez, Hawkins and StrØmman, 2011)	LFP	EU (2004)	2330	250
(Hawkins *et al.*, 2013)	LFP	EU		243
(Zackrisson, 2016)	LFP	EU, SE		215
(Zackrisson, Avellán and Orlenius, 2010)	LFP	EU (2004)		175
(Amarakoon, Smith and Segal, 2013)	LFP	US (2010)	2500	151
(Yang *et al.*, 2022)	LFP	CHINA		93.7
(McManus, 2012)	LFP	n/a	575	79.1
(Lu *et al.*, 2016)	LFP	China (2012)	1018	45.5
(Ambrose and Kendall, 2016)	LFP	US		33.9
(Simon and Weil, 2013)	LFP	n/a	770	

(Dunn *et al.*, 2015)	LFP	US	683
(Dunn, Gaines and Sullivan, 2014)	LFP	US, Chile (2009)	425

2.4 Battery Electric Vehicle Supply Chain

LIBs frequently rely on lithium, nickel, manganese, and cobalt, which are classified as critical materials for being vulnerable to supply risk. According to Brown *et al.* (2021)**,** nickel is mined in more than 25 countries worldwide and is found in either sulfide or laterite ore. Nickel is then processed into Class 1 nickel, and Class 1 nickel is then synthesised into nickel sulfate, which is the suitable composition for batteries. Class 1 nickel can be produced from both ore types (IEA, 2021). Sulfide ore nickel are mainly found Australia, Canada and Russia, while laterite are found in Indonesia, New, Caledonia and Philippines. Nowadays, The Asia-Pacific region represent about half of global nickel production with Indonesia and the Philippines being the largest nickel producers with 38% and 12%, respectively (Brown *et al.*, 2021). Regarding refining, China makes up 32% of global nickel refining, while Indonesia and Russia account for 16% and 9%, respectively (Brown *et al.*, 2021). Several nickel smelting and refining projects are being planned in Indonesia due to the ban of nickel exports (mainly to China) issued by the government in 2020, meaning that the future nickel supply is expected to be driven by Indonesia's development (IEA, 2021; Garcia-Ferrer and Verbanac, 2022).

Cobalt mining is mostly geographically concentrated in the Democratic Republic of Congo (DRC), producing around 63% of the world's cobalt resources (Brown *et al.*, 2021). DRC is known to have socio-political uncertainties and inadequate mining practices (Searcey and Lipton, 2022). Chinese-based companies operate the extraction of cobalt resources in the DRC, however, artisanal or small-scale mining (ASM) contributes around 10-20% of cobalt extraction in the DRC (IEA, 2021; Skidmore, 2021). The DRC exports cobalt hydroxide (intermediate chemical product) to China, which is then transformed into cobalt sulfate (CoSO4), suitable for LIBs (IEA, 2021). The largest cobalt processor is China, which refines around 63% of global cobalt, while the runners-up Finland, Belgium, Canada, Japan, and Norway, together account for 26% (Brown *et al.*, 2021).

Lithium is mainly mined in Australia (52%) and South America (Chile 22%, Argentina 7%). (Brown *et al.*, 2021). It is sourced from either spodumene ore or brine resources. Spodumene ore is a hard rock found in Australia, which undergoes a beneficiation process to produce lithium carbonate (Li_2CO_3) suitable for battery-grade and mainly used in cathode chemistries with relatively low nickel content (e.g., NMC111, NMC532, NMC622) (IEA, 2021). Lithium brines are deposits of salt groundwater with large lithium content, usually found in what is called the “lithium triangle” constituted by Chile, Argentina and Bolivia, containing around 67% of proven lithium reserves (HIR, 2020; Brown *et al.*, 2021). It undergoes through a process of solar evaporation in large ponds for several months and a process of chemical recovery where other elements are removed and Li_2CO_3 is extracted. Lithium hydroxide (LiOH) can also be obtained by the reaction heating Li_2CO_3 with lime. LiOH is typically used in cathode chemistries with high nickel content (e.g., NMC811, NMC955, NCA) (IEA, 2021). In relation to refining, China accounts for close to 35%, followed by Chile and Australia which correspond to 31% and 18% of global lithium refining, respectively (Sun *et al.*, 2019).

Graphite is the preferred anode material for automakers, whose supply has been historically dominated by China accounting for 62% of global graphite production followed by Mozambique (10%), Brazil (8%) and Madagascar (5%) (Brown *et al.*, 2021). However, recent announcements have confirmed the development of several graphite mining projects in Scandinavia, North America (Canada) and Australia, but mostly in east Africa including Tanzania, Mozambique and Madagascar; thus, diversifying the supply chain (Green Car Congress, 2021; Holman, 2022; Holman and Leech, 2022; Stockhead, 2022).

Manganese supplies continue to be reasonably priced and, compared to other battery materials, are widely dispersed throughout the world (IEA, 2021). It is mainly mined in South Africa which accounts for 30% of global manganese resources, followed by Gabon (13%), Australia (12%) and China (11.5%) (Brown *et al.*, 2021). The refining of manganese occurs predominantly in China (57%) (Sun *et al.*, 2019).

Battery cell production is led by three manufacturers, CATL (China), LG (S. Korea), and Panasonic (Japan) making up 65% of global production (Wood Mackenzie, 2022). Apart from dominating the entire battery material supply chain, China leads the global battery manufacturing capacity, accounting for over 75% of all LIBs (Statista, 2021). Europe is responsible for ~10% of global LIB manufacturing but is expected to increase its capacity to reach 25% by 2030. The US has 6% of LIB production capacity, while Japan and South Korea together have 5%. China's dominance is likely to remain through 2030 (IEA, 2022c).

The geographical distribution of key battery materials is sufficiently diverse to require detailed consideration of the multiple locations where each material is mined and processed throughout the supply chain to derive the global-average climate change impact of LIBs. Global-average impacts are important because they reveal the current state of LIBs manufacturing, whilst keeping consistency with previous studies. However, detailed emission factors for specific supply chains become more important because they allow quantification of current and future energy and GHG emissions of battery manufacturing. Therefore, because of spatial distribution and dependence of key LIB materials, we must consider specific locations where key activities are occurring today, how they will shift in the future, and the evolution of battery technologies over time**.**

2.5 Electricity

In the coming decades, the power sector must shift to more renewable electricity to be aligned with the 2 °C target, which implies a lower amount of GHG emitted per kWh of electricity generation. It is well-known that a decarbonised electricity sector is important for reducing the life cycle GHG emissions from BEV use (Abdul-Manan *et al.*, 2022), but ultimately it can also drive down the overall emissions from LIB production and vehicle manufacturing. The electricity power sector is the largest contributor to global energy-related CO2 emission (Ritchie, Roser and Rosado, 2020). Globally, nearly two thirds of electricity generation are provided by fossil fuels, which still dictate the worldwide electricity mix. Coal fired power plants supply around 40% of global electricity generation, and it constitutes 30% of energy-related CO2 emissions (IEA, 2020a). Nevertheless, energy coming from low-carbon sources has been exponentially increasing, providing a lower carbon footprint, thus decarbonising the sector globally (IEA, 2022a). essential crucial

As a result of the increasing penetration of BEVs, the electricity sector will play a major role on the transport sector in the upcoming years, not only for the EV use phase but for the material production processes and battery manufacturing (IEA, 2022b). The electricity consumed in the battery manufacturing process contributes nearly 37% to the overall final GHG emissions (Dai, Kelly, *et al.*, 2019b), meaning that decarbonisation of the electricity sector will play an important role in reducing the overall life cycle emissions. The average global carbon intensity for electricity generation is 0.578 kg of CO_2 equivalent per kilowatt hour ($kgCO_2eq/kWh$) (IEA, 2020a), but varies across geographical regions. For example, China and Indonesia (key countries directly involved in the battery supply chain) have a carbon intensity of 0.550 and 0.625 $kgCO_2eq/kWh$, respectively, while Brazil and Canada have a 0.117 and 0.120 $kgCO_2eq/kWh$ (Our World in Data, 2020). This implies that location hugely impacts the GHG emissions production of materials and components of a battery. A few studies have focused on country-specific electricity mix for their assessment. For example, the GHG emission findings of Dai, Kelly, *et al.* (2019a) are based on the U.S. national average electricity (72.9 kgCO_2eq/kWh battery) , while Kim *et al.* (2016) (141 kgCO_2eq/kWh battery) and Sun *et al.*, (2020) (124.5 kgCO_2eq/kWh) are based on the average mixes in South Korea and China, respectively. Whilst their findings are insightful, they may not be representative of LIB manufacturing elsewhere in the world.

The International Energy Agency (IEA) estimates the decarbonisation of the electricity sector towards 2050 by fostering renewable energy growth in its two core scenarios: The Stated Policies Scenario (SPS) and the Sustainable Development Scenario (SDS) from the World Energy Outlooks (WEO) 2020 and 2021 (Cozzi *et al.*, 2020; Cozzi and Gould, 2021).

a) The SPS contemplates the effect of current policy frameworks and anticipates the status of the future energy sector without further policy implementation. This scenario was identified in previous World Energy Outlooks as the New Policies Scenario (International Energy Agency, 2020a). It provides a very ambitious-positive perspective towards achieving the Sustainable Development Goals (SDGs) related to energy (SDG7), environmental impacts (SDG3) and climate change (SDG13).

b) The SDS provides the pathway to achieve the temperature goal of 1.65ºC agreed on the Paris Agreement as well as increasing the renewable energy integration and dramatically reducing the GHG emissions (International Energy Agency, 2020b). The SDS assumes that develop economies achieve net-zero by 2050, China by 2060, and developing countries by 2070. This suggests that all SDGs related to energy (SDG7, SDG3, SDG13) are achieved.

GHG emissions associated with LIB production can occur at various stages of the life cycle, both from process-related emissions and energy-related emissions. However, emissions can vary depending on factors such as the manufacturing processes, manufacturing technologies, location of production facilities, energy sources used and energy efficiency. Process-related emissions include emissions from the extraction and processing of raw materials, such as mining and refining, as well as emissions from battery manufacturing. Energy-related emissions include emissions associated with the use of fossil fuels for heat or steam generation, and the electricity used in the various manufacturing processes Estimates of energy-related emissions typically range from 50% to 80% of the total emissions associated with the battery life cycle, while process-related emissions range from 20% to 50% (Romare and Dahllöf, 2017; Dai, Kelly, *et al.*, 2019b). symmetrical

2.6 Recycling

If automakers reach their aforementioned BEV fleet goals of 965 million in 2050 (IRENA, 2020), their yearly manufacturing capacity would range between 4-12 terawatt-hour (TWh) per year, that would require around 19-50 million tonnes of LIB cathode materials per year (Usai *et al.*, 2022). Consequently, nations and automakers around the world have shown interest in a variety of end-of-life scenarios for spent batteries due to the massive production scale and amount of batteries that will be retired (Field, 2018; Stringer and Ma, 2018). One such scenario is the recovery and recycling of materials from used battery packs.

Currently, the European Union (EU) produces more than 1.9 million tonnes of battery waste each year, where the battery technology has a significant impact on the shares of collection and recycling (EEA, 2021). Consequently, the EU launched a legislative proposal that carries out a new regulatory framework to support the development and circularity of batteries (EPRS, 2022). This proposal states that 50% of a battery’s weight must be recycled. From 2025, this recycling rate requirement will increase to 65% and to 70% from 2030. There is currently a low volume of recovered metals used in battery manufacturing within the EU, even though closing the material loops as much as possible would help decrease risks associated with the supply of raw materials. In the EU best-case scenario, just 22% of the cobalt, 16% of the nickel, 12% of the aluminium, and 8% of the manganese are recycled (European Commission, 2020a). The EU battery circularity proposal declares that the compulsory minimum recovered material would be 12% for cobalt, 4% for nickel, and 4% for lithium, for 2030; increasing to 20% cobalt, 12% nickel, and 10% lithium, from 2035 (EPRS, 2022). Cobalt and nickel recycling efficiencies are expected to be around 98%, while lithium, copper, and graphite efficiencies are estimated at 90%, depending on the recycling process (Dai *et al.*, 2019). Nonetheless, this EU policy proposal does not specify the approach on how batteries should be recycled, or most importantly, whether a net decrease in GHG emissions is expected as a result of the recycling process.

Recycling LIBs is complicated and costly due to technological difficulties and low collection rates (Dils, 2019). For instance, because it is considered to be too expensive in comparison to primary supplies, lithium recovery in the EU is minimum. On the other hand, the main focus of LIB recycling is the recovery of cobalt, nickel, and copper, which are thought to be more profitable (European Commission, 2020b; Wang *et al.*, 2021). Exploring the benefits and limitations of recycling batteries for EVs will enable organisations to properly manage resources and minimise the environmental impacts of waste batteries (Hill *et al.*, 2019).

Benefits of recycling batteries

- **a)** *Environmental.* Recycling reduces the need for new mining and raw materials and prevents GHG emissions from being released into the environment. Recycling can also reduce the carbon footprint associated with battery manufacturing (Dai and Winjobi, 2019; Costa *et al.*, 2021).
- **b)** *Economic.* Recycling can provide a source of valuable materials such as lithium, cobalt, and nickel, which can be used in the manufacturing of new batteries. It can

also create job opportunities in the recycling industry (Skeete *et al.*, 2020; McKinsey, 2023)

c) *Resource.* Recycling batteries can strengthen circularity and contribute to supply security while alleviating resource extraction (Månberger, 2023).

Limitations of recycling batteries

a) *Technical.* The process of recycling batteries is complex and requires specialised equipment, technology and expertise (Skeete *et al.*, 2020; Latini *et al.*, 2022)

b) *Cost.* The cost of recycling batteries can be higher than the cost of mining and manufacturing new materials. This is due to the technical challenges of recycling and the fact that batteries are often transported long distances to recycling facilities (Latini *et al.*, 2022)

c) *Scale.* As the use of EVs continues to grow, there may not be enough recycling facilities to meet the demand for battery recycling. This could result in a backlog of used batteries and potential environmental risks (Engel, Hertzke and Siccardo, 2019).

Currently, several recycling techniques for LIBs exist, both already commercial and at the pilot level: pyrometallurgical recycling, hydrometallurgical recycling, and direct cathode recycling (hereinafter referred to as direct recycling) (Dai *et al.*, 2019; Latini *et al.*, 2022).

a) Pyrometallurgical recycling uses a high-temperature smelter to recover valuable materials such as cobalt, nickel, and copper that end up in the matte; plastics, electrolyte and lithium are burned off. Cobalt and nickel combinations are then processed by acid leaching and precipitation before they can be included in a new battery. ***Benefits.*** Can recover a high percentage of valuable materials (Co,Ni, Cu) and can be an efficient process for large volumes of batteries. ***Limitations.*** High energy consumption and GHG emissions. Graphite, plastics and electrolyte are burnt.

b) Hydrometallurgical recycling begins with discharging and disassembly of the battery, removing the cathode from the current collector. The cathode is then crushed and calcined, and the residual powder is put into aqueous solutions to leach materials from the cathode. This process recovers lithium, nickel, cobalt, manganese, aluminium, copper and graphite. ***Benefits.*** Can recover high percentage of valuable materials. Lower energy consumption than pyrometallurgical recycling and therefore can be more environmentally friendly. ***Limitations.*** Requires the use of toxic chemicals such as acids and solvents. Can generate hazardous waste streams.

c) Direct recycling process uses discharged and disassembled batteries where the electrolyte is recycled through supercritical CO_2 extraction. The cathode material, anode material (graphite), copper, and aluminium, are then recovered through physically separating out the components. ***Benefits.*** Low energy consumption and GHG emissions. Can be cost effective. Can recover a range of materials, including plastics, metals, and ceramics. ***Limitations.*** May not recover high-value metals such as cobalt and nickel. Limited capacity to handle large volumes of batteries.

Most of the current battery LCA studies evaluated either the battery manufacture phase (cradle-to-gate) or the extraction of raw materials to disposal (cradle-to-grave). Due to lack of information about the LIB recycling process, few studies have concentrated on the LCA of battery remanufacturing, which involves reusing recycled or secondary materials from waste batteries. Compared to manufacturing a battery from primary materials, secondary materials from recycling is less GHG emission intensity (Dunn *et al.*, 2015; Richa, Babbitt and Gaustad, 2017; Ciez and Whitacre, 2019; Mohr *et al.*, 2020). Current most common recycling technologies are: pyrometallurgical, hydrometallurgical and direct recycling. Generally, hydrometallurgical, and direct recycling recover more materials, consequently producing less GHG emissions than pyrometallurgical, and relying less in primary materials when remanufacturing a battery. For example, Dunn *et al.* (2012) found emissions reductions of approximately 54% on a cradle-to-gate using direct recycling method, while Hendrickson *et al.* (2015) revealed GHG emission reductions of 23% from pyrometallurgy. Chen *et al.* (2022) used a cradle-to-cradle LCA approach to evaluate the environmental impacts of a remanufactured NMC811 battery in China, resulting in GHG emissions reductions of 5% for pyrometallurgical, 33% for hydrometallurgical and 52% for direct recycling, compared to primary production. The materials that can be recover through each of the recycling technologies are shown in **Table 2**.

Table 2. Materials recovered using the different recycling methods adopted from (Dai *et al.*, 2019).

Pyrometallurgical	**Hydrometallurgical**	**Direct Recycling**
Co2+ in output	Co2+ in output	NMC111
Ni2+ in output	Ni2+ in output	NMC622
Copper compounds	Mn2+ in output	NMC811
	Lithium	NCA
	Copper	LFP
	Aluminium	Copper
	Graphite	Aluminium
	Steel	Graphite
	Electrolyte solvents	Steel

When batteries reach the end of their useful life, recycling their materials can help recover valuable materials and reduce the need for new mining and extraction, which can be energy-intensive and have significant environmental impacts. Secondary materials, via recycling, are particularly relevant for the development of this thesis because it includes a full-lifecycle approach that considers reusing waste battery materials for battery remanufacture. Enabling insights in determining the key factors of a sustainable battery.

2.7 Literature Summary and Research Gaps

Since many materials are concentrated in a few countries, several governments and BEV companies have expressed their concern about the geopolitical implications associated with the supply chain of battery materials. The source of battery materials and the mix of electricity used throughout the battery manufacturing process have a significant impact on the embodied GHG emissions from the production of BEVs. Therefore, as global sales are expected to increase in the next decades, it is necessary to understand the sustainability of future BEV deployment by evaluating the environmental impacts associated with LIB manufacturing. The GHG emissions that would result from the widespread use of BEVs were the subject of previous research, but the data on current and future battery technologies, market shares, and recycling scenarios were only partially covered. This thesis aims to address these research gaps by developing an LCA model with comprehensive battery production and recycling scenarios for a selection of existing battery technologies with anticipated battery market share and electricity mix scenarios. The pertinence of the research questions and the identified research gaps are summarised below.

RQ1. Which battery chemistry provides the least GHG emissions and which materials contribute the highest GHG emissions to the overall cradle-to-gate manufacturing process?

The manufacturing of LIBs produces GHG emissions at various stages of the supply chain, including mining, processing of raw materials, and manufacturing. The reported emissions range between 39-487 kgCO_2eq/kWh battery, depending on the battery technology, geographical location, electricity mix considered, life cycle inventory, etc. These studies show significant uncertainty about battery manufacturing emissions that lead to important research gaps. The total emissions associated with LIB manufacturing varies depending on the type of battery chemistry. LFP batteries are known for their low environmental impacts. They are manufactured using less energy and fewer materials than other battery chemistries. According to the literature, LFP batteries have a carbon footprint of 40-80 $kgCO_2eq/kWh$. NCA batteries have a higher energy density than LFP batteries, making them more suitable for use in EVs. However, they require more energy to manufacture and present higher emissions. NCA batteries have a carbon footprint of around 110-140 $kgCO_2eq/kWh$. NMC batteries are similar to NCA batteries in terms of energy density and manufacturing requirements. They have a slightly lower carbon footprint than NCA batteries of around 80-110 $kgCO_2eq/kWh$. This thesis provides a comprehensive framework for battery emissions estimates.

RQ2. In which geographical locations are these emissions expected to occur for different battery chemistries?

The geographical locations where GHG emissions associated with supply chain of LIBs are expected to occur depending on the specific stage of the supply chain and on the geographical region where the materials are sources. For the extraction of raw materials, lithium production is concentrated in Australia and in the “Lithium triangle” of south America (Argentina, Bolivia, Chile), cobalt production is concentrated in the Democratic Republic of Congo, nickel is concentrated mainly in Indonesia and Philippines. The processing of materials in mainly dominated by China, which refines almost 80% of the raw materials needed for batteries. Battery cell production is often concentrated un countries with large manufacturing industries such as China, South Korea, and Japan. These countries tend to rely heavily on fossil fuels for electricity generation, resulting in GHG emission from battery production. Battery assembly may take place in different geographic locations, depending on the location of the EV manufacturer. China dominates the global battery manufacturing capacity, accounting for over 75%. If the battery manufacturer is based in Europe, battery assembly may take place in Poland, Hungary or Germany, which together currently account for around 10%, but is expected to reach 25% by 2030. North America, mainly the US, accounts for 6% battery production capacity, while Japan and South Korea together are responsible for 5%. This thesis identifies the differences among global regions with respect to electricity mix and material sourcing as research gaps. Conducting a LCA analysis will help to better understand how regional supply chain variations impact GHG emissions, thus suggesting supply chain decarbonisation scenarios with lowest and highest GHG emissions contributors.

RQ3. How are the future global GHG emissions expected to change towards 2050 by decarbonising the electricity sector and considering various battery technology scenarios?

Future global GHG emissions are expected to change significantly towards 2050, as countries and industries take steps to decarbonise their economies and reduce their GHG emissions. The electricity sector is a key area to focus for emissions reductions, as it is responsible for 37% of the overall final GHG emissions of the whole battery manufacturing process. The carbon intensity for electricity generation varies across geographical regions, China and Indonesia (key countries directly involved in the battery supply chain) have a carbon intensity of 0.550 and 0.625 $kgCO_2eq/kWh$, respectively, while Brazil and Canada have a 0.117 and 0.120 $kgCO_2eq/kWh$. As countries shift away from fossil fuel-based electricity generation towards renewable energy sources, the IEA declares two main decarbonisation scenarios towards 2050: the Stated Policies Scenario (SPS), which states that current energy policies are followed without further improvement; and the Sustainable Development Scenario (SDS), which provides a more aggressive framework for decarbonising the electricity. Further, the development and deployment of different battery technologies can also have a significant impact on GHG emissions. For example, a LFP market-based scenario could lead to emissions reductions, as this battery chemistry requires less energy to produce and fewer raw materials.

RQ4. What are the GHG emissions reductions of battery manufacture using secondary materials via different recycling technologies?

Recycling batteries is complex and costly due to the technical difficulties and not being yet economic viable. Cobalt, nickel, lithium, and copper are the main focus for recycling batteries since are considered more valuable. Pyrometallurgical recycling, hydrometallurgical recycling and direct cathode recycling, are the current commercial and pilot level recycling techniques being considered on this thesis, where each one of them depict its own benefits and limitations. Several studies have found emissions reductions of 23%, 33% and 54%using pyrometallurgical, hydrometallurgical and direct recycling, respectively. Overall, recycling lithium-ion batteries can help reduce the emissions associated with the production of new batteries using secondary materials. While there are still energy and emissions associated with the recycling process itself, these are typically significantly lower than the energy and emissions associated with the production of new batteries from raw materials. Therefore, recycling should be considered an important component of any strategy to reduce the environmental impacts of battery manufacturing and the use of lithium-ion batteries.

CHAPTER 3 METHODOLOGY

3.1 Introduction

This chapter presents a novel modelling framework for the evaluation of the life cycle environmental impacts of LIB manufacture and battery recycling. It provides spatial and temporal resolution to quantify where in the global supply chain GHG emissions occur, and how these emissions are expected to vary over time due to anticipated uptake of competing battery chemistries and decarbonisation of the electricity sector as displayed in **Figure 1**. Life cycle inventories for LIB materials and manufacturing activities are coupled with data on the location of activities and location-specific emissions factors for energy and material inputs to assess the global GHG emissions implications of battery manufacture. A forward-looking analysis considers how the mix of LIB chemistries and background energy systems will drive future GHG emissions trends as in **CHAPTER 4 Battery Production.** Finally, recovered materials from spent batteries are incorporated back into the battery supply chain (i.e., closed-loop recycling) and discussed in **Chapter 5 Battery Recycling.**

3.2 Scope of Research

As shown in **Figure 1**, the thesis research scope accounts for all the battery production stages and their impacts associated with raw materials extractions, (i.e. cradle), through to the assembly of the finished battery pack (i.e. gate). It does not include the downstream use phase but assesses end-of-life and closed-loop recycling. Across the research undertaken, two environmental impact categories are considered: primary energy demand (PED), i.e., the cumulative energy use associated with the production processes including fossil and renewable energy (MJ); and greenhouse gas emissions (GHG), calculated based on 100-year global warming potentials (GWP) for different GHGs (i.e., CO_2, CH_4, and N_2O) as listed in the fifth assessment report of the Intergovernmental Panel on Climate Change (IPCC, 2014), expressed in kilograms of CO_2 equivalent (kgCO_2eq).

This thesis contains four assessments:

1) geographically explicit LCA study of battery manufacturing supply chain (section 3.3)
2) Future LCA study of battery manufacturing considering decarbonisation of the electricity sector to 2050 (section 3.4).
3) Future LCA study of battery manufacturing considering projected technology development and market share (section 3.5).
4) Closed-loop recycling and battery manufacture using secondary materials (section 3.6)

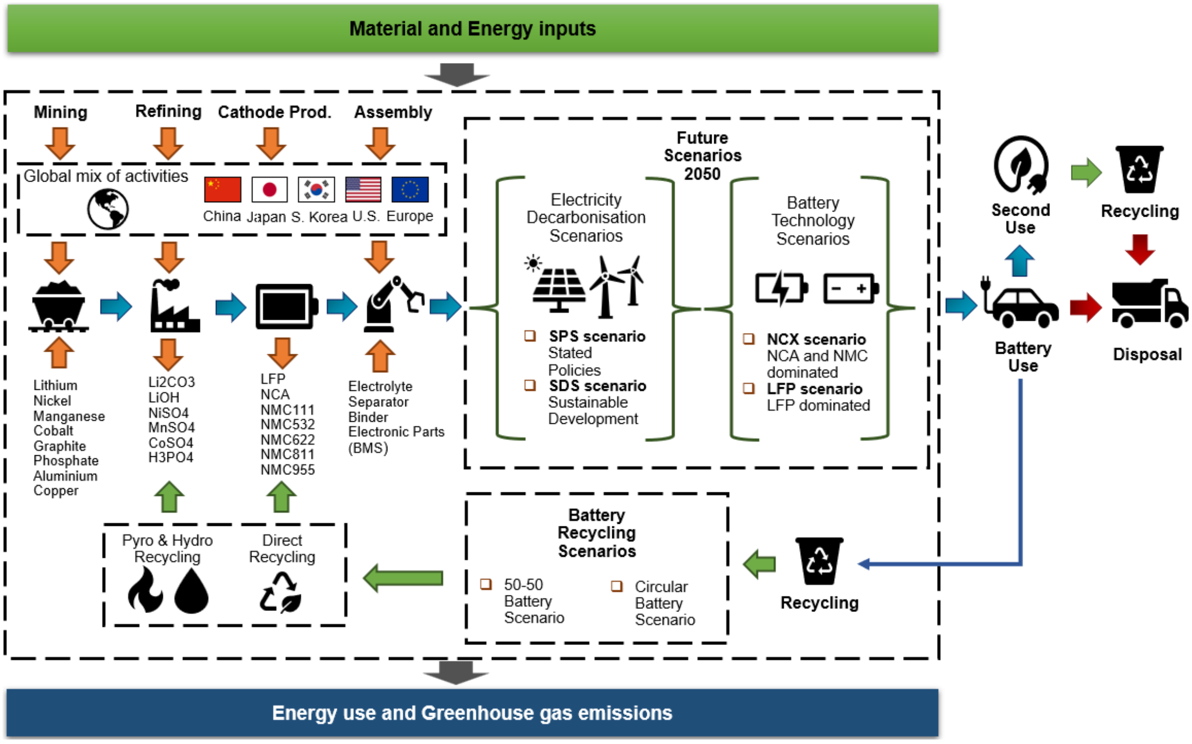

Figure 1. System boundary flowchart for battery chemistries, future scenarios to 2050 and battery recycling. Note: BEV = battery electric vehicles, Li_2CO_3 = lithium carbonate, LiOH = lithium hydroxide, $NiSO_4$ = nickel sulfate, $MnSO_4$ = manganese sulfate, $CoSO_4$ = cobalt sulfate, H_3PO_4 = Phosphoric acid, NMC = lithium nickel manganese cobalt oxide, NCA =

lithium nickel cobalt aluminium oxide, LFP = lithium iron phosphate, SPS = stated policies scenario, SDS = sustainable development scenario.

3.3 Supply chain inventory analysis

3.3.1 Current battery chemistries and materials inventories

Battery chemistries that are relevant to current and future BEV applications are selected for the analysis, which includes:

- Nickel-Manganese-Cobalt (NMC) of varying compositions: NMC111, NMC532, NMC622, and NMC811.
- Nickel-Cobalt-Aluminium (NCA).
- Lithium Iron Phosphate (LFP).

For each battery chemistry, the materials inventory from the *Greenhouse gases, Regulated Emissions, and Energy Use in Technologies* (GREET) model of the Argonne National Laboratory GREET 2020 (ANL, 2020a; Winjobi, Dai and Kelly, 2020) is assumed to be representative for current and future battery manufacture. Detailed bill-of-materials (BOM) for all LIB chemistries at the cell, module and pack level are shown in **Table 3**, which also indicates key materials that are assessed in additional spatial and temporal detail (see **CHAPTER 4 Battery Production**). Key battery materials are defined as those contributing more than 2% of total emissions as given by the GREET model. Materials contributing less than 2% were not considered in the thesis, e.g., binder, electrolytes ($LiPF_6$, ethylene carbonate, dimethyl carbonate), plastics (polypropylene, polyethylene, polyethylene terephthalate), steel, insulators, coolant (glycol) and electronic parts. It is worth mentioning that the BOM varies significantly depending on the battery size and characteristics. Assumptions regarding battery features such as battery weight, battery-specific energy, and battery material composition used by the GREET model are consistent in the analysis.

Table 3. Battery material composition by weight. Materials that contribute more than 2% threshold and are included in the spatial/temporal analysis are the active cathode materials (lithium, nickel, manganese, cobalt and phosphate), graphite, copper, and aluminium. Values expressed in kg of material (Winjobi, Dai and Kelly, 2020).

Materials	**Battery Chemistry**					
	NMC 111	**NMC 532**	**NMC 622**	**NMC 811**	**NCA**	**LFP**
Active cathode material	125.43	121.11	105.87	89.81	97.27	145.78
Graphite	63.67	62.07	62.52	64.60	63.87	74.44
Carbon black	2.61	2.52	2.21	4.99	2.03	3.04
Binder (PVDF)	5.96	3.79	3.48	6.31	3.33	4.56
Copper	23.17	21.97	20.25	20.06	18.67	32.90
Aluminium	13.13	12.38	11.50	11.45	10.70	18.50
Electrolyte: LiPF6	4.55	4.13	4.01	3.96	3.83	7.23
Electrolyte: Ethylene Carbonate	12.70	11.53	11.19	11.05	10.70	20.19
Electrolyte: Dimethyl Carbonate	12.70	11.53	11.19	11.05	10.70	20.19
Plastic: Polypropylene	2.17	2.48	1.85	2.18	1.68	3.23
Plastic: Polyethylene	0.47	0.56	0.40	0.48	0.36	0.72
Plastic: Polyethylene Terephthalate	0.62	0.58	0.55	0.56	0.53	0.82
Subtotal: Cell	**267.18**	**254.63**	**235.02**	**226.49**	**223.67**	**331.57**
Module components sans cell (kg)						
Copper	0.43	0.42	0.43	0.43	0.43	0.48
Aluminium	12.48	11.76	11.32	11.42	10.94	16.13
Plastic: Polyethylene	0.13	0.13	0.13	0.13	0.13	0.13
Insulation	0.11	0.11	0.11	0.11	0.11	0.12
Electronic part	1.12	1.12	1.12	1.12	1.12	1.12
Subtotal: Module sans cell	**14.27**	**13.54**	**13.10**	**13.20**	**12.74**	**17.98**
Pack components sans module (kg)						
Copper	0.09	0.09	0.09	0.09	0.09	0.10
Aluminium	31.09	30.31	29.52	29.56	29.00	36.37
Steel	1.98	1.83	1.76	1.78	1.69	2.71
Insulation	0.99	0.97	0.94	0.94	0.93	1.16
Coolant	8.58	8.50	8.65	8.47	8.97	10.94
Electronic part	4.43	4.22	4.22	4.22	4.23	4.50
Subtotal: Pack sans module	**47.16**	**45.91**	**45.18**	**45.06**	**44.90**	**55.79**
Total: Pack (kg)	**328.61**	**314.09**	**293.30**	**284.75**	**281.31**	**405.35**

The key characteristics of the chosen batteries are listed in **Table 4.** The specific energy of the battery is calculated by dividing the battery capacity (kWh) by the battery weight (kg). The battery capacity is assumed to be the same for all battery chemistries, 84 kWh, and the vehicle range is 300 miles as assumed by the GREET model 2020 (ANL, 2020a).

Table 4. Li-ion battery weight (kg) and battery-specific energy (Wh/kg) for chosen battery chemistries (ANL, 2020a).

Li-Ion Battery material	**NMC111**	**NMC532**	**NMC622**	**NMC811**	**NCA**	**LFP**
Battery weight (kg)	328.6	314.0	293.3	284.7	281.3	405.3
Pack specific Energy (Wh/kg)	255.9	267.8	286.8	295.4	299.0	207.5

3.3.2 Battery materials production

The materials used on LIB vary depending on their chemical composition. For NMC and NCA batteries, there are five key metals that are considered critical for LIBs production: lithium, nickel, manganese (only in NMCs), cobalt, and graphite; along with aluminium and copper. These materials were identified based on their overall GHG emissions contribution (2% cut off) and on the BOM presented in **Table 3** given by GREET 2020 (Winjobi, Dai and Kelly, 2020).

Certain nations are more crucial than others for the BEV battery supply chain. The mining, refining and production data of key battery materials such as lithium, nickel, manganese, cobalt, graphite, aluminium, copper, and phosphate, was obtained primarily from the *British Geological Survey World Mineral Production 2020* (Brown *et al.*, 2021) and complemented with other relevant sources (Sun *et al.*, 2019; USGS, 2020). **Table 5** summarises the countries with the largest mining and refining production of key materials. Notably, China holds a superior share in terms of refining capacity for key LIB materials, almost 80%. Additionally, China is the world’s largest producer of graphite, which is the principal anode material for batteries. Australia produces more than half the world's lithium and almost a third of the world's aluminium. Around 63% of the world's cobalt comes from mines in the Democratic Republic of Congo (DRC). Indonesia is the largest producer of nickel, South Africa produces around 30% of the world's manganese, and Chile is the biggest copper producer and the second largest lithium producer. In this analysis, a 2% cut off was used, meaning that countries producing less than 2% of any material were not included. Detailed mining and refining data of key materials production by country is presented in ANNEX **.**

Table 5. Summary of LIB materials mining and refining (Sun *et al.*, 2019; USGS, 2020; Brown *et al.*, 2021)

LIB material	**Mining**		**Refining**	
	Country	**Share (%)**	**Country**	**Share (%)**
Lithium	Australia	58%	China	34%
	Chile	22%	Chile	31%
	China	12%	Australia	18%
	Argentina	7%	Argentina	11%
Nickel	Indonesia	38%	China	32%
	Philippines	12%	Indonesia	16%
	Russia	8%	Russia	9%
	New Caledonia	8%	Japan	7%
Manganese	South Africa	30%	China	57%
	Gabon	13%	India	9%
	Australia	12%	South Africa	5%
	China	11%	Japan	4%
Cobalt	DRC	63%	China	63%
	Philippines	6%	Finland	9%
	Australia	5%	Belgium	5%
	Russia	4%	Canada	5%
Graphite	China	62%		
	Mozambique	10%		
	Brazil	9%		
	Madagascar	5%		
Aluminium	Australia	30%	China	54%
	Guinea	20%	Australia	15%
	China	18%	Brazil	7%
	Brazil	9%	India	5%
Copper	Chile	28%	China	40%
	Peru	12%	Chile	9%
	China	8	Japan	6
	DRC	7	DRC	5

This thesis analyses the global differences in manufacturing processes and supply chain of battery materials by considering the mining and refining production shares of each country, along with the specific electricity mixes within the geography. The material production model is developed using **equation (1)** based on the GREET 2020 life cycle inventory data on upstream materials and energy flows for key battery materials extended to include a greater number of countries that are significantly active in the mining and refining of key battery materials (responsible for more than 2% of mining or refining activity for each material). This is a wider reach of materials production than in the GREET 2020 model (ANL, 2020a). This equation comes from the energy mixes in the GREET model.

$$LCA\ Impact = \sum_{i} (DE * Ei) * FEi \tag{1}$$

where the LCA impact could be either GHG ($kgCO_2/kg$) or PED (MJ/kg*)*; *DE* is the direct energy consumption per production stage given by GREET; *Ei* is the share of energy sources, expressed in percentage unit (%); *FEi* is the fuels specific energy impact factors of specific energy source *i*. Energy sources (*i)* include residual oil, diesel, gasoline, natural gas, coal, liquefied petroleum gas (LPG), and electricity, and their overall impact factors are shown in **Table 8**, **section 3.3.4.** The life cycle inventory is assumed to be unchanged for different production locations, and location-specific GHG emissions are assessed to account for differences in the country-specific electricity generation mix (as explained in the next section).

3.3.3 Battery assembly

Global battery manufacturing is projected to boom this decade. In 2021, China had a production capacity of 558 GWh (79% world total), the USA has 44 GWh (6% world total), and Europe had 68 GWh (9.6% world total) (Statista, 2021). The Asia Pacific region, led by China, accounted for 84% of the global LIB's manufacturing in 2021, as shown. Battery cell companies and start-ups have announced plans to build a production capacity of up to 2357 GWh by 2030 (Nicholas. *et al.*, 2021). The growing sales of BEVs in China drive the country to lead the global LIB market capacity. China is projected to lead the market by 2030 with 1247 GWh (53% world total), the USA with 266 GWh (11.3% world total), and Europe with 618 GWh (23.6% world total) (Nicholas. *et al.*, 2021). In Europe, Germany will be dominating the LIB market capacity with 266 GWh (10.4% world total), followed by France with 82 GWh (3.48 % world total), the UK with 73 GWh (3.10% world total), and Poland with 68 GWh (2.89% world total) (Nicholas. *et al.*, 2021).

Furthermore, the global LIB capacity could rise by around ~6 TWh in the Stated Policies Scenario (SPS) and up to ~12 TWh in the Sustainable Development Scenario (SDS) by 2050 (Xu *et al.*, 2020). This analysis assumes the battery assembly market share stays constant after 2030, but the installed capacity follows the IEA's projections for 2050. Detailed projected battery assembly share mix by country and region is presented in **Table 6** and **Table 7**.

Table 6. Projected global lithium-ion battery manufacturing capacity by country between 2021 and 2030 (in gigawatt hours) (Nicholas. *et al.*, 2021; Statista, 2021)

Country	**2021**	**2025**	**2030**
China	558	944	1,247
US	44	91	266
Germany	11	164	245
Hungary	28	47	39
Poland	22	70	68
South Korea	18	18	54
Japan	17	17	132
Norway	0	0	58
Sweden	4	32	40
UK	2	12	73
Australia	1	7	5
India	0	0	33
Thailand	1	2	0
Italy	0	0	3
Taiwan	0	0	2
Czech Republic	1	1	0
France	0	32	82
Slovakia	0	10	10
Total	**707**	**1447**	**2357**

Table 7. Projected global lithium-ion battery manufacturing capacity by region between 2021 and 2030 (in gigawatt hours) (Xu *et al.*, 2020)

Region	**2021**	**2025**	**2030**
China	558	944	1,247
US	44	91	266
Asia ex. China	36	37	221
Europe	68	368	618
Austrasia	1	7	5
Total	**707**	**1447**	**2357**

3.3.4 Current electricity generation mix

Location-specific electricity supply mixes, and resulting GHG intensities, are assessed for all countries identified as being significantly involved in the mining and refining of battery materials (see **section 3.3.2**) and battery assembly (see **section 3.3.3**). Current country-specific electricity generations are assessed using available data from the IEA data browser (IEA, 2020a), and electric power transmission and distribution from (World Bank, 2014). Where specific electricity generation data for countries were not available, generic IEA average world data were considered. The primary energy demand (PED) and greenhouse gas emissions (GHG) impacts for 1 kWh of electricity generated in each country were calculated as the supply share weighted-average value, based on ecoinvent database version 3.7 (Ecoinvent, 2020). Detailed inventory data of electricity for all relevant countries in the LIB production supply chain including T&D losses and PED and GHG impacts are listed in **Table 10**. Electricity generation GHG emissions are assessed using **equation (2):**

$$GHG = \frac{\sum (E * EF)}{(1 - T\&D)} \quad (2)$$

where the *GHG* emissions generated are in $kgCO_2/kWh$ electricity mix; *E* is the share of electricity by energy source, e.g., coal, natural gas, oil, nuclear, hydro, biofuels, wind, solar

PV, geothermal, solar thermal, and tide, expressed in percentage unit (%); *EF* is the emission factor of electricity generated from one source in kgCO$_2$eq/kWh; *T&D* is the electric power transmission and distribution losses in % of output. Overall impact factors for energy sources are shown below in **Table 8** and for electricity generation in **Table 9**. The potential for decarbonising fuels (other than electricity) used in LIB manufacturing is discussed in the next section.

Table 8. Impact factors for various energy sources.

Energy Sources	**Overall Impact Factors**	
	PED MJ/MJ fuel	**GHG** kgCO$_2$eq/MJ
Residual Oil	1.626	0.111
Diesel	1.249	0.085
Gasoline	1.253	0.083
Liquefied Petroleum Gas	1.281	0.079
Natural Gas	1.184	0.069
Coal	1.565	0.109

Table 9. Electricity generation emission factors for different materials and their stages.

Material	**Stage**	**PED** MJ/MJ	**GHG** kgCO$_2$eq/MJ
Nickel	Mining	2.884	0.210
	Refining	2.775	0.193
Lithium	Mining	2.815	0.192
	Refining	2.808	0.193
Cobalt	Mining	1.821	0.061
	Refining	2.743	0.191
Manganese	Mining	3.173	0.197
	Refining	2.687	0.207
Copper	Mining	2.104	0.119
	Smelting	2.401	0.174
	Refined	2.261	0.158
Aluminium	Bauxite mining	2.620	0.179
	Alumina refining	2.575	0.198
	Production	2.589	0.191
Graphite	Production	2.554	0.189
Phosphate	Production	2.680	0.163

Table 10. Electricity mix of countries in the LIB supply chain (2020). Values for energy sources and T&D losses are expressed in percentage (%). GHG values are expressed in kgCO$_2$eq/kWh. PED values expressed in MJ/kWh.

Country	Coal	Natural gas	Oil	Nuclear	Hydro	Biofuel	Wind	Solar PV	Geotherm.	STE	Tide	Other	Waste	T&D loss	GHG	PED
Argentina	1.36%	60.89%	4.64%	7.39%	16.74%	1.56%	6.49%	0.93%	0.00%	0.00%	0.00%	0.00%	0.00%	15.00%	0.472	10.950
Australia	54.88%	20.82%	1.70%	0.00%	5.71%	1.26%	7.69%	7.93%	0.00%	0.00%	0.00%	0.00%	0.00%	5.00%	0.790	11.139
Bahrain	0.00%	99.99%	0.01%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	4.00%	0.539	10.548
Belgium	2.07%	29.97%	0.10%	38.92%	1.49%	4.89%	14.55%	5.62%	0.00%	0.00%	0.00%	0.36%	2.03%	5.00%	0.223	10.820
Brazil	2.82%	8.61%	1.73%	2.26%	63.80%	9.46%	9.18%	1.73%	0.00%	0.00%	0.00%	0.04%	0.37%	16.00%	0.172	6.654
Canada	4.87%	11.06%	0.80%	15.32%	60.03%	1.54%	5.63%	0.67%	0.00%	0.00%	0.00%	0.02%	0.05%	9.00%	0.168	7.561
Chile	31.14%	17.98%	3.72%	0.00%	25.31%	5.49%	6.75%	9.31%	0.30%	0.00%	0.00%	0.00%	0.00%	7.00%	0.538	8.512
China	64.13%	2.80%	0.14%	4.70%	17.12%	1.46%	6.04%	3.46%	0.00%	0.02%	0.00%	0.00%	0.14%	5.00%	0.941	11.297
Cote d'lvoire	0.00%	68.97%	0.08%	0.00%	30.19%	0.59%	0.00%	0.16%	0.00%	0.00%	0.00%	0.00%	0.00%	14.00%	0.429	9.509
Cuba	0.00%	12.65%	83.71%	0.00%	0.70%	2.13%	0.10%	0.71%	0.00%	0.00%	0.00%	0.00%	0.00%	15.00%	0.974	21.213
DRC	0.00%	0.02%	0.05%	0.00%	99.58%	0.26%	0.00%	0.09%	0.00%	0.00%	0.00%	0.00%	0.00%	21.00%	0.045	4.886
Finland	7.96%	5.37%	0.39%	33.78%	23.00%	15.95%	11.51%	0.37%	0.00%	0.00%	0.00%	0.38%	1.29%	4.00%	0.167	8.756
Gabon	0.00%	50.35%	9.98%	0.00%	39.11%	0.48%	0.00%	0.09%	0.00%	0.00%	0.00%	0.00%	0.00%	28.00%	0.507	10.931
Germany	25.46%	17.11%	0.84%	11.06%	4.27%	7.69%	22.50%	8.69%	0.04%	0.00%	0.00%	0.20%	2.13%	4.00%	0.412	8.510
Ghana	0.00%	58.79%	3.93%	0.00%	36.99%	0.00%	0.00%	0.29%	0.00%	0.00%	0.00%	0.00%	0.00%	23.00%	0.458	10.239
Guatemala	15.40%	0.05%	10.00%	0.00%	47.22%	20.50%	2.49%	1.75%	2.59%	0.00%	0.00%	0.00%	0.00%	9.00%	0.329	6.355
Guinea	0.00%	56.85%	8.83%	0.00%	34.33%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.313	7.171
Hungary	11.00%	25.99%	0.12%	45.97%	0.70%	5.69%	1.88%	7.02%	0.05%	0.00%	0.00%	0.43%	1.17%	12.00%	0.313	12.832
India	72.46%	4.24%	0.31%	2.67%	10.37%	1.94%	4.11%	3.81%	0.00%	0.00%	0.00%	0.00%	0.10%	19.00%	0.947	11.456
Indonesia	62.78%	17.63%	2.51%	0.00%	6.75%	4.71%	0.16%	0.03%	5.40%	0.00%	0.00%	0.00%	0.01%	9.00%	1.161	13.258
Iran	0.20%	72.79%	15.32%	2.13%	9.24%	0.01%	0.17%	0.13%	0.00%	0.00%	0.00%	0.00%	0.00%	13.00%	0.599	11.475
Jamaica	0.00%	10.77%	76.83%	0.00%	4.07%	0.43%	6.86%	1.04%	0.00%	0.00%	0.00%	0.00%	0.00%	27.00%	1.037	15.316
Japan	30.39%	37.73%	4.69%	3.76%	8.56%	2.16%	0.84%	7.63%	0.28%	0.00%	0.00%	1.81%	2.15%	4.00%	0.614	10.058

Jordan	0.00%	81.31%	4.36%	0.00%	0.09%	0.02%	4.20%	10.02%	0.00%	0.00%	0.00%	0.00%	0.00%	11.00%	0.530	10.673
Kazakhstan	69.54%	19.95%	0.06%	0.00%	9.66%	0.00%	0.43%	0.36%	0.00%	0.00%	0.00%	0.00%	0.00%	7.00%	0.869	10.432
Madagascar	33.20%	0.00%	11.64%	0.00%	55.10%	0.00%	0.06%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.459	7.045
Malaysia	45.34%	37.48%	0.61%	0.00%	15.44%	0.79%	0.00%	0.34%	0.00%	0.00%	0.00%	0.00%	0.00%	6.00%	0.705	9.838
Mexico	2.64%	63.42%	9.93%	3.16%	7.81%	0.67%	5.74%	3.94%	1.32%	0.00%	0.00%	1.34%	0.04%	14.00%	0.529	10.261
Morocco	67.92%	8.63%	1.72%	0.00%	3.22%	0.00%	11.46%	0.95%	0.00%	2.85%	0.00%	3.25%	0.00%	15.00%	0.883	10.424
Mozambique	0.00%	16.42%	0.00%	0.00%	83.56%	0.00%	0.00%	0.01%	0.00%	0.00%	0.00%	0.00%	0.00%	15.00%	0.134	5.747
New Caledoni	13.80%	0.00%	72.40%	0.00%	13.80%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	7.00%	0.859	11.826
Norway	0.12%	0.85%	0.14%	0.00%	91.96%	0.02%	6.44%	0.02%	0.00%	0.00%	0.00%	0.19%	0.26%	6.00%	0.032	5.382
Peru	0.11%	34.88%	1.28%	0.00%	57.74%	1.08%	3.42%	1.50%	0.00%	0.00%	0.00%	0.00%	0.00%	11.00%	0.244	6.953
Philippines	54.87%	21.19%	3.56%	0.00%	7.61%	0.46%	0.99%	1.18%	10.13%	0.00%	0.00%	0.00%	0.02%	9.00%	0.775	10.480
Poland	69.28%	10.63%	1.20%	0.00%	1.86%	5.14%	10.00%	1.26%	0.00%	0.00%	0.00%	0.21%	0.42%	6.00%	0.817	9.589
Qatar	0.00%	100.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	6.00%	0.550	10.772
Russia	16.20%	42.83%	0.75%	19.89%	19.74%	0.01%	0.10%	0.17%	0.04%	0.00%	0.00%	0.00%	0.27%	10.00%	0.768	16.387
Saudi Arabia	0.00%	56.40%	43.49%	0.00%	0.00%	0.00%	0.00%	0.11%	0.00%	0.00%	0.00%	0.00%	0.00%	7.00%	0.737	11.975
South Africa	87.70%	0.00%	0.08%	5.17%	2.29%	0.18%	2.48%	1.50%	0.00%	0.60%	0.00%	0.00%	0.00%	8.00%	1.010	15.419
South Korea	38.66%	25.82%	1.08%	27.32%	1.22%	1.36%	0.54%	3.11%	0.00%	0.00%	0.08%	0.62%	0.20%	3.00%	0.585	11.450
UAE	0.00%	98.34%	0.70%	0.00%	0.00%	0.00%	0.00%	0.79%	0.00%	0.17%	0.00%	0.00%	0.00%	7.00%	0.555	10.848
UK	1.98%	36.49%	0.28%	16.08%	2.52%	11.22%	24.18%	4.09%	0.00%	0.00%	0.00%	0.00%	3.15%	8.00%	0.232	8.035
USA	20.03%	39.27%	0.85%	19.36%	7.39%	1.25%	8.03%	2.74%	0.45%	0.10%	0.00%	0.11%	0.41%	6.00%	0.452	10.473
Ukraine	30.14%	7.92%	0.31%	53.59%	5.27%	0.27%	1.36%	1.15%	0.00%	0.00%	0.00%	0.00%	0.00%	11.00%	0.401	13.624
Vietnam	49.91%	17.86%	0.93%	0.00%	27.78%	1.19%	0.30%	2.02%	0.00%	0.00%	0.00%	0.00%	0.00%	9.00%	0.678	9.199
Zambia	12.50%	0.00%	2.12%	0.00%	84.39%	0.00%	0.00%	0.99%	0.00%	0.00%	0.00%	0.00%	0.00%	15.00%	0.205	5.674
Zimbabwe	43.89%	0.00%	0.52%	0.00%	53.60%	1.99%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	16.00%	0.558	8.075

The supply chain environmental impacts of current and future country-specific GHG emissions are assessed for mining and refining of battery materials, and battery assembly, using **equation (3)**:

$$GHG = NE + \sum_{i}(E * EFi) * Si \tag{3}$$

where the GHG generated are in $kgCO_2$/kg material; *NE* is the GHG emissions arising from non-electricity inputs in $kgCO_2eq$/kg, *E* is the electricity input in kWh, *EFi* is the emission factor of electricity intensity of a specific country ($kgCO_2eq$/kWh), and S_i is the supply share of specific country *i* (in percentage unit).

3.4 Future electricity decarbonisation scenarios

Two main IEA scenarios are considered to assess future electricity generations towards 2050 based on bottom-up electricity data: The Stated Policies Scenario (SPS) and the Sustainable Development Scenario (SDS) from the World Energy Outlooks (WEO) 2020 and 2021 (Cozzi *et al.*, 2020; Cozzi and Gould, 2021).

a) The ***Stated Policies Scenario (SPS)*** reflects the effects of current policy frameworks and existing policy ambitions on the energy sector towards 2050. This scenario explores where the energy system might go without additional policy implementation. (International Energy Agency, 2020a).

b) The ***Sustainable Development Scenario (SDS)*** is a “well below 2 ºC” pathway to achieve the temperature goal agreed upon by the Paris Agreement as well as increasing renewable energy integration and dramatically reducing GHG emissions (International Energy Agency, 2020b). In the SDS, many of the world’s advanced economies reach net-zero emissions by 2050, China around 2060, and all other countries by 2070 (Cozzi and Gould, 2021).

The electricity mix scenarios focuses on the 2020-2050 generations. IEA's WEO 2020 provides data for 2030-2040, while the WEO 2021 is for 2050. Each country's PED and GWP of electricity generation are modelled based on the SPS and SDS scenarios. Future electricity mix was available for various countries including Brazil, China, India, Japan, Japan, Russia, South Africa, and the United States; where specific future electricity generation data for countries were not available, regional data was considered. This approach considers efforts to decarbonise the electricity sector by switching to renewable energy sources. However, there is potential to decarbonising non-electricity energy inputs such as natural gas, residual oil, diesel, gasoline, and liquefied petroleum gas by switching to alternatives such as low-carbon fuels and energy efficiency improvements. This approach will reduce the overall GHG emissions throughout the battery life cycle stages. Future electricity generation GHG emissions are assessed using **equation (2)**. Detailed current and future electricity mix GHG emission factors for all countries are listed in **Table 11**.

Table 11. Current and future electricity GHG intensity for Stated Policies and Sustainable Development Scenarios to 2050. Values presented in $kgCO_2eq/kWh$ electricity. (Own calculated values based on the IEA's WEO 2020 and 2021)

Country	Current	SPS			SDS		
	2020	2030	2040	2050	2030	2040	2050
Australia	0.751	0.735	0.632	0.366	0.429	0.200	0.063
Argentina	0.472	0.216	0.201	0.148	0.123	0.076	0.053
Bahrain	0.539	0.557	0.481	0.407	0.435	0.249	0.113
Belgium	0.223	0.183	0.132	0.108	0.138	0.101	0.050
Brazil	0.172	0.142	0.130	0.121	0.097	0.076	0.074
Canada	0.168	0.163	0.154	0.133	0.252	0.121	0.070
Chile	0.538	0.208	0.192	0.148	0.112	0.068	0.057
China	0.941	0.787	0.657	0.445	0.559	0.265	0.076
Cote d'lvoire	0.429	0.352	0.296	0.285	0.270	0.120	0.055
Cuba	0.974	0.196	0.192	0.160	0.132	0.092	0.076
DRC	0.045	0.035	0.031	0.024	0.029	0.025	0.017
Finland	0.167	0.122	0.099	0.094	0.100	0.087	0.049
Gabon	0.507	0.425	0.343	0.319	0.348	0.190	0.127
Germany	0.412	0.181	0.130	0.107	0.136	0.100	0.049

Ghana	0.458	0.393	0.324	0.295	0.320	0.170	0.115
Guatemala	0.329	0.199	0.188	0.149	0.124	0.086	0.071
Guinea	0.313	0.303	0.250	0.227	0.247	0.131	0.089
Hungary	0.313	0.198	0.142	0.117	0.149	0.109	0.054
India	0.947	0.743	0.507	0.336	0.490	0.197	0.095
Indonesia	1.161	0.915	0.867	0.763	0.571	0.285	0.109
Iran	0.599	0.570	0.530	0.449	0.480	0.275	0.125
Jamaica	1.037	0.248	0.235	0.186	0.154	0.107	0.088
Japan	0.614	0.451	0.398	0.212	0.310	0.189	0.088
Jordan	0.530	0.520	0.487	0.439	0.469	0.269	0.122
Kazakhstan	0.869	0.447	0.412	0.420	0.339	0.201	0.123
Korea	0.585	0.589	0.491	0.355	0.412	0.210	0.081
Madagascar	0.459	0.439	0.270	0.218	0.337	0.160	0.103
Malaysia	0.705	0.641	0.608	0.540	0.405	0.209	0.091
Mexico	0.529	0.371	0.310	0.242	0.235	0.122	0.078
Morocco	0.883	0.547	0.409	0.383	0.405	0.187	0.120
Mozambique	0.134	0.313	0.273	0.288	0.248	0.187	0.120
New Caledonia	0.859	0.602	0.501	0.360	0.417	0.211	0.084
Norway	0.032	0.181	0.150	0.128	0.126	0.090	0.046
Peru	0.244	0.203	0.192	0.152	0.126	0.087	0.072
Philippines	0.775	0.657	0.621	0.554	0.410	0.204	0.085
Poland	0.817	0.172	0.120	0.100	0.125	0.089	0.041
Qatar	0.550	0.527	0.491	0.416	0.444	0.254	0.115
Russia	0.768	0.762	0.688	0.700	0.622	0.368	0.216
Saudi Arabia	0.737	0.575	0.496	0.420	0.449	0.257	0.117
South Africa	1.010	0.808	0.530	0.326	0.617	0.165	0.131
UAE	0.555	0.570	0.496	0.420	0.449	0.257	0.117
UK	0.232	0.195	0.160	0.137	0.135	0.094	0.048
USA	0.452	0.370	0.305	0.226	0.230	0.109	0.070
Ukraine	0.401	0.219	0.182	0.156	0.157	0.110	0.065
Vietnam	0.678	0.662	0.628	0.558	0.418	0.216	0.094
Zambia	0.205	0.516	0.401	0.366	0.328	0.187	0.121
Zimbabwe	0.558	0.327	0.188	0.135	0.229	0.073	0.022

3.5 Future battery chemistry scenarios

LIB manufacturers are transitioning towards lower-cobalt cathodes, which has led to an evolution from NMC111 to NMC523, NMC622, NMC811, and, more recently, NMC955 which is expected to be available by 2030 (The Investor, 2020; U.S. DOE, 2020). However, LFP batteries are also being considered favourably for BEVs, given their relatively low material cost and high abundance, including Tesla, which recently announced the use of LFP batteries in its Model 3 (CNBC, 2021). Therefore, we set two main scenarios with varying market shares based on the assumed technological progress by (Xu *et al.*, 2020), as shown in **Figure 2**.

- ***NCX scenario (X denotes either Al or Mn)***: Nickel and cobalt-containing batteries dominate the market in 2050. NMC955 is launched in 2030 and progressively substitute other NMC chemistries until achieving a third of the global market share by 2050. The shares of NCA and LFP chemistries reduce from 2030 at a similar rate. Numerical data can be found in **Table 12**.
- ***LFP scenario:*** The market share of LFP is assumed to increase steadily from 30% in 2020 to 60% by 2030 and remains constant until 2050. Non-LFP batteries lose market share proportionally compared to the NCX scenario. Data can be found in **Table 13**.

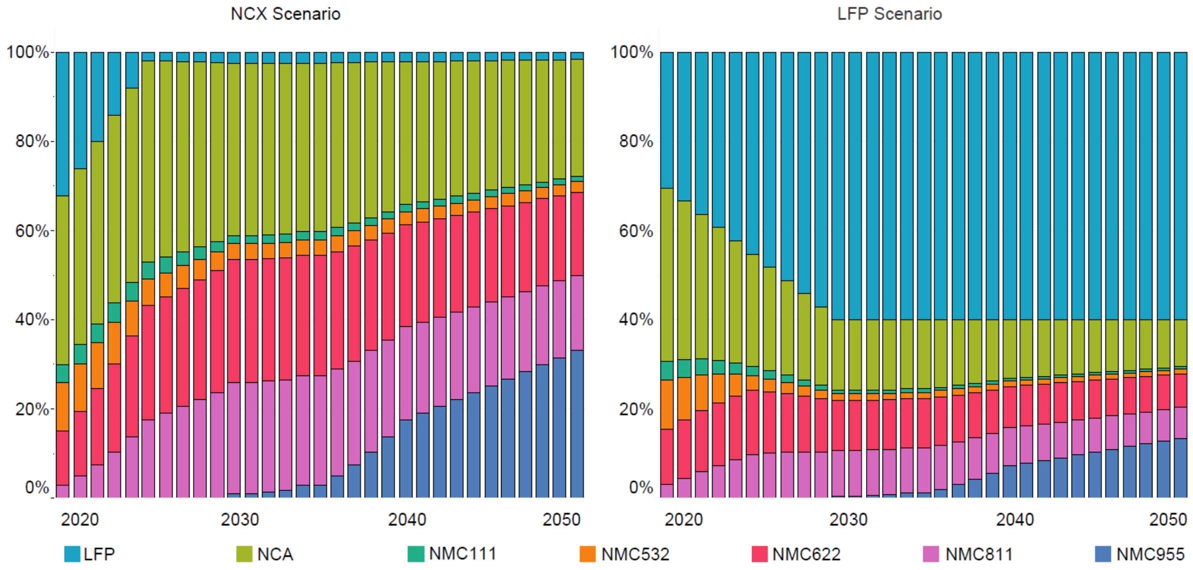

Figure 2. Battery market share by technology scenarios by 2050. Values based on the assumed technological progress by (Xu *et al.*, 2020). Numerical values shown below.

Table 12. NCX scenario battery market shares (values expressed in percentage unit%).

				NCX scenario			
Year	LFP	NCA	NMC111	NMC523	NMC622	NMC811	NMC955
2020	32.2%	37.9%	4.1%	10.7%	12.2%	2.9%	0.0%
2021	26.1%	39.3%	4.3%	10.7%	14.6%	5.0%	0.0%
2022	20.1%	40.8%	4.4%	10.2%	17.2%	7.5%	0.0%
2023	14.0%	42.2%	4.3%	9.2%	19.8%	10.4%	0.0%
2024	7.9%	43.7%	4.2%	7.8%	22.7%	13.8%	0.0%
2025	1.9%	45.1%	3.9%	5.9%	25.7%	17.6%	0.0%
2026	2.0%	43.9%	3.5%	5.5%	26.1%	19.0%	0.0%
2027	2.1%	42.6%	3.1%	5.1%	26.5%	20.5%	0.0%
2028	2.3%	41.4%	2.7%	4.6%	27.0%	22.0%	0.0%
2029	2.4%	40.2%	2.3%	4.1%	27.4%	23.6%	0.0%
2030	2.5%	38.6%	1.9%	3.6%	27.5%	25.0%	1.0%
2031	2.5%	38.5%	1.9%	3.6%	27.5%	25.0%	1.1%
2032	2.5%	38.4%	1.9%	3.6%	27.4%	24.9%	1.3%
2033	2.5%	38.3%	1.9%	3.5%	27.3%	24.8%	1.7%
2034	2.5%	37.8%	1.8%	3.5%	27.0%	24.5%	2.9%
2035	2.5%	37.8%	1.8%	3.5%	27.0%	24.5%	2.9%
2036	2.4%	37.0%	1.8%	3.4%	26.4%	24.0%	5.0%
2037	2.3%	36.0%	1.7%	3.3%	25.7%	23.4%	7.5%
2038	2.3%	34.9%	1.7%	3.2%	24.9%	22.6%	10.4%
2039	2.2%	33.6%	1.6%	3.1%	24.0%	21.8%	13.8%
2040	2.1%	32.1%	1.6%	3.0%	22.9%	20.8%	17.6%
2041	2.0%	31.5%	1.5%	2.9%	22.5%	20.4%	19.0%
2042	2.0%	31.0%	1.5%	2.9%	22.1%	20.1%	20.5%
2043	2.0%	30.4%	1.5%	2.8%	21.7%	19.7%	22.0%
2044	1.9%	29.7%	1.4%	2.8%	21.2%	19.3%	23.6%
2045	1.9%	29.1%	1.4%	2.7%	20.8%	18.9%	25.2%
2046	1.9%	28.5%	1.4%	2.6%	20.4%	18.5%	26.8%
2047	1.8%	27.9%	1.4%	2.6%	19.9%	18.1%	28.3%
2048	1.8%	27.3%	1.3%	2.5%	19.5%	17.7%	29.9%
2049	1.7%	26.7%	1.3%	2.5%	19.1%	17.3%	31.5%
2050	1.7%	26.1%	1.3%	2.4%	18.6%	16.9%	33.1%

Table 13. LFP scenario battery market shares (values expressed in percentage unit%).

LFP scenario							
Year	LFP	NCA	NMC111	NMC523	NMC622	NMC811	NMC955
2020	30.5%	38.8%	4.2%	11.0%	12.5%	3.0%	0.0%
2021	33.5%	35.4%	3.9%	9.6%	13.1%	4.5%	0.0%
2022	36.4%	32.4%	3.5%	8.1%	13.6%	5.9%	0.0%
2023	39.4%	29.8%	3.1%	6.5%	14.0%	7.3%	0.0%
2024	42.3%	27.4%	2.6%	4.9%	14.2%	8.6%	0.0%
2025	45.3%	25.2%	2.2%	3.3%	14.3%	9.8%	0.0%
2026	48.2%	23.2%	1.9%	2.9%	13.8%	10.0%	0.0%
2027	51.2%	21.3%	1.6%	2.5%	13.2%	10.2%	0.0%
2028	54.1%	19.4%	1.3%	2.2%	12.7%	10.3%	0.0%
2029	57.1%	17.7%	1.0%	1.8%	12.1%	10.4%	0.0%
2030	60.0%	15.8%	0.8%	1.5%	11.3%	10.3%	0.4%
2031	60.0%	15.8%	0.8%	1.5%	11.3%	10.2%	0.4%
2032	60.0%	15.8%	0.8%	1.5%	11.3%	10.2%	0.5%
2033	60.0%	15.7%	0.8%	1.5%	11.2%	10.2%	0.7%
2034	60.0%	15.5%	0.8%	1.4%	11.1%	10.0%	1.2%
2035	60.0%	15.5%	0.8%	1.4%	11.1%	10.0%	1.2%
2036	60.0%	15.2%	0.7%	1.4%	10.8%	9.8%	2.0%
2037	60.0%	14.8%	0.7%	1.4%	10.5%	9.6%	3.1%
2038	60.0%	14.3%	0.7%	1.3%	10.2%	9.3%	4.3%
2039	60.0%	13.7%	0.7%	1.3%	9.8%	8.9%	5.6%
2040	60.0%	13.1%	0.6%	1.2%	9.4%	8.5%	7.2%
2041	60.0%	12.9%	0.6%	1.2%	9.2%	8.3%	7.8%
2042	60.0%	12.6%	0.6%	1.2%	9.0%	8.2%	8.4%
2043	60.0%	12.4%	0.6%	1.1%	8.8%	8.0%	9.0%
2044	60.0%	12.1%	0.6%	1.1%	8.7%	7.9%	9.6%
2045	60.0%	11.9%	0.6%	1.1%	8.5%	7.7%	10.3%
2046	60.0%	11.6%	0.6%	1.1%	8.3%	7.5%	10.9%
2047	60.0%	11.4%	0.6%	1.1%	8.1%	7.4%	11.5%
2048	60.0%	11.1%	0.5%	1.0%	7.9%	7.2%	12.2%
2049	60.0%	10.9%	0.5%	1.0%	7.8%	7.0%	12.8%
2050	60.0%	10.6%	0.5%	1.0%	7.6%	6.9%	13.5%

3.6 Battery Recycling

The battery recycling LCA developed in this thesis uses data from the 2020 EverBatt model, developed by Argonne National Laboratory (ANL, 2020b). The EverBatt model is a closed-loop battery recycling cost and environmental impacts model that aims to inform decisions around the choice of the LIB recycling technique that ensures a sustainable battery metal supply chain (ANL, 2020b). For this model, all material recovery fractions, and recycling inventory derive from EverBatt. The recovery fractions are then utilised to calculate the GHG emissions from the different recycling technologies. These emissions data is then applied to a scenario of recycling in Europe (using current and future electricity grid mix). Additionally, two distinct scenarios are considered to evaluate the use of secondary battery materials: 50% recycling and ~100% recycling. Finally, a comparison of resulted GHG emissions is made, comparing manufacturing a battery from virgin materials with manufacturing a battery using secondary materials from the different recycling techniques.

This thesis considers three recycling techniques: pyrometallurgical, hydrometallurgical, and direct recycling (Dai *et al.*, 2019). Each recycling technique has its unique characteristics (as discussed in **Chapter 2**), and can recover specific components and materials of the LIB. This analysis provides the efficiency of material recovery (summarised in **Table 16**) as highlighted in (Dai *et al.*, 2019), and the battery materials that are recovered based on the recycling technology (**Table 17**). **Table 14** summarises the default assumption in EverBatt for the destinies of the materials in the battery for the different recycling routes.

Table 14. Fates of battery components for different recycling technologies (Dai *et al.*, 2019).

	Pyro	Hydro	Direct
Active cathode materials	Recycle	Recycle	Recycle
Graphite	Incineration with energy recovery	Recycle	Recycle
Copper	Recycle	Recycle	Recycle
Aluminium	Landfill	Recycle	Recycle
Plastics	Incineration with energy recovery	Incineration with energy recovery	Recycle
Electrolyte	Incineration with energy recovery	Incineration with energy recovery	Recycle
PVDF	Incineration with energy recovery	Landfill	Recycle
Steel	Recycle	Recycle	Recycle

The analysis tackles the environmental impacts of recycling techniques for different cathode chemistries, based on the amount of recovered material from the different recycling routes. The battery cathode chemistries analysed in this thesis include NMC111, NMC532, NMC622, NMC811, NCA and LFP In addition, there exist some added GHG emissions from the recycling processes. These emissions are obtained from GREET and summarised in **Table 15**. Hydrometallurgical uses more heat compared to electricity, however, pyrometallurgical and direct recycling uses significantly more electricity, and therefore their emission factors are impacted by the electricity mix of the recycling location. The recycling of battery materials as well as the battery assembly is assumed to take place in Europe as it is unknown where battery recycling infrastructure will exist in future and country-specific analysis is not possible.

Table 15. GHG emissions from pyrometallurgical, hydrometallurgical, and direct recycling techniques from GREET 2020 (ANL, 2020a).

Recycling technique	Share of heat energy use (%)	Share of electricity use (%)	Emissions (kgCO2eq/kg)
Pyrometallurgical	11.4%	88.6%	2.844
Hydrometallurgical	78.8%	21.2%	1.719
Direct	18.0%	82.0%	0.922

3.6.1 Secondary material

The amounts of materials recovered from each of the recycling technologies are determined by the amount of each material in the feedstock (as defined in the GREET model and shown in **Table 3**), and the default recovery efficiency of each material in EverBatt, as shown in **Table 16.** This analysis does not consider recovered plastics, electrolyte solvents, and binders, as recyclers may not be incentivised to recycle these materials compared with cobalt and nickel, which have a high value and are highly demanded. Also, because they fall outside the 2% emission threshold as discussed in **section 3.3.1**.

Table 16. The efficiency of material recovery for different recycling technologies. 0% indicates that materials are not recoverable (Dai *et al.*, 2019).

Material	Pyro	Hydro	Direct
Lithium	0%	90%	0%
Ni2+ in output	98%	98%	0%
Co2+ in output	98%	98%	0%
Mn2+ in output	0%	98%	0%
Aluminium	0%	90%	90%
Copper	90%	90%	90%
Graphite	0%	90%	90%
NMC111	0%	0%	90%
NMC622	0%	0%	90%
NMC811	0%	0%	90%
NCA	0%	0%	90%
LFP	0%	0%	90%

The feasibility of achieving high material recovery efficiencies depends on a variety of factors, including the availability and quality of the waste stream, the technical capabilities and cost-effectiveness of the recycling process, and the market demand for the recycled materials. If the waste stream is contaminated or mixed with other materials, it can be more difficult and expensive to achieve high recovery rates (Latini *et al.*, 2022). To improve the feasibility of achieving high recovery rates, governments and industry stakeholders can implement policies and programs that incentivise recycling and support the development of more efficient and cost-effective recycling technologies (European Commission, 2019; Hill *et al.*, 2019)

EverBatt allows users to customise the recycling process, battery chemistries, and cathode materials to further analysis. The cathode materials are recovered in chemical forms that can be incorporated back into the battery supply chain manufacturing (ANL, 2020b). The quantity of materials assumed to be recoverable from spent batteries through each of the recycling technologies for different battery chemistries is listed in **Table 17**.

Table 17. Quantity of material recovered via different recycling technologies for various battery chemistries. Values in kg/kg spent battery (from EverBatt model (ANL, 2020b)).

Recycling technique	Cathode	Co2+	Ni2+	Mn2+	Li	Gr	Cu	Al	Cathode
Pyro	**NMC111**	0.094	0.093	0.000	0.000	0.000	0.078	0.000	0.000
	NMC532	0.057	0.142	0.000	0.000	0.000	0.078	0.000	0.000
	NMC622	0.054	0.160	0.000	0.000	0.000	0.078	0.000	0.000
	NMC811	0.024	0.188	0.000	0.000	0.000	0.080	0.000	0.000
	NCA	0.039	0.208	0.000	0.000	0.000	0.075	0.000	0.000
	LFP	0.000	0.000	0.000	0.000	0.000	0.089	0.000	0.000
Hydro	**NMC111**	0.094	0.093	0.087	0.164	0.214	0.078	0.044	0.000
	NMC532	0.057	0.142	0.080	0.166	0.219	0.078	0.044	0.000
	NMC622	0.054	0.160	0.050	0.157	0.239	0.078	0.044	0.000
	NMC811	0.024	0.188	0.022	0.138	0.257	0.080	0.045	0.000
	NCA	0.039	0.208	0.000	0.153	0.257	0.075	0.043	0.000
	LFP	0.000	0.000	0.000	0.097	0.202	0.089	0.050	0.000
Direct	**NMC111**	0.000	0.000	0.000	0.000	0.214	0.078	0.044	0.423
	NMC532	0.000	0.000	0.000	0.000	0.219	0.078	0.044	0.428
	NMC622	0.000	0.000	0.000	0.000	0.239	0.078	0.044	0.405
	NMC811	0.000	0.000	0.000	0.000	0.257	0.080	0.045	0.357
	NCA	0.000	0.000	0.000	0.000	0.257	0.075	0.043	0.391
	LFP	0.000	0.000	0.000	0.000	0.202	0.089	0.050	0.396

3.6.2 Allocation

Since multiple materials are recovered from the recycling processes, choosing a coproduct handling methodology is needed in order to evaluate the environmental impacts of each of the recovered materials. In this thesis, mass-based allocation method is opted (and subsequently discussed in **Chapter 5**) since it aligns well with the new EU legislative proposal that states that 50% of a battery's weight must be recycled. From 2025, this requirement will increase to 65% and to 70% from 2030 (EPRS, 2022). The allocation factors are calculated based on the amount of the materials recovered from Everbatt as listed in **Table 18.**

Table 18. Mass-based allocation factors for recovered materials (from EverBatt).

Recycling technique	**Cathode**	Co2+	Ni2+	Mn2+	Li	Gr	Cu	Al	Cathode
Pyro	**NMC111**	35.3%	35.2%	0.0%	0.0%	N/A	29.5%	N/A	N/A
	NMC532	20.6%	51.3%	0.0%	0.0%	N/A	28.1%	N/A	N/A
	NMC622	18.4%	55.0%	0.0%	0.0%	N/A	26.6%	N/A	N/A
	NMC811	8.1%	64.5%	0.0%	0.0%	N/A	27.4%	N/A	N/A
	NCA	12.2%	64.6%	0.0%	0.0%	N/A	23.2%	N/A	N/A
	LFP	N/A	N/A	N/A	N/A	N/A	100%	N/A	N/A
Hydro	**NMC111**	12.1%	12.0%	11.3%	21.2%	27.7%	10.1%	5.7%	N/A
	NMC532	7.2%	18.0%	10.1%	21.2%	27.9%	9.9%	5.6%	N/A
	NMC622	6.9%	20.5%	6.4%	20.1%	30.6%	9.9%	5.6%	N/A
	NMC811	3.1%	24.9%	2.9%	18.4%	34.1%	10.6%	6.0%	N/A
	NCA	5.1%	26.8%	0.0%	19.7%	33.1%	9.7%	5.5%	N/A
	LFP	N/A	N/A	N/A	22.1%	46.1%	20.4%	11.5%	N/A
Direct	**NMC111**	N/A	N/A	N/A	N/A	28.2%	10.3%	5.8%	55.6%
	NMC532	0.0%	0.0%	0.0%	0.0%	28.5%	10.1%	5.7%	55.7%
	NMC622	N/A	N/A	N/A	N/A	31.2%	10.1%	5.7%	52.9%
	NMC811	N/A	N/A	N/A	N/A	34.7%	10.8%	6.2%	48.3%
	NCA	N/A	N/A	N/A	N/A	33.5%	9.8%	5.6%	51.1%
	LFP	N/A	N/A	N/A	N/A	27.4%	12.1%	6.8%	53.7%

3.6.3 Battery closed-loop recycling

This thesis aims to benchmark production with virgin materials against production with secondary materials[*], and/or a combination of both, to provide a holistic picture of the benefits and tradeoffs of battery recycling. Therefore, this analysis assumes two distinct recycling scenarios:

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[*] Secondary materials mean used material which has been recycled at their end of life and placed back into use as valuable material.

- **50-50 Scenario.** It is a current requirement that half of battery's weight must be recycled. Therefore, this scenario assumes that 50% of the recyclable materials in a battery come from virgin materials and 50% from secondary materials; as stated by the new European battery legislation (EPRS, 2022).
- **Circular battery scenario.** Most materials are secondary materials (recycled). This scenario assumes a complete closed loop, where battery reaches end-of-life, and is replaced. Secondary materials available from recycling are then used, alongside supplement with primary materials to create new battery to replace same battery chemistry at the same capacity. The ratio of recycled materials included in secondary battery manufacturing is based on the efficiency of material recovery for different recycling technologies given in **Table 16**, i.e., lithium recovered via hydro at 90% efficiency will include 10% virgin lithium and 90% secondary lithium.

These two scenarios are applied to the cathode and battery manufacturing processes and discussed later in **Chapter 5. Table 19** summarises the assumptions for closed-loop recycling scenarios. These scenarios are not predicting what will happen but will try to put into context how recycling could reduce impacts in the future. Secondary supply, via recycling, can help reduce primary supply requirements and alleviate the environmental burdens associated with the extraction and processing of materials from primary sources. Therefore, these recycling scenarios look at the range of potential outcomes, comparing production from all materials with maximum secondary material scenario (circular battery scenario) and a slightly more realistic scenario with 50% from virgin materials and 50% from secondary materials (50-50 scenario). The recycling scenarios are hypothetical since secondary materials will never meet rising demand for batteries, meaning that although recycling provide useful complementary resources, it can only provide a tiny fraction of total demand (Bloodworth, 2014). However, this provides a holistic view on the possible outcomes of recycling. Worth mentioning that battery use phase is not included in the thesis, as shown in **Figure 1.**

Table 19. Shares of sources of battery materials for different recycling techniques.

Recycling technique			Li	Ni2+	Co2+	Mn2+	Gr	Al	Cu	Cathode
Pyro	**50-50 Recycled**	**Via Pyro**	0%	50%	50%	0%	0%	0%	50%	N/A
		Via Hydro	0%	0%	0%	0%	0%	0%	0%	0%
		Via Direct	0%	0%	0%	0%	0%	0%	0%	0%
		Virgin	100%	50%	50%	100%	100%	100%	50%	100%
	Circular Battery	**Via Pyro**	0%	98%	98%	0%	0%	0%	90%	0%
		Via Hydro	0%	0%	0%	0%	0%	0%	0%	0%
		Via Direct	0%	0%	0%	0%	0%	0%	0%	0%
		Virgin	100%	2%	2%	100%	100%	100%	10%	100%
Hydro	**50-50 Recycled**	**Via Pyro**	0%	0%	0%	0%	0%	0%	0%	0%
		Via Hydro	50%	50%	50%	50%	50%	50%	50%	0%
		Via Direct	0%	0%	0%	0%	0%	0%	0%	0%
		Virgin	50%	50%	50%	50%	50%	50%	50%	100%
	Circular Battery	**Via Pyro**	0%	0%	0%	0%	0%	0%	0%	0%
		Via Hydro	90%	98%	98%	98%	90%	90%	90%	0%
		Via Direct	0%	0%	0%	0%	0%	0%	0%	0%
		Virgin	10%	2%	2%	2%	10%	10%	10%	100%
Direct	**50-50 Recycled**	**Via Pyro**	0%	0%	0%	0%	0%	0%	0%	0%
		Via Hydro	0%	0%	0%	0%	0%	0%	0%	0%
		Via Direct	0%	0%	0%	0%	50%	50%	50%	50%
		Virgin	0%	0%	0%	0%	50%	50%	50%	50%
	Circular Battery	**Via Pyro**	0%	0%	0%	0%	0%	0%	0%	N/A
		Via Hydro	0%	0%	0%	0%	0%	0%	0%	N/A
		Via Direct	N/A	N/A	N/A	N/A	90%	90%	90%	90%
		Virgin	0%	0%	0%	0%	10%	10%	10%	10%

CHAPTER 4 CHAPTER 4 Battery Production

This section explores the GHG emissions of different LIB technologies by looking at where in the world materials and battery manufacturing processes take place, the emissions associated with these activities, and how these emissions are expected to change in the future over the supply chain. Thus, this section presents five assessment results: **4.1)** cathode active material impacts, **4.2)** total battery impacts, **4.3)** supply chain impacts and their contribution to the cathode and battery manufacturing, **4.4)** impacts of future battery production by decarbonising the electricity sector, **4.5)** future battery technology mix and projected impacts. For simplicity, results and discussion focus primarily on NMC811 and LFP battery chemistries throughout the thesis, however, numerical data for all chemistries is provided. NMC811 is selected because of its current global relevance in BEVs and its high energy density, while LFP is selected as it is expected to make up an increasingly important share of LIB in the market (Erriquez *et al.*, 2021).

4.1 Current impacts of cathode active material production

Figure 3 shows the cradle-to-gate PED and GHG emissions of different materials and production processes of the cathode active material for 1 kWh of various LIB technologies. Nickel-based cathode materials are characterised by comparatively high GHG emissions, ranging from 45 kgCO_2eq/kWh (NMC111 and NMC811) to over 50 kgCO_2eq/kWh (NCA). GHG emissions for these chemistries are dominated by the active materials used (primarily nickel and lithium carbonate/hydroxide, but also cobalt for more cobalt-rich chemistries) and the process of cathode production. Nickel production is GHG-intensive, mainly due to the high electricity consumption of nickel mining in Indonesia (38.3%) and nickel refining in China (32.3%), and their correspondingly higher electricity GHG emissions intensities (see **Table 10**

in methods). In contrast, an LFP cathode has lower GHG emissions of 17 kgCO_2eq/kWh due to less reliance on GHG-intensive active materials. For LFP cathodes, most emissions are derived from lithium hydroxide input and the cathode production process. Detailed GHG emissions breakdown by material types for each LIB cathode are shown in **Table 20**. PED results largely parallel the GHG emissions results: nickel-based cathode chemistries are more energy intensive than the LFP alternative, driven by the cathode active materials used in NCA and NMC chemistries (see **Figure 3B** for PED figure).

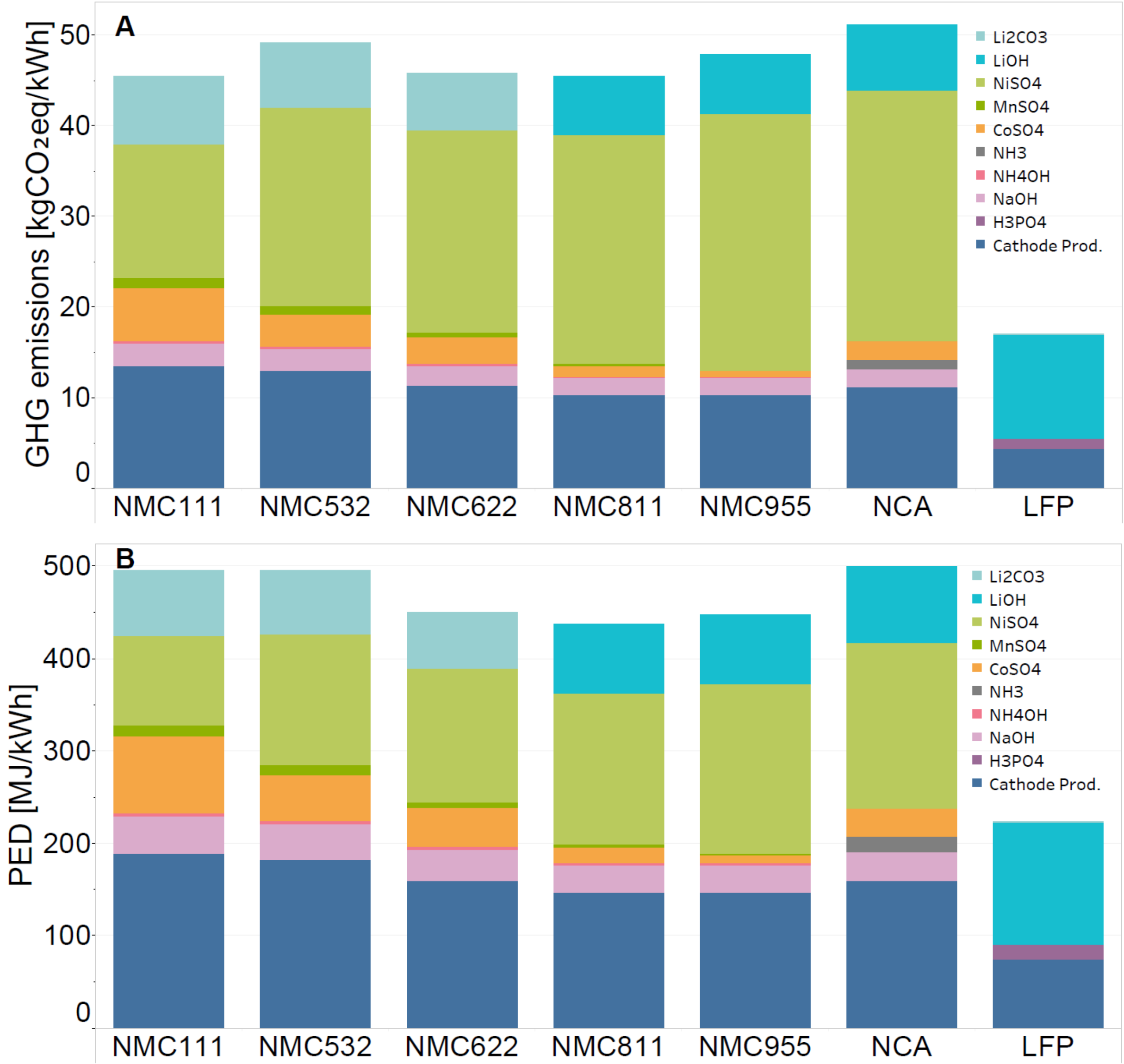

Figure 3. Cradle-to-gate environmental impacts for 1 kWh of cathode materials and cathode production processes for different LIBs **(A)** GHG emissions expressed in kgCO_2eq/kWh **(B)**

PED expressed in MJ/kWh. The cathode production process includes precursor co-precipitation and cathode production via calcination. Numerical data can be found in **Table 20**.

4.2 Total battery production

In line with results for cathode materials, whole battery analysis reveals similar GHG emissions for all nickel-based chemistries ranging from ~ 80 $kgCO_2eq/kWh$ (NMC111, NMC622, NMC 811) to a maximum of 84 $kgCO_2eq/kWh$ (NCA). Detailed GHG and PED impacts for all chemistries are given in **Table 21**. Across all nickel-based battery chemistries, the manufacturing of the cathode, including the active material and cathode production process, contributes the largest GHG emissions share, accounting for nearly 60% of the total (cathode active material 44% and cathode production 13%). The relative contributions of cathode active material production are discussed in **section 4.1**. Apart from the active material, wrought aluminium, which is used as the current collector for the cathode electrode, as well as for the battery enclosure, contributes approximately 12% of the total emissions. The battery management system (BMS) or electronic components, whilst having a high energy demand in their production (505 MJ per kg of BMS; ~ 29.39 $kgCO_2eq$ per kg of BMS), are only responsible for ~2% of the total emissions per kWh of battery due to their minor share of battery material composition by weight (~1.75%). Copper contributes the lowest GHG emissions: just over 1% of the total. In comparison, battery assembly is a significant source of emissions, representing about 21% of the total GHG emissions. Therefore, the location of the assembly plant is important due to variations in the electricity grid's GHG intensities.

The LFP battery has lower GHG emissions than any of the nickel-based chemistries, with an intensity of 56 $kgCO_2eq/kWh$. This is due primarily to the lower impacts associated with cathode production. However, because of its lower energy density, an LFP battery is considerably bigger and heavier than nickel-based chemistry, which has about 20-40% higher gravimetric energy density. Therefore, other battery materials and the assembly process, have a greater impact on an LFP battery than any of the nickel-based chemistries due to the lower energy density of the LFP chemistry and correspondingly greater battery size. (See **Figure 4B** for PED figure). **Figure 4** shows the cradle-to-gate GHG and PED for 1 kWh of different LIB technologies.

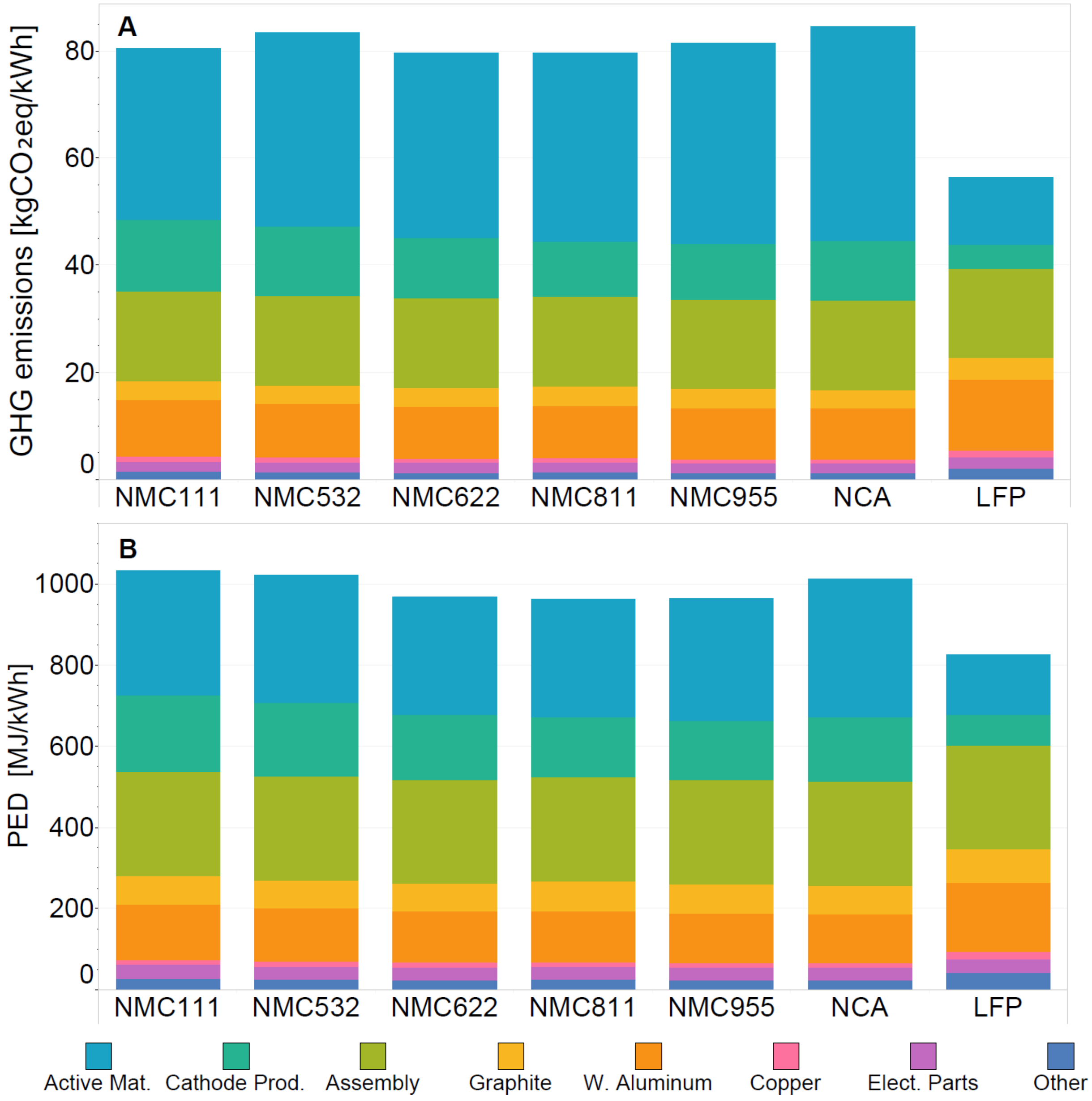

Figure 4. Cradle-to-gate environmental impacts for 1 kWh of different LIB technologies and the breakdown of contributions of the materials, along the BOM (i.e., weights of different

materials/components) and battery assembly. **(A)** GHG emissions expressed in $kgCO_2eq/kWh$ **(B)** PED expressed in MJ/kWh. Materials such as binder (polyvinylidene fluoride), electrolytes ($LiPF_6$, Ethylene Carbonate, Dimethyl Carbonate), plastics (polypropylene, polyethylene, polyethylene terephthalate), steel, thermal insulation, and coolant are grouped into "Other", because they each contribute less than 1% to the total GHG emissions. Numerical data can be found in **Table 21**.

Currently, Tesla uses nickel-based batteries for most of its models sold in the US. However, based on recent announcement, Tesla plans to use iron-based batteries to its semi electric trucks and mid-size vehicles (Jin and Lienert, 2023). LFP batteries are heavier and usually hold less energy density than nickel-based batteries, providing shorter range. Notwithstanding, LFP batteries are suitable for daily use commuting vehicles within short distances due to their long cycle life, safety and low self-discharge rate (Miao *et al.*, 2019a). Also, the abundance, cheaper prices, and low carbon footprint of LFP batteries make them suitable option for decarbonising the personal transport sector. For longer distances, other types of batteries such as nickel-based batteries may be more suitable due to their higher density and faster charging time. In summary, in the near future, nickel-based batteries are expected to be used only for extremely long range EVs and trucks, everything else will be iron-based.

Table 20. GHG emissions and PED of cathode active material production. GHG is expressed in $kgCO_2eq/kWh$ and PED is expressed in MJ/kWh.

Materials	**NMC111**		**NMC532**		**NMC622**		**NMC811**		**NMC955**		**NCA**		**LFP**	
	PED	**GHG**	**PED**	**GHG**	**PED**	**GHG**	**PED**	**GHG**	**PED**	**GHG**	**PED**	**GHG**	**PED**	**GHG**
Nickel Sulfate	95.87	14.78	142.06	21.89	144.94	22.34	163.34	25.18	183.66	28.31	179.62	27.68	0.00	0.00
Cobalt Sulfate	83.18	5.85	49.62	3.49	41.92	2.95	17.72	1.25	8.90	0.63	29.75	2.09	0.00	0.00
Manganese Sulfate	12.22	1.11	10.56	0.96	6.16	0.56	2.60	0.24	1.31	0.12	0.00	0.00	0.00	0.00
Lithium Carbonate	71.26	7.47	68.45	7.18	59.85	6.27	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Lithium Hydroxide	0.00	0.00	0.00	0.00	0.00	0.00	74.90	6.52	74.93	6.52	82.38	7.17	132.54	11.53
Sodium Hydroxide	40.41	2.53	38.86	2.43	34.12	2.13	28.95	1.81	28.96	1.81	31.04	1.94	0.00	0.00
Ammonium Hydroxide	3.59	0.22	3.45	0.21	3.03	0.19	2.57	0.16	2.57	0.16	0.00	0.00	0.00	0.00
Ammonia	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	17.18	1.06	0.00	0.00
Aluminium Sulfate	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.08	0.01	0.00	0.00
Oxygen	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.14	0.01	0.00	0.00
Phosphoric Acid	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	15.74	1.07
Precursor Co-precipitation	75.29	4.41	72.39	4.24	63.56	3.73	53.93	3.16	53.95	3.16	58.45	3.43	0.00	0.00
Cathode Prod. via Calcination	113.88	9.09	109.95	8.77	96.12	7.67	93.18	7.16	93.22	7.16	100.93	7.75	75.02	4.40
Total	**495.69**	**45.46**	**495.33**	**49.18**	**449.70**	**45.84**	**437.18**	**45.47**	**447.50**	**47.87**	**499.57**	**51.14**	**223.30**	**17.00**

Table 21. GHG emissions and PED of total battery production. GHG expressed in $kgCO_2eq/kWh$ and PED expressed in MJ/kWh.

Materials	**NMC111**		**NMC532**		**NMC622**		**NMC811**		**NMC955**		**NCA**		**LFP**	
	PED	**GHG**	**PED**	**GHG**	**PED**	**GHG**	**PED**	**GHG**	**PED**	**GHG**	**PED**	**GHG**	**PED**	**GHG**
Active Material (materials production)	306.52	31.96	312.99	36.16	290.02	34.44	290.08	35.14	300.33	37.54	340.19	39.96	148.28	12.60
Cathode Production	189.17	13.50	182.34	13.02	159.68	11.40	147.11	10.32	147.17	10.32	159.38	11.18	75.02	4.40
Battery Assembly	256.36	16.68	256.36	16.68	256.36	16.68	256.36	16.68	256.36	16.68	256.36	16.68	256.36	16.68
Graphite	70.45	3.50	68.65	3.41	68.80	3.42	73.96	3.68	71.85	3.57	70.05	3.48	82.35	4.09
Wrought aluminium	135.33	10.54	129.95	10.12	124.92	9.73	125.13	9.75	122.00	9.50	120.87	9.41	169.46	13.20
Copper	13.30	0.94	12.62	0.89	11.66	0.83	11.55	0.82	11.14	0.79	10.77	0.76	18.80	1.33
Electronic Parts	33.33	1.94	32.06	1.87	32.06	1.87	32.06	1.87	31.53	1.83	32.13	1.87	33.75	1.96
Binder	2.06	0.12	1.31	0.08	1.20	0.07	2.18	0.13	1.58	0.09	1.15	0.07	1.57	0.09
Electrolyte: LiPF6	12.68	0.74	11.51	0.67	11.18	0.65	11.04	0.64	10.52	0.61	10.68	0.62	20.15	1.17
Electrolyte: EC	1.51	0.06	1.37	0.05	1.33	0.05	1.32	0.05	1.25	0.05	1.27	0.05	2.40	0.09
Electrolyte: DMC	5.56	0.21	5.05	0.19	4.90	0.18	4.84	0.18	4.61	0.17	4.68	0.17	8.84	0.33
Plastic: PP	2.01	0.06	2.30	0.07	1.71	0.05	2.02	0.06	1.97	0.06	1.56	0.05	2.99	0.09
Plastic: PE	0.57	0.02	0.66	0.02	0.51	0.02	0.58	0.02	0.58	0.02	0.47	0.02	0.81	0.03
Plastic: PET	0.56	0.02	0.53	0.02	0.50	0.02	0.51	0.02	0.49	0.02	0.48	0.02	0.74	0.03
Steel	0.72	0.06	0.66	0.06	0.64	0.05	0.64	0.05	0.62	0.05	0.61	0.05	0.98	0.08
Thermal Insulation	0.34	0.02	0.34	0.02	0.33	0.02	0.33	0.02	0.32	0.02	0.33	0.02	0.40	0.03
Coolant: Glycol	2.00	0.18	1.99	0.17	2.02	0.18	1.98	0.17	1.99	0.17	2.09	0.18	2.55	0.22
Total per battery	**1,032**	**80.55**	**1,021**	**83.51**	**967.8**	**79.66**	**961.7**	**79.60**	**964.3**	**81.52**	**1,013**	**84.60**	**825.5**	**56.44**

4.3 Supply chain environmental impacts

Globally, GHG emissions associated with LIB manufacture are concentrated in a small number of countries where material extraction, processing and refining, and battery manufacturing processes take place. As described in section 3.3, key drivers of GHG emissions include the production of nickel-based cathode materials, lithium, aluminium and graphite, as well as cathode manufacturing and battery assembly. Globally, GHG emissions hotspots relate to these key materials and LIB production activities. Global supply chain emissions for NMC811 cathode active material production and total battery production are shown in **Figure 5A** and **Figure 5B**, respectively; LFP cathode active material and total battery production are shown in **Figure 7A** and **Figure 7B**, represented in a map-based figure.

For the NMC811 cathode active material production and total battery production (**Figure 5**), global GHG emissions are highly concentrated in China, which represents 28% of cathode production and 45% of total battery production GHG emissions. As the world's largest battery producer (78% of global production), a significant share of cathode production and battery assembly occurs in China and these activities dominate China's contribution to the global GHG emissions of LIB manufacture. China is also a key nation for the refining of key battery materials. Although China does not possess an abundance of LIB deposits, it operates over 80% of global raw LIB material refining and is the world's largest producer of graphite, which is the primary anode material. With a fossil fuel-dominated electricity grid, China also has a GHG-intensive electricity mix (0.941 kgCO_2eq/kWh) resulting in relatively high GHG emissions per unit of activity (IEA, 2020a). Indonesia contributes the second largest share of NMC811 global total battery production emissions (13%) due to its large share of nickel mining and extraction activities (38%) and the highly emissions-intensive generation of 1.16 kgCO_2eq/kWh of its electricity mix, which is also fossil-fuel dominated (83%), with coal-fired generation representing 62.7%, (IEA, 2020a). In **Figure 5B,** the value of 10.02 for Indonesia indicates its emission contribution in kgCO_2eq per kWh battery. Australia contributes 9% to global emissions for NMC811 total battery production, due to its role in producing approximately half of the global lithium supply and significant nickel mining and refining operations. Detailed GHG emissions and PED data by country for the NMC811 battery are presented in **Table 22** and **Table 23** for cathode production, and in **Table 24** and **Table 25** for total battery production. In addition, **Figure 6** illustrates the GHG emissions contributions breakdown by country for the NMC811 battery.

Only a small number of countries represent significant contributions to the global supply chain GHG emissions of LFP batteries (**Figure 7**). Parallel to NMC811, China dominates GHG emissions related to its dominating market share of cathode and battery manufacturing, as well as its role in refining key battery materials (lithium, aluminium, graphite, and copper). In total, 57% of LFP battery production emissions occur in China. Australia is the second greatest emissions source for LFP batteries due to its role in lithium and aluminium production, representing 17% of total emissions. Other countries that represent significant shares of LFP battery production are Chile (5%), Brazil (3%), and the USA (3%). Detailed GHG emissions and PED data by country are presented in **Table 26** and **Table 27** for LFP active material, and **Table 28** and **Table 29** for total LFP battery. In addition, **Figure 8** illustrates the GHG emissions contributions by the country for LFP batteries.

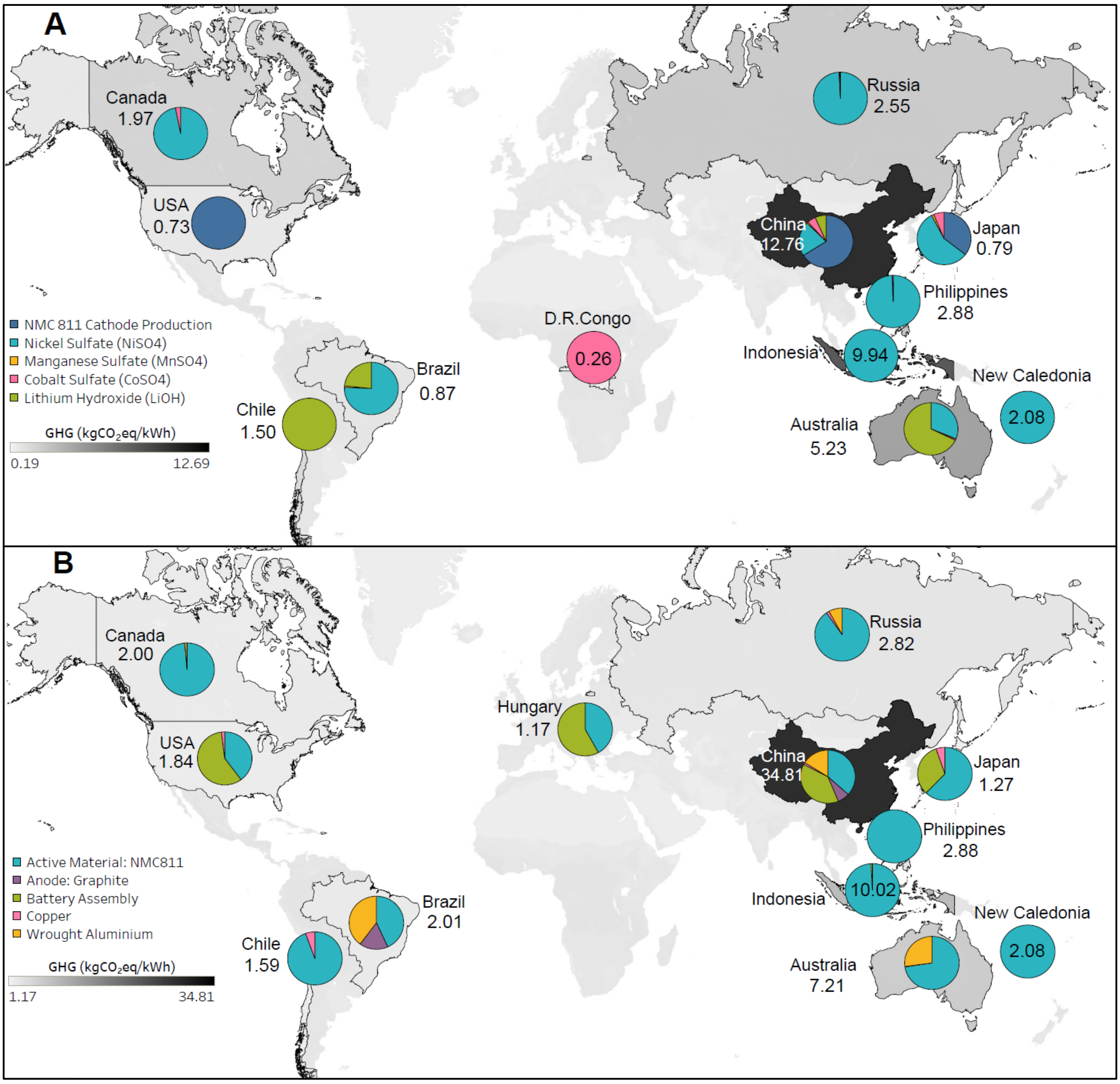

Figure 5. (A) Supply Chain GHG emissions of the Cathode Active Material (precursor) for NMC811 Li-ion battery - global production emissions of 45 kgCO$_2$eq/kWh **(B)** Supply Chain GHG emissions of the total NMC811 battery – Global average production emissions of 79 kgCO$_2$eq/kWh. Note: Values on the map indicate the emissions in kgCO$_2$eq per kWh battery. Detailed numerical values can be found in **Table 22.**

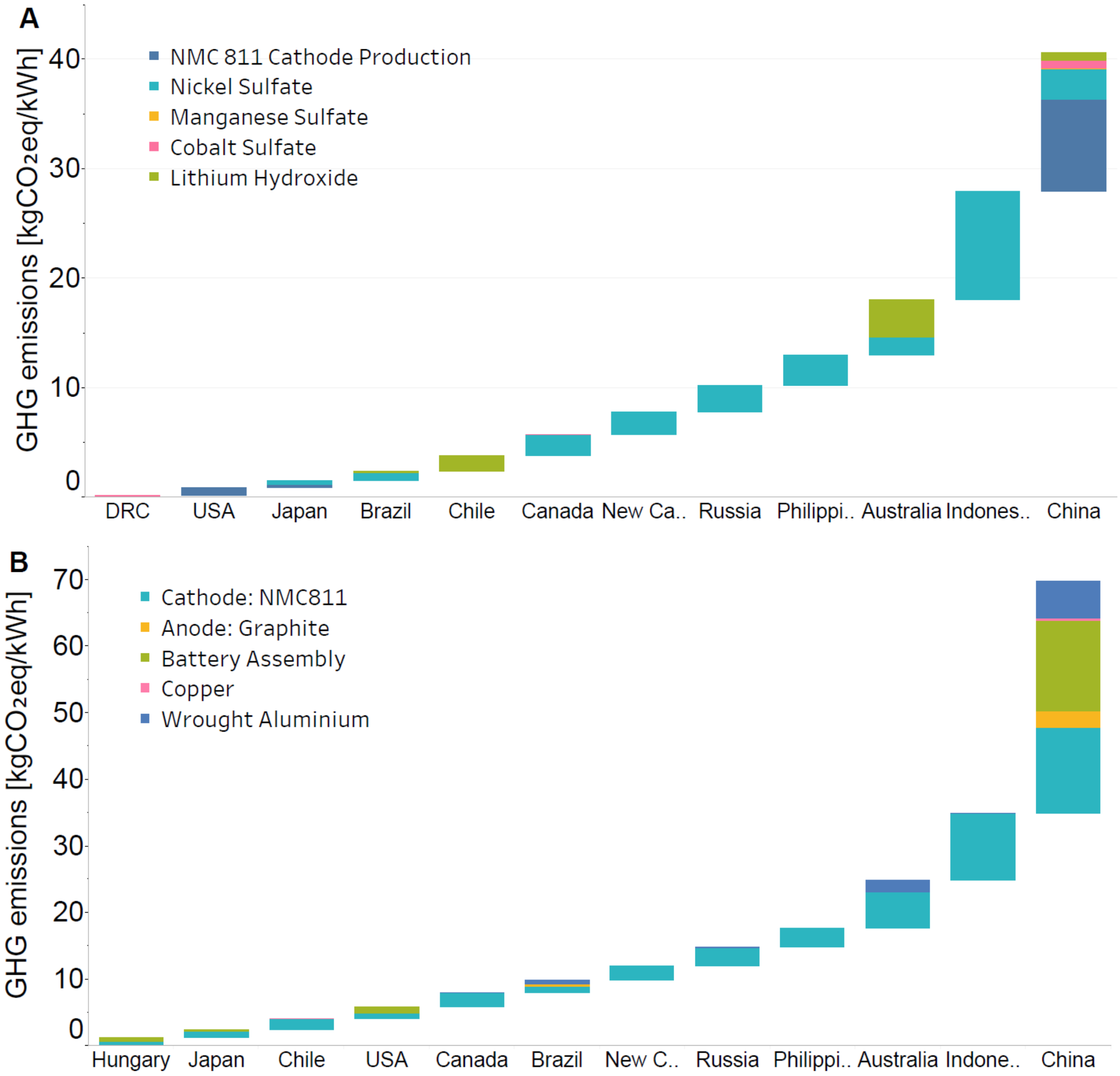

Figure 6. NMC811 supply chain GHG emissions of **(A)** cathode active material - global production emissions of 45.47 kgCO_2eq/kWh. Sodium hydroxide (1.81 kgCO_2eq/kWh) and ammonium hydroxide (0.16 kgCO_2eq/kWh) are not included in the figure. Numerical values can be found in **Table 22 (B)** Total NMC811 battery production – global average production emissions of 79.6 kgCO_2eq/kWh. Numerical values can be found in **Table 24**.

Table 22. Global supply chain GHG emissions of NMC811 active cathode materials. NiSO4 = nickel sulfate, CoSO4 = cobalt sulfate, MnSO4 = manganese sulfate, NaOH = sodium hydroxide, NH4OH = ammonium hydroxide, LiCO3 = lithium carbonate, NMC = precursor co-precipitation, Li-NMC = cathode production via calcination. GHG emissions expressed in kgCO$_2$eq/kWh.

NMC811	NiSO4	CoSO4	MnSO4	NaOH	NH4OH	LiCO3	NMC	Li-NMC	**Total**
Argentina	0.00	0.00	0.00	0.00	0.00	0.49	0.00	0.00	**0.49**
Australia	1.61	0.04	0.01	0.06	0.01	3.50	0.00	0.00	**5.23**
Belgium	0.00	0.05	0.00	0.06	0.01	0.00	0.00	0.00	**0.12**
Brazil	0.60	0.00	0.01	0.06	0.01	0.19	0.00	0.00	**0.87**
Canada	1.84	0.06	0.00	0.06	0.01	0.00	0.00	0.00	**1.97**
Chile	0.00	0.00	0.00	0.00	0.00	1.50	0.00	0.00	**1.50**
China	2.71	0.66	0.10	0.06	0.01	0.84	2.57	5.81	**12.76**
Cote d'lvoire	0.00	0.00	0.01	0.06	0.01	0.00	0.00	0.00	**0.08**
Cuba	0.00	0.01	0.00	0.06	0.01	0.00	0.00	0.00	**0.08**
DRC	0.00	0.19	0.00	0.06	0.01	0.00	0.00	0.00	**0.26**
Finland	0.20	0.10	0.00	0.06	0.01	0.00	0.00	0.00	**0.37**
Gabon	0.00	0.00	0.01	0.06	0.01	0.00	0.00	0.00	**0.09**
Ghana	0.00	0.00	0.01	0.06	0.01	0.00	0.00	0.00	**0.08**
Guatemala	0.48	0.00	0.00	0.06	0.01	0.00	0.00	0.00	**0.55**
Hungary	0.00	0.00	0.00	0.06	0.01	0.00	0.13	0.29	**0.49**
India	0.00	0.00	0.02	0.06	0.01	0.00	0.00	0.00	**0.09**
Indonesia	9.87	0.00	0.00	0.06	0.01	0.00	0.00	0.00	**9.94**
Japan	0.41	0.05	0.01	0.06	0.01	0.00	0.08	0.18	**0.79**
Korea	0.00	0.00	0.01	0.06	0.01	0.00	0.08	0.19	**0.35**
Madagascar	0.00	0.03	0.00	0.06	0.01	0.00	0.00	0.00	**0.10**
Malaysia	0.00	0.00	0.01	0.06	0.01	0.00	0.00	0.00	**0.08**
New Caledonia	2.01	0.00	0.00	0.06	0.01	0.00	0.00	0.00	**2.08**
Norway	0.21	0.03	0.00	0.06	0.01	0.00	0.00	0.00	**0.31**
PNG	0.00	0.01	0.00	0.06	0.01	0.00	0.00	0.00	**0.08**
Poland	0.00	0.00	0.00	0.06	0.01	0.00	0.10	0.23	**0.40**
Philippines	2.79	0.02	0.00	0.06	0.01	0.00	0.00	0.00	**2.88**
Russia	2.46	0.01	0.01	0.06	0.01	0.00	0.00	0.00	**2.55**
South Africa	0.00	0.00	0.03	0.06	0.01	0.00	0.00	0.00	**0.10**
Ukraine	0.00	0.00	0.01	0.06	0.01	0.00	0.00	0.00	**0.08**
USA	0.00	0.00	0.00	0.06	0.01	0.00	0.20	0.46	**0.73**
Total	**25.18**	**1.25**	**0.24**	**1.81**	**0.16**	**6.52**	**3.16**	**7.16**	**45.47**

Table 23. Global supply chain PED of NMC811 active cathode materials. NiSO4 = nickel sulfate, CoSO4 = cobalt sulfate, MnSO4 = manganese sulfate, NaOH = sodium hydroxide, NH4OH = ammonium hydroxide, LiCO3 = lithium carbonate, NMC = precursor co-precipitation, Li-NMC = cathode production via calcination. PED expressed in MJ/kWh.

NMC811	NiSO4	CoSO4	MnSO4	NaOH	NH4OH	LiCO3	NMC	Li-NMC	**Total**
Argentina	0.00	0.00	0.00	0.00	0.00	5.63	0.00	0.00	**5.63**
Australia	10.06	0.60	0.10	1.03	0.09	40.22	0.00	0.00	**52.11**
Belgium	0.00	0.69	0.00	1.03	0.09	0.00	0.00	0.00	**1.81**
Brazil	3.93	0.00	0.05	1.03	0.09	2.15	0.00	0.00	**7.25**
Canada	11.54	0.83	0.00	1.03	0.09	0.00	0.00	0.00	**13.50**
Chile	0.00	0.00	0.00	0.00	0.00	17.25	0.00	0.00	**17.25**
China	24.22	9.09	1.33	1.03	0.09	9.65	43.80	75.68	**164.91**
Cote d'lvoire	0.00	0.00	0.02	1.03	0.09	0.00	0.00	0.00	**1.15**
Cuba	0.00	0.19	0.00	1.03	0.09	0.00	0.00	0.00	**1.32**
DRC	0.00	2.91	0.00	1.03	0.09	0.00	0.00	0.00	**4.04**
Finland	2.16	1.32	0.00	1.03	0.09	0.00	0.00	0.00	**4.61**
Gabon	0.00	0.00	0.16	1.03	0.09	0.00	0.00	0.00	**1.29**
Ghana	0.00	0.00	0.08	1.03	0.09	0.00	0.00	0.00	**1.21**
Guatemala	2.60	0.00	0.00	1.03	0.09	0.00	0.00	0.00	**3.73**
Hungary	0.00	0.00	0.00	1.03	0.09	0.00	2.20	3.80	**7.12**
India	0.00	0.00	0.25	1.03	0.09	0.00	0.00	0.00	**1.37**
Indonesia	58.82	0.00	0.00	1.03	0.09	0.00	0.00	0.00	**59.95**
Japan	4.37	0.62	0.08	1.03	0.09	0.00	1.33	2.31	**9.84**
Korea	0.00	0.00	0.07	1.03	0.09	0.00	1.41	2.44	**5.05**
Madagascar	0.00	0.42	0.00	1.03	0.09	0.00	0.00	0.00	**1.54**
Malaysia	0.00	0.00	0.02	1.03	0.09	0.00	0.00	0.00	**1.15**
New Caledonia	12.02	0.00	0.00	1.03	0.09	0.00	0.00	0.00	**13.15**
Norway	2.20	0.46	0.00	1.03	0.09	0.00	0.00	0.00	**3.79**
PNG	0.00	0.11	0.00	1.03	0.09	0.00	0.00	0.00	**1.23**
PNG	0.00	0.00	0.00	1.03	0.09	0.00	1.73	2.98	**5.84**
Philippines	15.30	0.25	0.00	1.03	0.09	0.00	0.00	0.00	**16.68**
Russia	16.11	0.21	0.06	1.03	0.09	0.00	0.00	0.00	**17.50**
South Africa	0.00	0.00	0.34	1.03	0.09	0.00	0.00	0.00	**1.47**
Ukraine	0.00	0.00	0.03	1.03	0.09	0.00	0.00	0.00	**1.16**
USA	0.00	0.00	0.00	1.03	0.09	0.00	3.45	5.97	**10.55**
Total	**163.34**	**17.72**	**2.60**	**28.95**	**2.57**	**74.90**	**53.93**	**93.18**	**437.18**

Table 24. Global supply chain GHG emissions of total NMC811 battery production. GHG emissions are expressed in kgCO_2eq/kWh. Other emissions (not included in analysis) = 3.22 kgCO_2eq/kWh. Other emissions include a binder, electrolytes (LiPF6, ethylene carbonate, dimethyl carbonate), plastics (polypropylene, polyethylene, polyethylene terephthalate), steel, thermal insulation, coolant and electronic parts.

NMC811	Active Material	Graphite	Copper	Wrought Aluminium	Battery Assembly	**Total**
Argentina	0.49	0.00	0.00	0.00	0.00	**0.49**
Australia	5.23	0.00	0.02	1.95	0.00	**7.21**
Bahrain	0.00	0.00	0.00	0.01	0.00	**0.01**
Belgium	0.12	0.00	0.00	0.00	0.00	**0.12**
Brazil	0.87	0.34	0.00	0.80	0.00	**2.01**
Canada	1.97	0.00	0.00	0.03	0.00	**2.00**
Chile	1.50	0.00	0.09	0.00	0.00	**1.59**
China	12.76	2.48	0.42	5.60	13.55	**34.81**
Cote d'lvoire	0.08	0.00	0.00	0.00	0.00	**0.08**
Cuba	0.08	0.00	0.00	0.00	0.00	**0.08**
DRC	0.26	0.00	0.02	0.00	0.00	**0.28**
Finland	0.37	0.00	0.00	0.00	0.00	**0.37**
Gabon	0.09	0.00	0.00	0.00	0.00	**0.09**
Ghana	0.09	0.00	0.00	0.00	0.00	**0.09**
Germany	0.00	0.00	0.01	0.00	0.00	**0.01**
Guatemala	0.55	0.00	0.00	0.00	0.68	**1.23**
Guinea	0.00	0.00	0.00	0.35	0.00	**0.35**
Hungary	0.49	0.00	0.00	0.00	0.00	**0.49**
India	0.09	0.12	0.01	0.61	0.00	**0.83**
Indonesia	9.94	0.00	0.00	0.08	0.00	**10.02**
Jamaica	0.00	0.00	0.00	0.05	0.00	**0.05**
Japan	0.79	0.00	0.07	0.00	0.00	**0.86**
Korea	0.35	0.14	0.03	0.00	0.00	**0.52**
Madagascar	0.10	0.19	0.00	0.00	0.00	**0.29**
Malaysia	0.08	0.00	0.00	0.00	0.00	**0.08**
Mexico	0.00	0.00	0.00	0.00	0.00	**0.00**
Mozambique	0.00	0.40	0.00	0.00	0.00	**0.40**
New Caledonia	2.08	0.00	0.00	0.00	0.00	**2.08**
Norway	0.31	0.00	0.00	0.01	0.00	**0.32**
PNG	0.08	0.00	0.00	0.00	0.53	**0.61**
Peru	0.00	0.00	0.01	0.00	0.00	**0.01**
Philippines	2.88	0.00	0.00	0.00	0.00	**2.88**
Poland	0.40	0.00	0.03	0.00	0.00	**0.43**
Russia	2.55	0.00	0.05	0.22	0.00	**2.82**
South Africa	0.10	0.00	0.00	0.00	0.00	**0.10**
Ukraine	0.05	0.00	0.00	0.00	0.00	**0.05**
UAE	0.00	0.00	0.00	0.02	0.00	**0.02**
USA	0.73	0.00	0.04	0.00	0.00	**0.77**
Zambia	0.00	0.00	0.03	0.00	0.00	**0.03**
Total	**45.47**	**3.68**	**0.82**	**9.75**	**16.68**	**76.39**

Table 25. Global supply chain PED of total NMC811 battery production. PED expressed in MJ/kWh. Other PED (not included in analysis) = 57.5 MJ/kWh. Other emissions include a binder, electrolytes (LiPF6, ethylene carbonate, dimethyl carbonate), plastics (polypropylene, polyethylene, polyethylene terephthalate), steel, thermal insulation, coolant and electronic parts.

NMC811	Active Material	Graphite	Copper	Wrought Aluminium	Battery Assembly	**Total**
Argentina	5.63	0.00	0.00	0.00	0.00	**5.63**
Australia	52.11	0.00	0.27	26.30	0.00	**78.67**
Bahrain	0.00	0.00	0.00	0.19	0.00	**0.19**
Belgium	1.81	0.00	0.00	0.00	0.00	**1.81**
Brazil	7.25	6.85	0.00	10.31	0.00	**24.42**
Canada	13.50	0.00	0.03	0.41	0.00	**13.94**
Chile	17.25	0.00	1.27	0.00	0.00	**18.52**
China	164.91	49.97	5.87	67.67	208.22	**496.63**
Cote d'lvoire	1.15	0.00	0.00	0.00	0.00	**1.15**
Cuba	1.32	0.00	0.00	0.00	0.00	**1.32**
DRC	4.04	0.00	0.28	0.00	0.00	**4.32**
Finland	4.61	0.00	0.00	0.00	0.00	**4.61**
Gabon	1.29	0.00	0.00	0.00	0.00	**1.29**
Ghana	1.29	0.00	0.00	0.00	0.00	**1.29**
Germany	0.00	0.00	0.11	0.00	0.00	**0.12**
Guatemala	3.81	0.00	0.00	0.00	10.45	**14.26**
Guinea	0.00	0.00	0.00	6.63	0.00	**6.63**
Hungary	7.12	0.00	0.00	0.00	0.00	**7.12**
India	1.37	2.35	0.19	7.94	0.00	**11.85**
Indonesia	59.95	0.00	0.00	1.57	0.00	**61.52**
Jamaica	0.00	0.00	0.00	0.85	0.00	**0.85**
Japan	9.84	0.00	0.93	0.00	0.00	**10.77**
Korea	5.05	2.86	0.41	0.00	0.00	**8.32**
Madagascar	1.54	3.81	0.00	0.00	0.00	**5.35**
Malaysia	1.17	0.00	0.00	0.00	0.00	**1.17**
Mexico	0.00	0.00	0.04	0.00	0.00	**0.04**
Mozambique	0.00	8.12	0.00	0.00	0.00	**8.12**
New Caledonia	13.15	0.00	0.00	0.00	0.00	**13.15**
Norway	3.79	0.00	0.00	0.18	0.00	**3.97**
PNG	1.23	0.00	0.00	0.00	8.21	**9.44**
Peru	0.00	0.00	0.12	0.00	0.00	**0.12**
Philippines	16.68	0.00	0.00	0.00	0.00	**16.68**
Poland	5.84	0.00	0.40	0.00	0.00	**6.24**
Russia	17.50	0.00	0.67	2.71	0.00	**20.88**
South Africa	1.47	0.00	0.00	0.00	0.00	**1.47**
Ukraine	0.97	0.00	0.00	0.00	0.00	**0.97**
UAE	0.00	0.00	0.00	0.37	0.00	**0.37**
USA	10.55	0.00	0.51	0.00	0.00	**11.06**
Zambia	0.00	0.00	0.40	0.00	0.00	**0.40**
Total	**437.18**	**73.96**	**11.55**	**125.13**	**256.36**	**904.19**

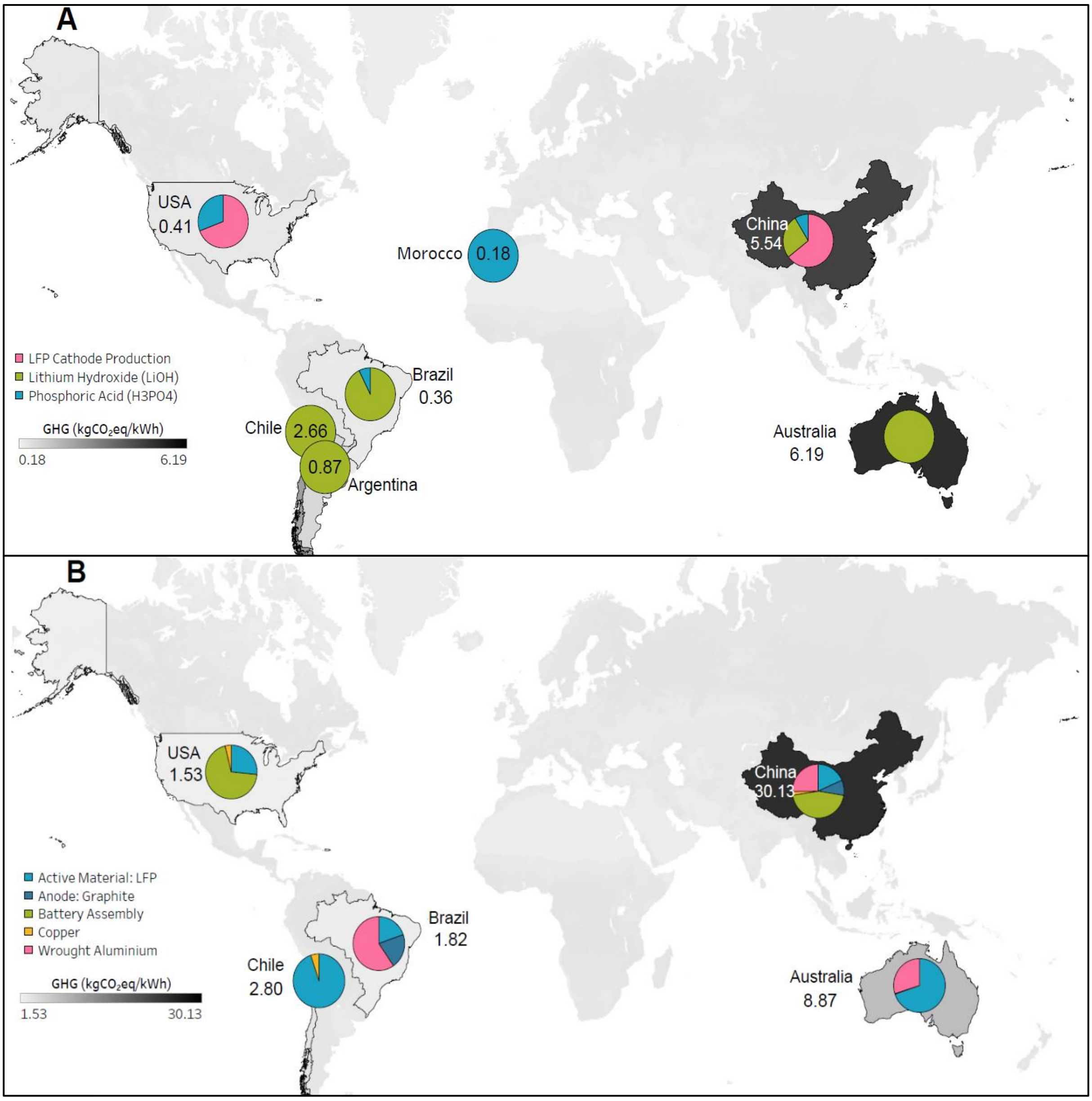

Figure 7. (A) Supply Chain GHG emissions of the Cathode Active Material for LFP Li-ion battery: global production emissions of 17 $kgCO_2eq/kWh$ **(B)** Supply Chain GHG emissions of the total LFP Li-ion battery production: global production emissions of 56 $kgCO_2eq/kWh$. Note: Values on the map indicate the emissions in $kgCO_2eq/kWh$. Detailed numerical values can be found in **Table 26** and **Table 28.**

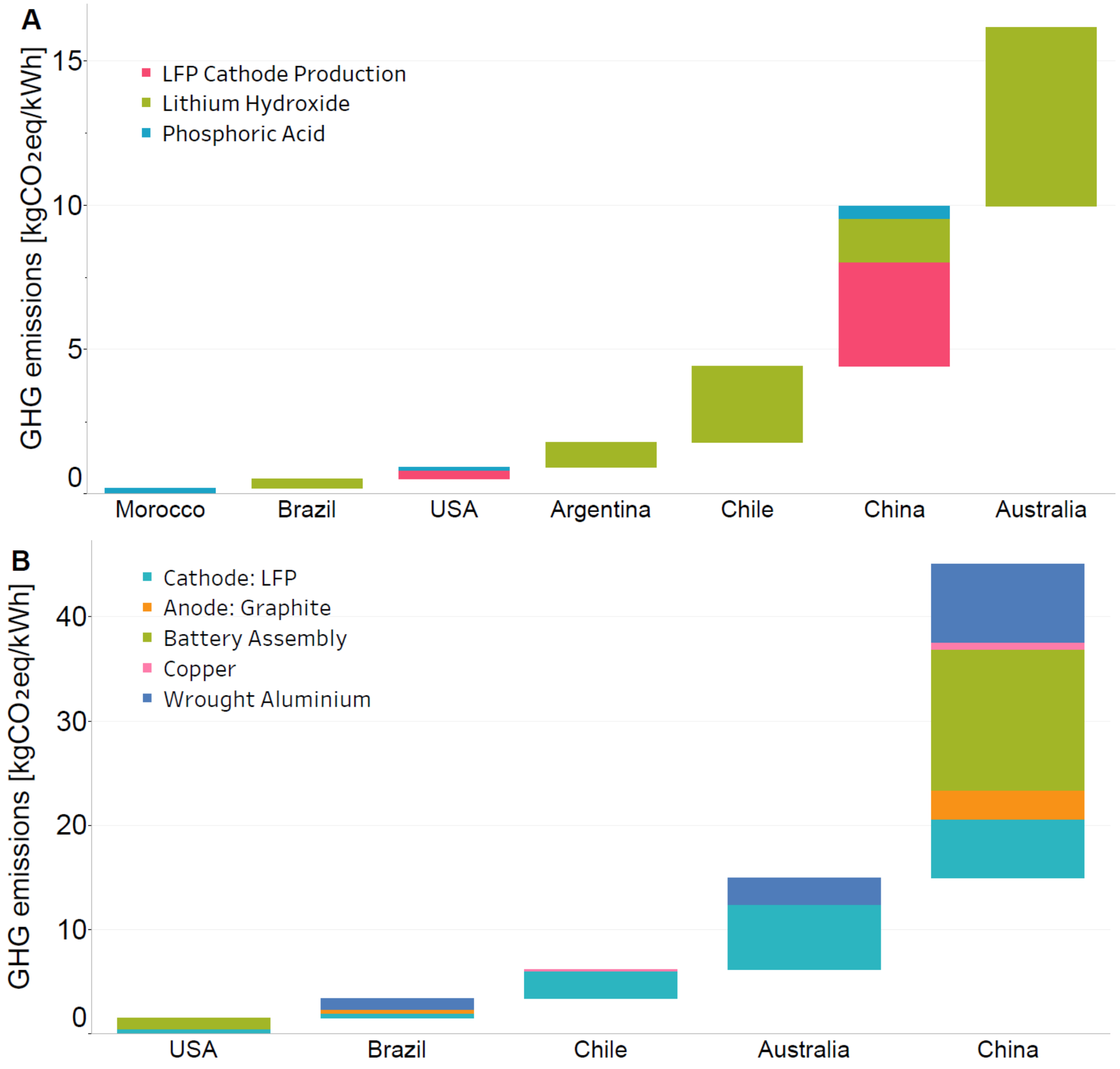

Figure 8. LFP supply chain GHG emissions of **(A)** cathode active material - global production emissions of 17 kgCO$_2$eq/kWh. Numerical values can be found in **Table 26** **(B)** Total LFP battery production - global production emissions of 56.4 kgCO$_2$eq/kWh. Numerical values can be found in **Table 28**.

Table 26. Global supply chain GHG emissions of LFP active cathode materials. GHG emissions expressed in $kgCO_2eq/kWh$.

LFP	Lithium Hydroxide (LiOH)	Phosphoric Acid (H3PO4)	Li-LFP	**Total**
Argentina	0.867	0.000	0.000	**0.867**
Australia	6.192	0.000	0.000	**6.192**
Brazil	0.330	0.026	0.000	**0.357**
Canada	0.000	0.008	0.000	**0.008**
Chile	2.656	0.000	0.000	**2.656**
China	1.486	0.483	3.573	**5.543**
Hungary	0.000	0.000	0.179	**0.179**
India	0.000	0.004	0.000	**0.004**
Iran	0.000	0.003	0.000	**0.003**
Japan	0.000	0.004	0.109	**0.113**
Jordan	0.000	0.046	0.000	**0.046**
Kazakhstan	0.000	0.004	0.000	**0.004**
Korea	0.000	0.004	0.115	**0.119**
Morocco	0.000	0.175	0.000	**0.175**
Peru	0.000	0.055	0.000	**0.055**
Philippines	0.000	0.000	0.141	**0.141**
Qatar	0.000	0.002	0.000	**0.002**
Russia	0.000	0.064	0.000	**0.064**
Saudi Arabia	0.000	0.039	0.000	**0.039**
UAE	0.000	0.004	0.000	**0.004**
USA	0.000	0.125	0.282	**0.407**
Vietnam	0.000	0.023	0.000	**0.023**
Total	**11.531**	**1.069**	**4.399**	**17.000**

Table 27. Global supply chain PED of LFP active cathode materials. PED expressed in MJ/kWh.

LFP	Lithium Hydroxide (LiOH)	Phosphoric Acid (H3PO4)	Li-LFP	**Total**
Argentina	9.96	0.00	0.00	**9.96**
Australia	71.17	0.00	0.00	**71.17**
Brazil	3.80	0.39	0.00	**4.18**
Canada	0.00	0.11	0.00	**0.11**
Chile	30.52	0.00	0.00	**30.52**
China	17.08	7.12	60.93	**85.14**
Hungary	0.00	0.00	3.06	**3.06**
India	0.00	0.06	0.00	**0.06**
Iran	0.00	0.04	0.00	**0.04**
Japan	0.00	0.06	1.86	**1.91**
Jordan	0.00	0.68	0.00	**0.68**
Kazakahstan	0.00	0.06	0.00	**0.06**
Korea	0.00	0.05	1.97	**2.02**
Morocco	0.00	2.59	0.00	**2.59**
Peru	0.00	0.81	0.00	**0.81**
Philippines	0.00	0.00	2.40	**2.40**
Qatar	0.00	0.03	0.00	**0.03**
Russia	0.00	0.94	0.00	**0.94**
Saudi Arabia	0.00	0.56	0.00	**0.56**
UAE	0.00	0.06	0.00	**0.06**
USA	0.00	1.84	4.80	**6.65**
Vietnam	0.00	0.34	0.00	**0.34**
Total	**132.54**	**15.74**	**75.02**	223.30

Table 28. Global supply chain GHG emissions of total LFP battery production. GHG emissions are expressed in kgCO$_2$eq/kWh. Other emissions (not included in the analysis) = 4.13 kgCO$_2$eq/kWh. Other emissions include a binder, electrolytes (LiPF6, ethylene carbonate, dimethyl carbonate), plastics (polypropylene, polyethylene, polyethylene terephthalate), steel, thermal insulation, coolant and electronic parts.

LFP	Active Material	Graphite	Copper	Wrought Aluminium	Battery Assembly	**Total**
Argentina	0.867	0.000	0.000	0.000	0.000	**0.867**
Australia	6.193	0.000	0.031	2.647	0.000	**8.872**
Bahrain	0.000	0.000	0.000	0.017	0.000	**0.017**
Brazil	0.357	0.379	0.000	1.083	0.000	**1.818**
Canada	0.008	0.000	0.003	0.035	0.000	**0.045**
Chile	2.656	0.000	0.143	0.000	0.000	**2.799**
China	5.543	2.766	0.683	7.586	13.548	**30.126**
DRC	0.000	0.000	0.031	0.000	0.000	**0.031**
Germany	0.000	0.000	0.013	0.000	0.000	**0.013**
Guinea	0.000	0.000	0.000	0.479	0.000	**0.479**
Hungary	0.179	0.000	0.000	0.000	0.680	**0.859**
India	0.004	0.130	0.023	0.827	0.000	**0.984**
Indonesia	0.000	0.000	0.000	0.113	0.000	**0.113**
Iran	0.003	0.000	0.000	0.000	0.000	**0.003**
Jamaica	0.000	0.000	0.000	0.062	0.000	**0.062**
Japan	0.113	0.000	0.109	0.000	0.413	**0.635**
Jordan	0.046	0.000	0.000	0.000	0.000	**0.046**
Kazakhstan	0.004	0.000	0.003	0.000	0.000	**0.007**
Korea	0.119	0.158	0.048	0.000	0.437	**0.762**
Madagascar	0.000	0.211	0.000	0.000	0.000	**0.211**
Mexico	0.000	0.000	0.004	0.000	0.000	**0.004**
Morocco	0.175	0.000	0.000	0.000	0.000	**0.175**
Mozambique	0.000	0.450	0.000	0.000	0.000	**0.450**
Norway	0.000	0.000	0.000	0.016	0.000	**0.016**
Peru	0.055	0.000	0.012	0.000	0.000	**0.067**
Poland	0.141	0.000	0.047	0.000	0.534	**0.722**
Qatar	0.002	0.000	0.000	0.000	0.000	**0.002**
Russia	0.064	0.000	0.078	0.304	0.000	**0.446**
Saudi Arabia	0.039	0.000	0.000	0.000	0.000	**0.039**
UAE	0.004	0.000	0.000	0.031	0.000	**0.036**
USA	0.407	0.000	0.059	0.000	1.068	**1.534**
Zambia	0.000	0.000	0.046	0.000	0.000	**0.046**
Vietnam	0.023	0.000	0.000	0.000	0.000	**0.023**
Total	**17.00**	**4.09**	**1.33**	**13.20**	**16.68**	52.31

Table 29. Global supply chain PED of total LFP battery production. PED expressed in MJ/kWh. Other PED (not included in the analysis) = 75.2 MJ/kWh. Other emissions include a binder, electrolytes (LiPF6, ethylene carbonate, dimethyl carbonate), plastics (polypropylene, polyethylene, polyethylene terephthalate), steel, thermal insulation, coolant and electronic parts.

LFP	Active Material	Graphite	Copper	Wrought Aluminium	Battery Assembly	**Total**
Argentina	9.96	0.00	0.00	0.00	0.00	**9.96**
Australia	71.17	0.00	0.44	35.61	0.00	**107.22**
Bahrain	0.00	0.00	0.00	0.26	0.00	**0.26**
Brazil	4.18	7.63	0.00	13.96	0.00	**25.78**
Canada	0.11	0.00	0.05	0.55	0.00	**0.70**
Chile	30.52	0.00	2.07	0.00	0.00	**32.59**
China	85.14	55.64	9.54	91.65	208.22	**450.18**
DRC	0.00	0.00	0.46	0.00	0.00	**0.46**
Germany	0.00	0.00	0.19	0.00	0.00	**0.19**
Guinea	0.00	0.00	0.00	8.99	0.00	**8.99**
Hungary	3.06	0.00	0.00	0.00	10.45	**13.51**
India	0.06	2.62	0.31	10.75	0.00	**13.74**
Indonesia	0.00	0.00	0.00	2.12	0.00	**2.12**
Iran	0.04	0.00	0.00	0.00	0.00	**0.04**
Jamaica	0.00	0.00	0.00	1.16	0.00	**1.16**
Japan	1.91	0.00	1.52	0.00	6.34	**9.78**
Jordan	0.68	0.00	0.00	0.00	0.00	**0.68**
Kazakhstan	0.06	0.00	0.05	0.00	0.00	**0.11**
Korea	2.02	3.18	0.67	0.00	6.72	**12.59**
Madagascar	0.00	4.24	0.00	0.00	0.00	**4.24**
Mexico	0.00	0.00	0.06	0.00	0.00	**0.06**
Morocco	2.59	0.00	0.00	0.00	0.00	**2.59**
Mozambique	0.00	9.05	0.00	0.00	0.00	**9.05**
Norway	0.00	0.00	0.00	0.25	0.00	**0.25**
Peru	0.81	0.00	0.20	0.00	0.00	**1.01**
Poland	2.40	0.00	0.65	0.00	8.21	**11.27**
Qatar	0.03	0.00	0.00	0.00	0.00	**0.03**
Russia	0.94	0.00	1.10	3.67	0.00	**5.70**
Saudi Arabia	0.56	0.00	0.00	0.00	0.00	**0.56**
UAE	0.06	0.00	0.00	0.50	0.00	**0.56**
USA	6.65	0.00	0.84	0.00	16.42	**23.90**
Zambia	0.00	0.00	0.65	0.00	0.00	**0.65**
Vietnam	0.34	0.00	0.00	0.00	0.00	**0.34**
Total	**223.30**	**82.35**	**18.80**	**169.46**	**256.36**	**750.27**

The total GHG emissions of LIB could be minimised by selecting material extraction, refining, and battery assembly locations with the lowest GHG emissions. For NMC811, this would entail mining nickel in Canada and refining in Norway; mining lithium in Brazil and refining it in the USA; and assembling batteries in Hungary. This hypothetical scenario in 2020 would achieve life cycle GHG emissions of 57 kgCO_2eq/kWh, a reduction of 28% compared to the current global average production (79.6 kgCO_2eq/kWh). Conversely, the greatest GHG emissions could be achieved by mining and refining nickel in Indonesia, mining and refining lithium in China, and assembling the battery in China, resulting in a total GHG emission of 89 kgCO_2eq/kWh, an increase of more than 20% compared to the current global average production. This suggests that there is considerable scope to reduce LIB production emissions by optimising global supply chains, however, this can only happen with global governance on battery resources and manufacturing. **Figure 9** illustrates the sensitivity of GHG emissions considering the locations with the highest and lowest assessed emissions for each activity related to LIB production. Detailed sensitivity data for LIB materials production is given in **Table 30** and **Table 31** and data for active cathode material and total battery production is presented in **Table 32** and **Table 33**, respectively.

Table 30. Sensitivity GHG emissions in material production and battery assembly. GHG emissions for materials are expressed in kgCO_2eq per kg of material. GHG emissions for battery assembly are expressed in kgCO_2eq/kWh battery assembled.

Materials	Current	Lowest	Highest
Nickel sulfate	18.531	14.700	21.181
Manganese sulfate	1.425	0.989	1.805
Cobalt sulfate	7.330	6.355	8.275
Lithium Carbonate	13.081	12.672	13.430
Lithium Hydroxide	24.798	23.213	26.210
Graphite	4.445	1.990	5.647
Phosphate	1.686	1.192	1.948
Copper	3.349	1.884	4.497
Aluminium	15.639	7.130	19.438
Battery Assembly	16.680	12.323	17.533

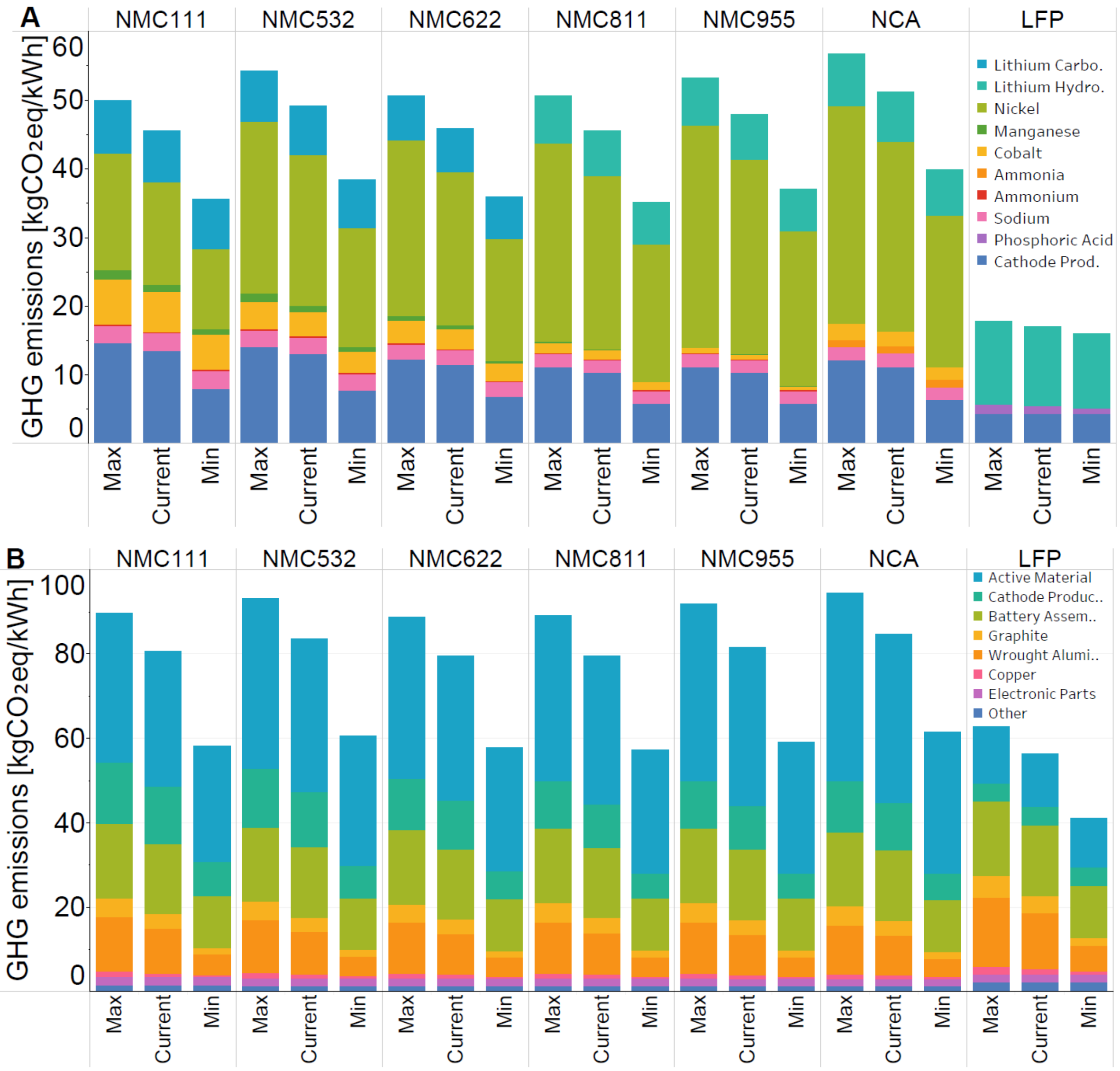

Figure 9. Sensitivity GHG emissions for **(A)** **C**athode production **(B)** Total battery production. Numerical data are available in the tables above. GHG emissions expressed in $kgCO_2eq/kWh$.

Table 31. Summary of sensitivity of battery materials producing countries for a lowest or highest source of electricity emission factor (EF).

Material			Nickel sulfate	Manganese sulfate	Cobalt sulfate	Lithium Carbonate	Lithium Hydroxide	Graphite	Phosphate	Copper	Aluminium	Battery Asembly
Mining	**Low**	**Country**	Canada	Brazil	DRC	Brazil	Brazil	Mozambique	Brazil	DRC		
		EF	0.168	0.172	0.045	0.172	0.172	0.134	0.172	0.045		
	High	**Country**	Indonesia	South Africa	Philippines	China	China	India	China	China		
		EF	1.161	1.010	0.775	0.941	0.941	0.947	0.941	0.941		
Refining	**Low**	**Country**	Norway	Gabon	Norway	USA	USA			Zambia		
		EF	0.032	0.507	0.032	0.452	0.452			0.205		
	High	**Country**	Indonesia	South Africa	China	China	China			India		
		EF	1.161	1.010	0.941	0.941	0.941			0.947		
Bauxite	**Low**	**Country**									Brazil	
		EF									0.172	
	High	**Country**									Australia	
		EF									0.751	
Alumina	**Low**	**Country**									Brazil	
		EF									0.172	
	High	**Country**									China	
		EF									0.941	
Aluminium Production	**Low**	**Country**									Norway	
		EF									0.032	
	High	**Country**									China	
		EF									0.941	
Assembly	**Low**	**Country**										Hungary
		EF										0.313
	High	**Country**										China
		EF										0.941

Table 32. Sensitivity GHG emissions of cathode active materials for all chemistries. GHG emissions expressed in $kgCO_2eq/kWh$.

Active material	NMC111			NMC532			NMC622			NMC811			NMC955			NCA			LFP		
	Current	Max	Min	Current	Max	Min	Current	Max	Min	Current	Max	Min	Current	Max	Min	Current	Max	Min	Current	Max	Min
Nickel Sulfate	14.8	16.9	11.7	21.9	25.0	17.4	22.3	25.5	17.7	25.2	28.8	20.0	28.3	32.3	22.4	27.7	31.6	22.0	0.0	0.0	0.0
Cobalt Sulfate	5.9	6.6	5.1	3.5	3.9	3.0	3.0	3.3	2.6	1.2	1.4	1.1	0.6	0.7	0.5	2.1	2.4	1.8	0.0	0.0	0.0
Manganese Sulfate	1.1	1.4	0.8	1.0	1.2	0.7	0.6	0.7	0.4	0.2	0.3	0.2	0.1	0.2	0.1	0.0	0.0	0.0	0.0	0.0	0.0
Lithium Carbonate	7.5	7.7	7.2	7.2	7.4	7.0	6.3	6.4	6.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Lithium Hydroxide	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	6.5	6.9	6.1	6.5	6.9	6.1	7.2	7.6	6.7	11.5	12.2	10.8
Sodium Hydroxide	2.5	2.5	2.5	2.4	2.4	2.4	2.1	2.1	2.1	1.8	1.8	1.8	1.8	1.8	1.8	1.9	1.9	1.9	0.0	0.0	0.0
Ammonium Hydroxide	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.0	0.0	0.0	0.0	0.0	0.0
Ammonia	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.1	1.1	1.1	0.0	0.0	0.0
Aluminium hydroxide	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Oxygen	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Phosphoric Acid	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.1	1.2	0.8
Precursor	4.4	4.4	4.4	4.2	4.2	4.2	3.7	3.7	3.7	3.2	3.2	3.2	3.2	3.2	3.2	3.4	3.4	3.4	0.0	0.0	0.0
Cathode Production via Calcination	9.1	10.2	3.6	8.8	9.8	3.5	7.7	8.6	3.0	7.2	8.0	2.7	7.2	8.0	2.7	7.8	8.7	2.9	4.4	4.4	4.4
Cathode Production	13.5	14.6	8.0	13.0	14.1	7.7	11.4	12.3	6.8	10.3	11.2	5.8	10.3	11.2	5.8	11.2	12.1	6.3	4.4	4.4	4.4
Active material (w/o production)	32.0	35.3	27.6	36.2	40.2	30.7	34.4	38.3	29.1	35.1	39.3	29.3	37.5	42.1	31.1	40.0	44.6	33.5	12.6	13.4	11.6
Total	**45.5**	**49.9**	**35.6**	**49.2**	**54.2**	**38.4**	**45.8**	**50.6**	**35.8**	**45.5**	**50.5**	**35.1**	**47.9**	**53.3**	**37.0**	**51.1**	**56.7**	**39.8**	**17.0**	**17.8**	**16.0**

Table 33. Sensitivity GHG emissions of total battery for all chemistries. GHG emissions expressed in $kgCO_2eq/kWh$.

Battery Materials	NMC111			NMC532			NMC622			NMC811			NMC955			NCA			LFP		
	Current	Max	Min	Current	Max	Min	Current	Max	Min	Current	Max	Min	Current	Max	Min	Current	Max	Min	Current	Max	Min
Active Material	45.46	49.89	35.58	49.18	54.24	38.38	45.84	50.64	35.84	45.47	50.54	35.12	47.87	53.26	36.98	51.14	56.73	39.83	17.00	17.82	15.95
Graphite	3.50	4.45	1.57	3.41	4.34	1.53	3.42	4.35	1.53	3.68	4.67	1.65	3.57	4.67	1.65	3.48	4.42	1.56	4.09	5.20	1.83
Silicon	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Binder	0.12	0.12	0.12	0.08	0.08	0.08	0.07	0.07	0.07	0.13	0.13	0.13	0.09	0.13	0.13	0.07	0.07	0.07	0.09	0.09	0.09
Copper	0.94	1.27	0.53	0.89	1.20	0.50	0.83	1.11	0.47	0.82	1.10	0.46	0.79	1.10	0.46	0.76	1.03	0.43	1.33	1.79	0.75
W.Aluminum	10.54	13.10	4.81	10.12	12.58	4.61	9.73	12.09	4.44	9.75	12.11	4.44	9.50	12.11	4.44	9.41	11.70	4.29	13.20	16.41	6.02
C. Aluminum	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Electrolyte: LiPF6	0.74	0.74	0.74	0.67	0.67	0.67	0.65	0.65	0.65	0.64	0.64	0.64	0.61	0.64	0.64	0.62	0.62	0.62	1.17	1.17	1.17
Electrolyte: EC	0.06	0.06	0.06	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.09	0.09	0.09
Electrolyte: DMC	0.21	0.21	0.21	0.19	0.19	0.19	0.18	0.18	0.18	0.18	0.18	0.18	0.17	0.18	0.18	0.17	0.17	0.17	0.33	0.33	0.33
Plastic: PP	0.06	0.06	0.06	0.07	0.07	0.07	0.05	0.05	0.05	0.06	0.06	0.06	0.06	0.06	0.06	0.05	0.05	0.05	0.09	0.09	0.09
Plastic: PE	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.03	0.03	0.03
Plastic: PET	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.03	0.03	0.03
Steel	0.06	0.06	0.06	0.06	0.06	0.06	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.08	0.08	0.08
Thermal Insulation	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.03	0.03	0.03
Coolant: Glycol	0.18	0.18	0.18	0.17	0.17	0.17	0.18	0.18	0.18	0.17	0.17	0.17	0.17	0.17	0.17	0.18	0.18	0.18	0.22	0.22	0.22
Electronic Parts	1.94	1.94	1.94	1.87	1.87	1.87	1.87	1.87	1.87	1.87	1.87	1.87	1.83	1.87	1.87	1.87	1.87	1.87	1.96	1.96	1.96
Battery Assembly	16.68	17.53	12.32	16.68	17.53	12.32	16.68	17.53	12.32	16.68	17.53	12.32	16.68	17.53	12.32	16.68	17.53	12.32	16.68	17.53	12.32
Total per battery	**80.55**	**89.67**	**58.23**	**83.51**	**93.11**	**60.57**	**79.66**	**88.88**	**57.76**	**79.60**	**89.17**	**57.21**	**81.52**	**91.89**	**59.07**	**84.60**	**94.53**	**61.55**	**56.44**	**62.88**	**41.00**

4.4 Impact of electricity decarbonisation on future LIB production

Anticipated reductions in the GHG intensity of electricity generation reduce the life cycle GHG emissions of LIB manufacture towards 2050 in both scenarios. **Figure 10** shows the GHG emissions of LIB technologies considering the decarbonisation of the electricity sector by 2050 in SPS and SDS scenarios. Under the SPS scenario, life cycle GHG emissions of nickel-based batteries decline by 20 - 22% (from 79.6 to 62.5 kgCO_2eq/kWh for NMC811, and from 84.6 to 67.2 kgCO_2eq/kWh for NCA), primarily due to anticipated electricity sector decarbonisation. This result is driven by reductions in the GHG intensity of wrought aluminium production (68%), battery assembly (38%) and cathode active material production (30%). Under the more ambitious Sustainable Development Scenario (SDS), GHG emissions would reduce by 37 – 39%. Similarly, for LFP, GHG emissions are reduced to ~43 kgCO_2eq/kWh (23% reduction) and ~34 kgCO_2eq/kWh (40% reduction) respectively under the SPS and SDS scenarios in 2050. Some key materials see minor changes as a result of power sector decarbonisation, such as nickel and lithium, with GHG emissions reducing to ~19 and ~5 kgCO_2eq/kWh, a drop of 22% and 15% respectively, under the SDS scenario. However, graphite and aluminium would experience substantial GHG emission reductions. Under the SDS scenario, graphite would reduce to about 1.4 kgCO_2eq/kWh and aluminium to 3.3 kgCO_2eq/kWh, a reduction of 61% and 65% respectively. For the SPS scenario, GHG emissions of the cathode production process can be reduced to around ~6.4 kgCO_2eq/kWh by 2050, a 38% reduction, and ~3.7 kgCO_2eq/kWh in the SDS (63% reduction). GHG emissions from battery assembly, led by China, would reduce by 22% and 38% respectively, under the SDS scenario.

Electricity consumption contributes approximately 37% to the total current GHG emissions of LIB manufacture, so decarbonisation of the electricity sector is an important lever in reducing the overall life cycle emissions. Non-electricity decarbonisation inputs to material and battery manufacture are not considered in the present analysis, as there is generally greater uncertainty about the technological pathways and the timing of their deployments. This can include fuel switching potential and carbon capture and sequestration solutions.

A critical enabler for achieving these emissions reductions for LIB manufacture is linked to China's power sector decarbonisation, which is anticipated to lead to a significant reduction from 0.941 in 2020 to 0.076 in 2050 (kgCO_2eq/kWh) under the SDS scenario, with total GHG emissions of 48.8 kgCO_2eq/kWh battery (39% reduction). If a less aggressive GHG reduction is achieved by the electricity sector, e.g., 0.445 kgCO_2eq/kWh, as under the SPS scenario, then a more modest reduction in LIB production emissions is realised (21% reduction) (see **Table 37** and **Table 44** for detailed results on NMC811 for all scenarios). Importantly, there are other factors not included in the present analysis that could potentially have significant impacts on future LIB production emissions, positively and negatively. This includes reserve depletion (requiring energy-intensive extraction and processing of lower grade ores) and decarbonisation of non-electricity energy inputs, such as fuels consumed by plant equipment and transport, and industrial heat. Opportunities for remanufacturing and recycling are limited in the near future as LIB capacity rapidly grows but will become more important as greater quantities of LIB reach their end of life; these factors are discussed in the next section.

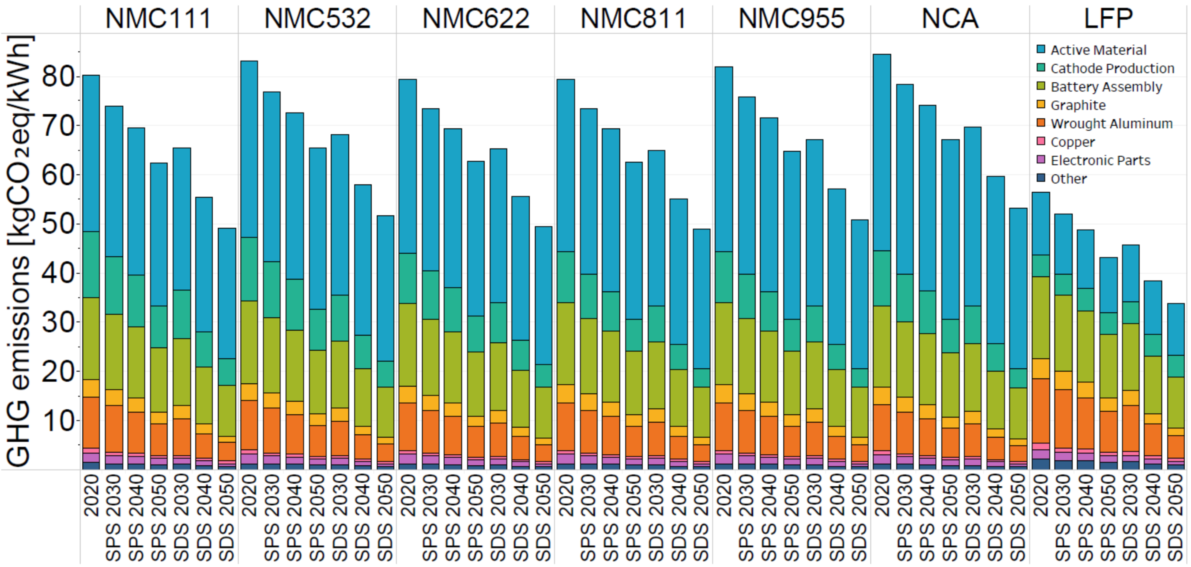

Figure 10. GHG emissions of LIB technologies considering the decarbonisation of the electricity sector by 2050 in SPS and SDS scenarios. Note: y-axis indicates the GHG emissions in $kgCO_2eq/kWh$ battery, x-axis indicates the decarbonisation scenario by year. GHG emissions expressed in $kgCO_2eq/kWh$.

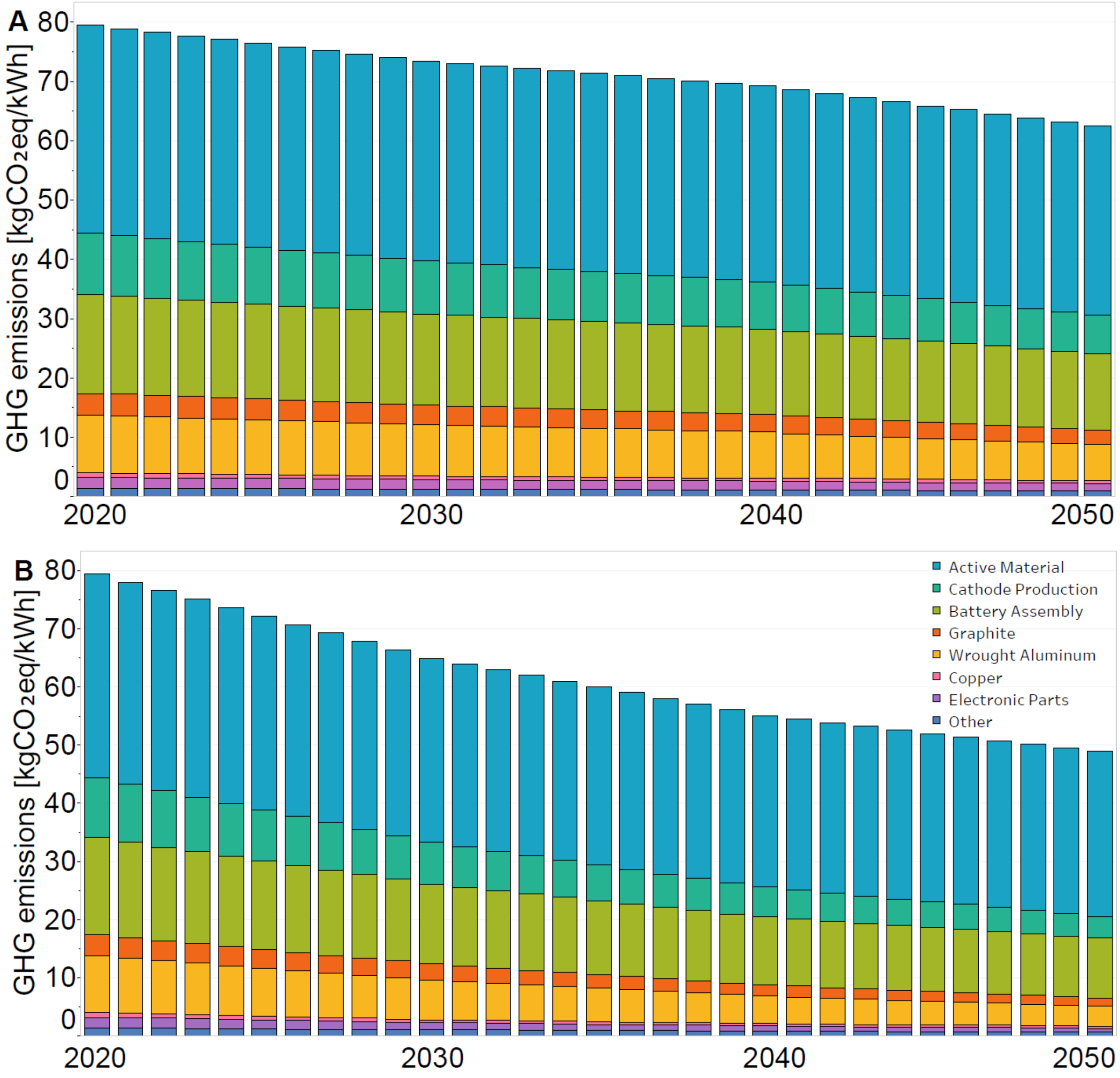

Figure 11. GHG emissions of NMC811 battery by decarbonising the electricity sector to the year 2050 in the SPS and SDS scenarios. **(A)** Stated Policies Scenario **(B)** Sustainable Development scenario. Detailed numerical data is presented in **Table 44**.

Table 34. Current and future PED and GHG emissions of NMC111 active cathode material by decarbonising the electricity sector to 2050 in the SPS and SDS scenarios. PED expressed in MJ/kWh and GHG emissions expressed in kgCO_2eq/kWh.

NMC111	**Current 2020**		**SPS 2030**		**SPS 2040**		**SPS 2050**		**SDS 2030**		**SDS 2040**		**SDS 2050**	
Materials	**PED**	**GHG**	**PED**	**GHG**	**PED**	**GHG**	**PED**	**GHG**	**PED**	**GHG**	**PED**	**GHG**	**PED**	**GHG**
Nickel Sulfate	95.9	14.8	158.2	14.2	158.2	13.9	157.9	13.4	153.8	13.2	150.4	12.1	144.1	11.5
Cobalt Sulfate	83.2	5.9	63.7	5.7	63.7	5.6	63.7	5.4	64.4	5.5	65.2	5.3	63.9	5.1
Manganese Sulfate	12.2	1.1	6.3	0.6	5.4	0.5	4.1	0.3	5.0	0.4	2.9	0.2	1.7	0.1
Lithium Carbonate	71.3	7.5	81.5	7.3	82.4	7.2	83.4	7.1	83.2	7.1	86.5	7.0	86.3	6.9
Lithium Hydroxide	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Sodium Hydroxide	40.4	2.5	28.2	2.5	28.8	2.5	29.7	2.5	29.5	2.5	31.3	2.5	31.6	2.5
Ammonium Hydroxide	3.6	0.2	2.5	0.2	2.5	0.2	2.6	0.2	2.6	0.2	2.7	0.2	2.8	0.2
Ammonia	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Aluminium hydroxide	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Oxygen	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Phosphoric Acid	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Precursor Co-precipitation	75.3	4.4	49.3	4.4	50.3	4.4	51.9	4.4	51.6	4.4	54.7	4.4	55.2	4.4
Cathode Production via Calcination	113.9	9.1	81.9	7.3	70.5	6.2	50.4	4.3	61.9	5.3	33.6	2.7	13.4	1.1
Cathode Production	189.2	13.5	131.2	11.8	120.8	10.6	102.3	8.7	113.4	9.7	88.3	7.1	68.6	5.5
Active material (without production)	306.5	32.0	340.4	30.5	341.1	29.9	341.4	29.0	338.5	29.0	339.1	27.4	330.3	26.4
Total per kWh battery	**495.7**	**45.5**	**471.6**	**42.2**	**461.9**	**40.5**	**443.7**	**37.7**	**452.0**	**38.7**	**427.4**	**34.5**	**398.9**	**31.9**

Table 35. Current and future PED and GHG emissions of NMC532 active cathode material by decarbonising the electricity sector to 2050 in the SPS and SDS scenarios. PED expressed in MJ/kWh and GHG emissions expressed in kgCO_2eq/kWh.

NMC532	**Current 2020**		**SPS 2030**		**SPS 2040**		**SPS 2050**		**SDS 2030**		**SDS 2040**		**SDS 2050**	
Materials	**PED**	**GHG**	**PED**	**GHG**	**PED**	**GHG**	**PED**	**GHG**	**PED**	**GHG**	**PED**	**GHG**	**PED**	**GHG**
Nickel Sulfate	142.1	21.9	215.8	21.0	215.1	20.6	213.5	19.9	208.9	19.5	202.6	18.0	192.7	17.1
Cobalt Sulfate	49.6	3.5	35.0	3.4	34.9	3.3	34.7	3.2	35.2	3.3	35.4	3.1	34.4	3.0
Manganese Sulfate	10.6	1.0	5.1	0.5	4.3	0.4	3.2	0.3	3.9	0.4	2.3	0.2	1.3	0.1
Lithium Carbonate	68.5	7.2	72.0	7.0	72.6	6.9	73.1	6.8	73.2	6.8	75.5	6.7	74.8	6.6
Lithium Hydroxide	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Sodium Hydroxide	38.9	2.4	25.0	2.4	25.4	2.4	26.1	2.4	26.0	2.4	27.4	2.4	27.4	2.4
Ammonium Hydroxide	3.5	0.2	2.2	0.2	2.2	0.2	2.3	0.2	2.3	0.2	2.4	0.2	2.4	0.2
Ammonia	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Aluminium hydroxide	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Oxygen	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Phosphoric Acid	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Precursor Co-precipitation	72.4	4.2	43.6	4.2	44.4	4.2	45.6	4.2	45.5	4.2	47.8	4.2	47.9	4.2
Cathode Production via Calcination	109.9	8.8	72.8	7.1	62.4	6.0	44.4	4.1	54.7	5.1	29.5	2.6	11.6	1.0
Cathode Production	182.3	13.0	116.4	11.3	106.8	10.2	89.9	8.4	100.2	9.4	77.3	6.9	59.5	5.3
Active material (without production)	313.0	36.2	355.0	34.5	354.5	33.9	352.9	32.9	349.6	32.6	345.6	30.7	333.0	29.5
Total per kWh battery	**495.3**	**49.2**	**471.4**	**45.9**	**461.3**	**44.1**	**442.9**	**41.3**	**449.8**	**42.0**	**423.0**	**37.5**	**392.6**	**34.8**

Table 36. Current and future PED and GHG emissions of NMC622 active cathode material by decarbonising the electricity sector to 2050 in the SPS and SDS scenarios. PED expressed in MJ/kWh and GHG emissions expressed in kgCO$_2$eq/kWh.

NMC622	**Current 2020**		**SPS 2030**		**SPS 2040**		**SPS 2050**		**SDS 2030**		**SDS 2040**		**SDS 2050**	
Materials	**PED**	**GHG**	**PED**	**GHG**	**PED**	**GHG**	**PED**	**GHG**	**PED**	**GHG**	**PED**	**GHG**	**PED**	**GHG**
Nickel Sulfate	144.9	22.3	214.0	21.4	213.0	21.0	210.9	20.3	206.7	19.9	199.6	18.4	189.2	17.4
Cobalt Sulfate	41.9	3.0	28.7	2.9	28.6	2.8	28.4	2.7	28.8	2.8	28.9	2.7	28.0	2.6
Manganese Sulfate	6.2	0.6	2.9	0.3	2.4	0.2	1.8	0.2	2.2	0.2	1.3	0.1	0.7	0.1
Lithium Carbonate	59.9	6.3	61.2	6.1	61.6	6.1	61.9	6.0	62.1	6.0	63.8	5.9	63.0	5.8
Lithium Hydroxide	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Sodium Hydroxide	34.1	2.1	21.3	2.1	21.6	2.1	22.2	2.1	22.1	2.1	23.2	2.1	23.2	2.1
Ammonium Hydroxide	3.0	0.2	1.9	0.2	1.9	0.2	1.9	0.2	1.9	0.2	2.0	0.2	2.0	0.2
Ammonia	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Aluminium hydroxide	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Oxygen	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Phosphoric Acid	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Precursor Co-precipitation	63.6	3.7	37.2	3.7	37.8	3.7	38.7	3.7	38.7	3.7	40.5	3.7	40.5	3.7
Cathode Production via Calcination	96.1	7.7	61.9	6.2	53.0	5.2	37.6	3.6	46.4	4.5	24.9	2.3	9.8	0.9
Cathode Production	159.7	11.4	99.1	9.9	90.8	8.9	76.3	7.3	85.1	8.2	65.5	6.0	50.3	4.6
Active material (without production)	290.0	34.4	330.0	33.0	329.2	32.5	327.1	31.5	323.9	31.2	318.8	29.3	306.2	28.2
Total per kWh battery	**449.7**	**45.8**	**429.1**	**42.9**	**419.9**	**41.4**	**403.4**	**38.8**	**409.0**	**39.4**	**384.3**	**35.3**	**356.5**	**32.8**

Table 37. Current and future PED and GHG emissions of NMC811 active cathode material by decarbonising the electricity sector to 2050 in the SPS and SDS scenarios. PED expressed in MJ/kWh and GHG emissions expressed in kgCO_2eq/kWh.

NMC811	**Current 2020**		**SPS 2030**		**SPS 2040**		**SPS 2050**		**SDS 2030**		**SDS 2040**		**SDS 2050**	
Materials	**PED**	**GHG**	**PED**	**GHG**	**PED**	**GHG**	**PED**	**GHG**	**PED**	**GHG**	**PED**	**GHG**	**PED**	**GHG**
Nickel Sulfate	163.3	25.2	236.5	24.1	235.2	23.7	232.9	22.9	228.5	22.4	220.6	20.7	208.8	19.6
Cobalt Sulfate	17.7	1.2	11.9	1.2	11.8	1.2	11.8	1.2	12.0	1.2	12.0	1.1	11.6	1.1
Manganese Sulfate	2.6	0.2	1.2	0.1	1.0	0.1	0.8	0.1	0.9	0.1	0.5	0.1	0.3	0.0
Lithium Carbonate	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Lithium Hydroxide	74.9	6.5	61.7	6.3	61.5	6.2	60.2	5.9	60.8	6.0	60.9	5.7	59.2	5.6
Sodium Hydroxide	28.9	1.8	17.7	1.8	18.0	1.8	18.4	1.8	18.4	1.8	19.3	1.8	19.3	1.8
Ammonium Hydroxide	2.6	0.2	1.6	0.2	1.6	0.2	1.6	0.2	1.6	0.2	1.7	0.2	1.7	0.2
Ammonia	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Aluminium hydroxide	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Oxygen	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Phosphoric Acid	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Precursor Co-precipitation	53.9	3.2	31.0	3.2	31.4	3.2	32.2	3.2	32.2	3.2	33.7	3.2	33.6	3.2
Cathode Production via Calcination	93.2	7.2	56.1	5.7	47.6	4.8	32.8	3.2	41.3	4.1	20.7	1.9	6.3	0.6
Cathode Production	147.1	10.3	87.1	8.9	79.0	7.9	65.1	6.4	73.5	7.2	54.5	5.1	40.0	3.8
Active material (without production)	290.1	35.1	330.6	33.7	329.1	33.1	325.7	32.0	322.2	31.6	315.1	29.5	300.8	28.3
Total per kWh battery	**437.2**	**45.5**	**417.7**	**42.6**	**408.1**	**41.1**	**390.7**	**38.4**	**395.7**	**38.8**	**369.5**	**34.6**	**340.8**	**32.0**

Table 38. Current and future PED and GHG emissions of NMC955 active cathode material by decarbonising the electricity sector to 2050 in the SPS and SDS scenarios. PED expressed in MJ/kWh and GHG emissions expressed in $kgCO_2eq/kWh$.

NMC955	**Current 2020**		**SPS 2030**		**SPS 2040**		**SPS 2050**		**SDS 2030**		**SDS 2040**		**SDS 2050**	
Materials	**PED**	**GHG**	**PED**	**GHG**	**PED**	**GHG**	**PED**	**GHG**	**PED**	**GHG**	**PED**	**GHG**	**PED**	**GHG**
Nickel Sulfate	183.7	28.3	258.2	27.1	256.5	26.6	253.4	25.7	248.9	25.2	239.5	23.3	226.0	22.1
Cobalt Sulfate	8.9	0.6	5.8	0.6	5.8	0.6	5.7	0.6	5.8	0.6	5.8	0.6	5.6	0.5
Manganese Sulfate	1.3	0.1	0.6	0.1	0.5	0.1	0.4	0.0	0.5	0.0	0.3	0.0	0.1	0.0
Lithium Carbonate	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Lithium Hydroxide	74.9	6.5	60.0	6.3	59.6	6.2	58.3	5.9	58.9	6.0	58.9	5.7	57.0	5.6
Sodium Hydroxide	29.0	1.8	17.2	1.8	17.4	1.8	17.8	1.8	17.9	1.8	18.6	1.8	18.5	1.8
Ammonium Hydroxide	2.6	0.2	1.5	0.2	1.5	0.2	1.6	0.2	1.6	0.2	1.6	0.2	1.6	0.2
Ammonia	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Aluminium hydroxide	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Oxygen	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Phosphoric Acid	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Precursor Co-precipitation	53.9	3.2	30.1	3.2	30.5	3.2	31.2	3.2	31.2	3.2	32.6	3.2	32.4	3.2
Cathode Production via Calcination	93.2	7.2	54.5	5.7	46.1	4.8	31.8	3.2	40.0	4.1	20.0	1.9	6.1	0.6
Cathode Production	147.2	10.3	84.6	8.9	76.6	7.9	63.0	6.4	71.2	7.2	52.6	5.1	38.5	3.8
Active material (without production)	300.3	37.5	343.3	36.1	341.4	35.4	337.2	34.2	333.5	33.8	324.7	31.5	308.9	30.2
Total per kWh battery	**447.5**	**47.9**	**427.9**	**45.0**	**418.0**	**43.4**	**400.2**	**40.6**	**404.8**	**41.0**	**377.4**	**36.6**	**347.4**	**33.9**

Table 39. Current and future PED and GHG emissions of NCA active cathode material by decarbonising the electricity sector to 2050 in the SPS and SDS scenarios. PED expressed in MJ/kWh and GHG emissions expressed in $kgCO_2eq/kWh$.

NCA	**Current 2020**		**SPS 2030**		**SPS 2040**		**SPS 2050**		**SDS 2030**		**SDS 2040**		**SDS 2050**	
Materials	**PED**	**GHG**	**PED**	**GHG**	**PED**	**GHG**	**PED**	**GHG**	**PED**	**GHG**	**PED**	**GHG**	**PED**	**GHG**
Nickel Sulfate	179.6	27.7	264.0	26.5	262.5	26.0	259.8	25.1	254.8	24.7	245.8	22.7	232.8	21.6
Cobalt Sulfate	29.7	2.1	20.3	2.0	20.2	2.0	20.0	1.9	20.4	2.0	20.3	1.9	19.7	1.8
Manganese Sulfate	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Lithium Carbonate	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Lithium Hydroxide	82.4	7.2	68.9	6.9	68.6	6.8	67.2	6.5	67.8	6.6	67.9	6.3	66.0	6.1
Sodium Hydroxide	31.0	1.9	19.3	1.9	19.6	1.9	20.0	1.9	20.0	1.9	21.0	1.9	20.9	1.9
Ammonium Hydroxide	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Ammonia	17.2	1.1	10.6	1.1	10.7	1.1	11.0	1.1	11.0	1.1	11.5	1.1	11.5	1.1
Aluminium hydroxide	0.1	0.0	0.1	0.0	0.1	0.0	0.1	0.0	0.1	0.0	0.1	0.0	0.1	0.0
Oxygen	0.1	0.0	0.1	0.0	0.1	0.0	0.1	0.0	0.1	0.0	0.1	0.0	0.1	0.0
Phosphoric Acid	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Precursor Co-precipitation	58.4	3.4	34.1	3.4	34.6	3.4	35.4	3.4	35.4	3.4	37.0	3.4	37.0	3.4
Cathode Production via Calcination	100.9	7.8	61.7	6.2	52.3	5.2	36.1	3.5	45.4	4.4	22.8	2.1	7.0	0.6
Cathode Production	159.4	11.2	95.8	9.6	86.8	8.6	71.5	6.9	80.8	7.8	59.8	5.5	43.9	4.1
Active material (without production)	340.2	40.0	383.2	38.5	381.7	37.8	378.1	36.6	374.2	36.2	366.7	33.9	351.1	32.5
Total per kWh battery	**499.6**	**51.1**	**479.0**	**48.2**	**468.5**	**46.5**	**449.6**	**43.5**	**455.0**	**44.0**	**426.4**	**39.5**	**395.1**	**36.6**

Table 40. Current and future PED and GHG emissions of LFP active cathode material by decarbonising the electricity sector to 2050 in the SPS and SDS scenarios. PED expressed in MJ/kWh and GHG emissions expressed in kgCO_2eq/kWh.

LFP	**Current 2020**		**SPS 2030**		**SPS 2040**		**SPS 2050**		**SDS 2030**		**SDS 2040**		**SDS 2050**	
Materials	**PED**	**GHG**	**PED**	**GHG**	**PED**	**GHG**	**PED**	**GHG**	**PED**	**GHG**	**PED**	**GHG**	**PED**	**GHG**
Nickel Sulfate	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Cobalt Sulfate	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Manganese Sulfate	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Lithium Carbonate	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Lithium Hydroxide	132.5	11.5	148.2	11.1	146.3	10.9	141.8	10.5	142.7	10.6	138.8	10.1	135.8	9.8
Sodium Hydroxide	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Ammonium Hydroxide	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Ammonia	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Aluminium hydroxide	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Oxygen	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Phosphoric Acid	15.7	1.1	13.1	1.0	12.5	0.9	11.7	0.9	12.1	0.9	10.6	0.8	9.7	0.7
Precursor Co-precipitation	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Cathode Production via Calcination	75.0	4.4	58.5	4.4	58.8	4.4	59.6	4.4	59.4	4.4	60.4	4.4	60.7	4.4
Cathode Production	75.0	4.4	58.5	4.4	58.8	4.4	59.6	4.4	59.4	4.4	60.4	4.4	60.7	4.4
Active material (without production)	148.3	12.6	161.4	12.1	158.8	11.9	153.5	11.3	154.8	11.5	149.4	10.9	145.5	10.5
Total per kWh battery	**223.3**	**17.0**	**219.9**	**16.5**	**217.6**	**16.3**	**213.1**	**15.7**	**214.2**	**15.9**	**209.8**	**15.3**	**206.2**	**14.9**

Table 41. Current and future PED and GHG emissions of NMC111 total battery by decarbonising the electricity sector to 2050 in the SPS and SDS scenarios. PED expressed in MJ/kWh and GHG emissions expressed in kgCO$_2$eq/kWh.

NMC111	**Current 2020**		**SPS 2030**		**SPS 2040**		**SPS 2050**		**SDS 2030**		**SDS 2040**		**SDS 2050**	
Materials	**PED**	**GHG**	**PED**	**GHG**	**PED**	**GHG**	**PED**	**GHG**	**PED**	**GHG**	**PED**	**GHG**	**PED**	**GHG**
Active Material	495.7	45.5	471.6	42.2	461.9	40.5	443.7	37.7	452.0	38.7	427.4	34.5	398.9	31.9
Graphite	70.4	3.5	68.9	3.1	68.0	2.8	64.9	2.3	66.8	2.6	62.6	1.8	57.8	1.4
Binder	2.1	0.1	1.9	0.1	1.8	0.1	1.6	0.1	1.8	0.1	1.5	0.0	1.1	0.0
Copper	13.3	0.9	12.2	0.8	11.8	0.7	11.2	0.6	11.5	0.7	10.8	0.5	9.8	0.5
Wrought Aluminium	135.3	10.5	131.0	9.4	124.8	8.4	112.9	6.6	118.6	7.4	105.7	5.1	91.2	3.7
Electrolyte: LiPF6	12.7	0.7	11.7	0.6	11.0	0.5	9.9	0.4	10.7	0.4	9.1	0.2	6.1	0.1
Electrolyte: EC	1.5	0.1	1.5	0.1	1.5	0.1	1.5	0.1	1.5	0.1	1.5	0.1	1.5	0.1
Electrolyte: DMC	5.6	0.2	5.6	0.2	5.6	0.2	5.5	0.2	5.6	0.2	5.5	0.2	5.5	0.2
Plastic: PP	2.0	0.1	2.0	0.1	2.0	0.1	2.0	0.1	2.0	0.1	2.0	0.1	2.0	0.1
Plastic: PE	0.6	0.0	0.6	0.0	0.6	0.0	0.6	0.0	0.6	0.0	0.6	0.0	0.6	0.0
Plastic: PET	0.6	0.0	0.6	0.0	0.6	0.0	0.6	0.0	0.6	0.0	0.6	0.0	0.6	0.0
Steel	0.7	0.1	0.7	0.1	0.7	0.1	0.7	0.1	0.7	0.1	0.7	0.1	0.7	0.1
Thermal Insulation	0.3	0.0	0.3	0.0	0.3	0.0	0.3	0.0	0.3	0.0	0.3	0.0	0.3	0.0
Coolant: Glycol	2.0	0.2	2.0	0.2	2.0	0.2	2.0	0.2	2.0	0.2	2.0	0.2	2.0	0.2
Electronic Parts	33.3	1.9	31.3	1.7	29.8	1.5	27.6	1.2	29.2	1.3	26.0	0.9	20.0	0.6
Battery Assembly	256.4	16.7	250.4	15.4	245.3	14.4	235.5	12.9	242.0	13.7	230.5	11.7	216.4	10.3
Total per kWh battery	**1,032**	**80.6**	**992.3**	**74.0**	**967.7**	**69.6**	**920.7**	**62.5**	**945.8**	**65.5**	**886.9**	**55.5**	**814.6**	**49.1**

Table 42. Current and future PED and GHG emissions of NMC532 total battery by decarbonising the electricity sector to 2050 in the SPS and SDS scenarios. PED expressed in MJ/kWh and GHG emissions expressed in kgCO$_2$eq/kWh.

NMC532	**Current 2020**		**SPS 2030**		**SPS 2040**		**SPS 2050**		**SDS 2030**		**SDS 2040**		**SDS 2050**	
Materials	**PED**	**GHG**	**PED**	**GHG**	**PED**	**GHG**	**PED**	**GHG**	**PED**	**GHG**	**PED**	**GHG**	**PED**	**GHG**
Active Material	495.3	49.2	471.4	45.9	461.3	44.1	442.9	41.3	449.8	42.0	423.0	37.5	392.6	34.8
Graphite	68.6	3.4	67.2	3.1	66.3	2.8	63.2	2.3	65.1	2.5	61.0	1.8	56.3	1.3
Binder	1.3	0.1	1.2	0.1	1.1	0.1	1.0	0.0	1.1	0.0	1.0	0.0	0.7	0.0
Copper	12.6	0.9	11.6	0.8	11.2	0.7	10.6	0.6	11.0	0.6	10.2	0.5	9.3	0.4
Wrought Aluminium	130.0	10.1	125.8	9.1	119.8	8.0	108.4	6.3	113.9	7.1	101.5	4.9	87.6	3.6
Electrolyte: LiPF6	11.5	0.7	10.6	0.6	10.0	0.5	9.0	0.3	9.7	0.4	8.3	0.2	5.6	0.1
Electrolyte: Ethylene Carbonate	1.4	0.1	1.4	0.1	1.4	0.1	1.4	0.1	1.4	0.1	1.4	0.0	1.4	0.0
Electrolyte: Dimethyl Carbonate	5.0	0.2	5.0	0.2	5.0	0.2	5.0	0.2	5.0	0.2	5.0	0.2	5.0	0.2
Plastic: Polypropylene	2.3	0.1	2.3	0.1	2.3	0.1	2.3	0.1	2.3	0.1	2.3	0.1	2.3	0.1
Plastic: Polyethylene	0.7	0.0	0.7	0.0	0.7	0.0	0.7	0.0	0.6	0.0	0.7	0.0	0.7	0.0
Plastic: Polyethylene Terephthalate	0.5	0.0	0.5	0.0	0.5	0.0	0.5	0.0	0.5	0.0	0.5	0.0	0.5	0.0
Steel	0.7	0.1	0.7	0.1	0.7	0.1	0.7	0.1	0.7	0.1	0.7	0.1	0.7	0.1
Thermal Insulation	0.3	0.0	0.3	0.0	0.3	0.0	0.3	0.0	0.3	0.0	0.3	0.0	0.3	0.0
Coolant: Glycol	2.0	0.2	2.0	0.2	2.0	0.2	2.0	0.2	2.0	0.2	2.0	0.2	2.0	0.2
Electronic Parts	32.1	1.9	30.1	1.6	28.7	1.4	26.6	1.2	28.1	1.3	25.0	0.9	19.2	0.6
Battery Assembly	256.4	16.7	250.4	15.4	245.3	14.4	235.5	12.9	242.0	13.7	230.5	11.7	216.4	10.3
Total per kWh battery	**1,021**	**83.5**	**981.2**	**77.0**	**956.6**	**72.6**	**910.2**	**65.6**	**933.4**	**68.3**	**873.3**	**58.1**	**800.5**	**51.7**

Table 43. Current and future PED and GHG emissions of NMC622 total battery by decarbonising the electricity sector to 2050 in the SPS and SDS scenarios. PED expressed in MJ/kWh and GHG emissions expressed in kgCO$_2$eq/kWh.

NMC622	**Current 2020**		**SPS 2030**		**SPS 2040**		**SPS 2050**		**SDS 2030**		**SDS 2040**		**SDS 2050**	
Materials	**PED**	**GHG**	**PED**	**GHG**	**PED**	**GHG**	**PED**	**GHG**	**PED**	**GHG**	**PED**	**GHG**	**PED**	**GHG**
Active Material	449.7	45.8	429.1	42.9	419.9	41.4	403.4	38.8	409.0	39.4	384.3	35.3	356.5	32.8
Graphite	68.8	3.4	67.3	3.1	66.4	2.8	63.4	2.3	65.2	2.5	61.1	1.8	56.4	1.3
Binder	1.2	0.1	1.1	0.1	1.1	0.1	1.0	0.0	1.0	0.0	0.9	0.0	0.6	0.0
Copper	11.7	0.8	10.7	0.7	10.4	0.6	9.8	0.6	10.1	0.6	9.4	0.5	8.6	0.4
Wrought Aluminium	124.9	9.7	120.9	8.7	115.2	7.7	104.2	6.1	109.5	6.8	97.6	4.7	84.2	3.4
Electrolyte: LiPF6	11.2	0.7	10.3	0.5	9.7	0.5	8.7	0.3	9.4	0.4	8.0	0.2	5.4	0.1
Electrolyte: Ethylene Carbonate	1.3	0.0	1.3	0.0	1.3	0.0	1.3	0.0	1.3	0.0	1.3	0.0	1.3	0.0
Electrolyte: Dimethyl Carbonate	4.9	0.2	4.9	0.2	4.9	0.2	4.9	0.2	4.9	0.2	4.9	0.2	4.9	0.2
Plastic: Polypropylene	1.7	0.1	1.7	0.1	1.7	0.1	1.7	0.1	1.7	0.1	1.7	0.1	1.7	0.1
Plastic: Polyethylene	0.5	0.0	0.5	0.0	0.5	0.0	0.5	0.0	0.5	0.0	0.5	0.0	0.5	0.0
Plastic: Polyethylene Terephthalate	0.5	0.0	0.5	0.0	0.5	0.0	0.5	0.0	0.5	0.0	0.5	0.0	0.5	0.0
Steel	0.6	0.1	0.6	0.1	0.6	0.1	0.6	0.1	0.6	0.1	0.6	0.1	0.6	0.1
Thermal Insulation	0.3	0.0	0.3	0.0	0.3	0.0	0.3	0.0	0.3	0.0	0.3	0.0	0.3	0.0
Coolant: Glycol	2.0	0.2	2.0	0.2	2.0	0.2	2.0	0.2	2.0	0.2	2.0	0.2	2.0	0.2
Electronic Parts	32.1	1.9	30.1	1.6	28.7	1.4	26.6	1.2	28.1	1.3	25.0	0.9	19.2	0.6
Battery Assembly	256.4	16.7	250.4	15.4	245.3	14.4	235.5	12.9	242.0	13.7	230.5	11.7	216.4	10.3
Total per kWh battery	**968**	**79.7**	**931.9**	**73.6**	**908.5**	**69.5**	**864.6**	**62.8**	**886.3**	**65.3**	**828.8**	**55.6**	**759.2**	**49.5**

Table 44. Current and future PED and GHG emissions of NMC811 total battery by decarbonising the electricity sector to 2050 in the SPS and SDS scenarios. PED expressed in MJ/kWh and GHG emissions expressed in kgCO$_2$eq/kWh.

NMC811	**Current 2020**		**SPS 2030**		**SPS 2040**		**SPS 2050**		**SDS 2030**		**SDS 2040**		**SDS 2050**	
Materials	**PED**	**GHG**	**PED**	**GHG**	**PED**	**GHG**	**PED**	**GHG**	**PED**	**GHG**	**PED**	**GHG**	**PED**	**GHG**
Active Material	437.2	45.5	417.7	42.6	408.1	41.1	390.7	38.4	395.7	38.8	369.5	34.6	340.8	32.0
Graphite	74.0	3.7	72.4	3.3	71.4	3.0	68.1	2.4	70.1	2.7	65.7	1.9	60.6	1.4
Binder	2.2	0.1	2.0	0.1	1.9	0.1	1.7	0.1	1.9	0.1	1.6	0.0	1.1	0.0
Copper	11.6	0.8	10.6	0.7	10.3	0.6	9.7	0.6	10.0	0.6	9.3	0.5	8.5	0.4
Wrought Aluminium	125.1	9.7	121.1	8.7	115.3	7.7	104.4	6.1	109.7	6.9	97.7	4.7	84.4	3.4
Electrolyte: LiPF6	11.0	0.6	10.2	0.5	9.6	0.5	8.6	0.3	9.3	0.4	7.9	0.2	5.3	0.1
Electrolyte: Ethylene Carbonate	1.3	0.0	1.3	0.0	1.3	0.0	1.3	0.0	1.3	0.0	1.3	0.0	1.3	0.0
Electrolyte: Dimethyl Carbonate	4.8	0.2	4.8	0.2	4.8	0.2	4.8	0.2	4.8	0.2	4.8	0.2	4.8	0.2
Plastic: Polypropylene	2.0	0.1	2.0	0.1	2.0	0.1	2.0	0.1	2.0	0.1	2.0	0.1	2.0	0.1
Plastic: Polyethylene	0.6	0.0	0.6	0.0	0.6	0.0	0.6	0.0	0.6	0.0	0.6	0.0	0.6	0.0
Plastic: Polyethylene Terephthalate	0.5	0.0	0.5	0.0	0.5	0.0	0.5	0.0	0.5	0.0	0.5	0.0	0.5	0.0
Steel	0.6	0.1	0.6	0.1	0.6	0.1	0.6	0.1	0.6	0.1	0.6	0.1	0.6	0.1
Thermal Insulation	0.3	0.0	0.3	0.0	0.3	0.0	0.3	0.0	0.3	0.0	0.3	0.0	0.3	0.0
Coolant: Glycol	2.0	0.2	2.0	0.2	2.0	0.2	2.0	0.2	2.0	0.2	2.0	0.2	2.0	0.2
Electronic Parts	32.1	1.9	30.1	1.6	28.7	1.4	26.6	1.2	28.1	1.3	25.0	0.9	19.2	0.6
Battery Assembly	256.4	16.7	250.4	15.4	245.3	14.4	235.5	12.9	242.0	13.7	230.5	11.7	216.4	10.3
Total per kWh battery	**962**	**79.6**	**926.7**	**73.6**	**902.8**	**69.4**	**857.7**	**62.6**	**878.9**	**65.0**	**819.7**	**55.1**	**748.6**	**48.9**

Table 45. Current and future PED and GHG emissions of NCA total battery by decarbonising the electricity sector to 2050 in the SPS and SDS scenarios. PED expressed in MJ/kWh and GHG emissions expressed in kgCO_2eq/kWh.

NCA	**Current 2020**		**SPS 2030**		**SPS 2040**		**SPS 2050**		**SDS 2030**		**SDS 2040**		**SDS 2050**	
Materials	**PED**	**GHG**	**PED**	**GHG**	**PED**	**GHG**	**PED**	**GHG**	**PED**	**GHG**	**PED**	**GHG**	**PED**	**GHG**
Active Material	499.6	51.1	479.0	48.2	468.5	46.5	449.6	43.5	455.0	44.0	426.4	39.5	395.1	36.6
Graphite	70.0	3.5	68.5	3.1	67.6	2.8	64.5	2.3	66.4	2.6	62.3	1.8	57.4	1.4
Binder	1.1	0.1	1.1	0.1	1.0	0.0	0.9	0.0	1.0	0.0	0.9	0.0	0.6	0.0
Copper	10.8	0.8	9.9	0.6	9.6	0.6	9.1	0.5	9.3	0.6	8.7	0.4	7.9	0.4
Wrought Aluminium	120.9	9.4	117.0	8.4	111.4	7.5	100.8	5.9	105.9	6.6	94.4	4.6	81.5	3.3
Electrolyte: LiPF6	10.7	0.6	9.9	0.5	9.3	0.4	8.4	0.3	9.0	0.4	7.7	0.2	5.2	0.1
Electrolyte: Ethylene Carbonate	1.3	0.0	1.3	0.0	1.3	0.0	1.3	0.0	1.3	0.0	1.3	0.0	1.3	0.0
Electrolyte: Dimethyl Carbonate	4.7	0.2	4.7	0.2	4.7	0.2	4.7	0.2	4.7	0.2	4.7	0.2	4.7	0.2
Plastic: Polypropylene	1.6	0.0	1.6	0.0	1.6	0.0	1.6	0.0	1.6	0.0	1.6	0.0	1.6	0.0
Plastic: Polyethylene	0.5	0.0	0.5	0.0	0.5	0.0	0.5	0.0	0.5	0.0	0.5	0.0	0.5	0.0
Plastic: Polyethylene Terephthalate	0.5	0.0	0.5	0.0	0.5	0.0	0.5	0.0	0.5	0.0	0.5	0.0	0.5	0.0
Steel	0.6	0.1	0.6	0.1	0.6	0.1	0.6	0.1	0.6	0.1	0.6	0.1	0.6	0.1
Thermal Insulation	0.3	0.0	0.3	0.0	0.3	0.0	0.3	0.0	0.3	0.0	0.3	0.0	0.3	0.0
Coolant: Glycol	2.1	0.2	2.1	0.2	2.1	0.2	2.1	0.2	2.1	0.2	2.1	0.2	2.1	0.2
Electronic Parts	32.1	1.9	30.2	1.6	28.8	1.4	26.7	1.2	28.1	1.3	25.1	0.9	19.2	0.6
Battery Assembly	256.4	16.7	250.4	15.4	245.3	14.4	235.5	12.9	242.0	13.7	230.5	11.7	216.4	10.3
Total per kWh battery	**1,013**	**84.6**	**977.4**	**78.5**	**952.9**	**74.3**	**907.0**	**67.3**	**928.2**	**69.7**	**867.4**	**59.6**	**794.8**	**53.2**

Table 46. Current and future PED and GHG emissions of LFP total battery by decarbonising the electricity sector to 2050 in the SPS and SDS scenarios. PED expressed in MJ/kWh and GHG emissions expressed in $kgCO_2eq/kWh$.

LFP	**Current 2020**		**SPS 2030**		**SPS 2040**		**SPS 2050**		**SDS 2030**		**SDS 2040**		**SDS 2050**	
Materials	**PED**	**GHG**	**PED**	**GHG**	**PED**	**GHG**	**PED**	**GHG**	**PED**	**GHG**	**PED**	**GHG**	**PED**	**GHG**
Active Material	223.3	17.0	219.9	16.5	27.6	16.3	213.1	15.7	214.2	15.9	209.8	15.3	206.2	14.9
Graphite	82.4	4.1	80.6	3.7	79.5	3.3	75.9	2.7	78.1	3.0	73.2	2.1	67.5	1.6
Binder	1.6	0.1	1.5	0.1	1.4	0.1	1.3	0.1	1.3	0.1	1.2	0.0	0.8	0.0
Copper	18.8	1.3	17.2	1.1	16.7	1.0	15.8	0.9	16.3	1.0	15.2	0.8	13.8	0.7
Wrought Aluminium	169.5	13.2	164.0	11.8	156.2	10.5	141.4	8.3	148.5	9.3	132.4	6.4	114.3	4.6
Electrolyte: LiPF6	20.2	1.2	18.6	1.0	17.5	0.8	15.8	0.6	17.0	0.7	14.5	0.4	9.7	0.1
Electrolyte: Ethylene Carbonate	2.4	0.1	2.4	0.1	2.4	0.1	2.4	0.1	2.4	0.1	2.4	0.1	2.4	0.1
Electrolyte: Dimethyl Carbonate	8.8	0.3	8.8	0.3	8.8	0.3	8.8	0.3	8.8	0.3	8.8	0.3	8.8	0.3
Plastic: Polypropylene	3.0	0.1	3.0	0.1	3.0	0.1	3.0	0.1	3.0	0.1	3.0	0.1	3.0	0.1
Plastic: Polyethylene	0.8	0.0	0.8	0.0	0.8	0.0	0.8	0.0	0.8	0.0	0.8	0.0	0.8	0.0
Plastic: Polyethylene Terephthalate	0.7	0.0	0.7	0.0	0.7	0.0	0.7	0.0	0.7	0.0	0.7	0.0	0.7	0.0
Steel	1.0	0.1	1.0	0.1	1.0	0.1	1.0	0.1	1.0	0.1	1.0	0.1	1.0	0.1
Thermal Insulation	0.4	0.0	0.4	0.0	0.4	0.0	0.4	0.0	0.4	0.0	0.4	0.0	0.4	0.0
Coolant: Glycol	2.6	0.2	2.6	0.2	2.6	0.2	2.6	0.2	2.6	0.2	2.6	0.2	2.6	0.2
Electronic Parts	33.7	2.0	31.7	1.7	30.2	1.5	28.0	1.2	29.6	1.3	26.3	0.9	20.2	0.6
Battery Assembly	256.4	16.7	250.4	15.4	245.3	14.4	235.5	12.9	242.0	13.7	230.5	11.7	216.4	10.3
Total per kWh battery	**825**	**56.4**	**803.6**	**52.2**	**784.1**	**48.9**	**746.5**	**43.3**	**766.7**	**45.8**	**722.8**	**38.5**	**668.7**	**33.8**

Table 47. GHG emissions of LIBs by decarbonising the electricity sector year by year to 2050 in the SPS and SDS scenarios. GHG emissions expressed in kgCO2eq/kWh.

	Stated policies scenario							**Sustainable development scenario**						
Year	LFP	NCA	NMC111	NMC523	NMC622	NMC811	NMC955	LFP	NCA	NMC111	NMC523	NMC622	NMC811	NMC955
2020	56.4	84.6	80.6	83.5	79.7	79.6	81.5	56.4	84.6	80.6	83.5	79.7	79.6	81.5
2021	56.0	84.0	79.9	82.9	79.1	79.0	80.9	55.4	83.1	79.0	82.0	78.2	78.1	80.1
2022	55.6	83.4	79.2	82.2	78.4	78.4	80.3	54.3	81.6	77.5	80.5	76.8	76.7	78.6
2023	55.2	82.8	78.6	81.5	77.8	77.8	79.7	53.3	80.1	76.0	79.0	75.4	75.2	77.1
2024	54.7	82.2	77.9	80.9	77.2	77.2	79.1	52.2	78.7	74.5	77.4	73.9	73.8	75.7
2025	54.3	81.5	77.3	80.2	76.6	76.6	78.5	51.1	77.2	73.0	75.9	72.5	72.3	74.2
2026	53.9	80.9	76.6	79.6	76.0	76.0	77.9	50.1	75.7	71.5	74.4	71.1	70.9	72.7
2027	53.5	80.3	76.0	78.9	75.4	75.4	77.3	49.0	74.2	70.0	72.9	69.6	69.4	71.3
2028	53.0	79.7	75.3	78.3	74.8	74.8	76.7	47.9	72.7	68.5	71.4	68.2	67.9	69.8
2029	52.6	79.1	74.7	77.6	74.2	74.2	76.1	46.9	71.2	67.0	69.8	66.8	66.5	68.3
2030	52.2	78.5	74.0	77.0	73.6	73.6	75.5	45.8	69.7	65.5	68.3	65.3	65.0	66.9
2031	51.9	78.1	73.6	76.5	73.2	73.2	75.1	45.1	68.7	64.5	67.3	64.4	64.0	65.9
2032	51.5	77.6	73.1	76.1	72.8	72.7	74.7	44.3	67.7	63.5	66.3	63.4	63.1	64.9
2033	51.2	77.2	72.7	75.7	72.4	72.3	74.2	43.6	66.7	62.5	65.3	62.4	62.1	63.9
2034	50.9	76.8	72.3	75.2	72.0	71.9	73.8	42.9	65.7	61.5	64.2	61.5	61.1	62.9
2035	50.5	76.4	71.8	74.8	71.5	71.5	73.4	42.1	64.7	60.5	63.2	60.5	60.1	61.9
2036	50.2	76.0	71.4	74.4	71.1	71.1	73.0	41.4	63.7	59.5	62.2	59.5	59.1	60.9
2037	49.9	75.5	71.0	73.9	70.7	70.7	72.6	40.7	62.6	58.5	61.2	58.6	58.1	59.9
2038	49.5	75.1	70.5	73.5	70.3	70.2	72.2	39.9	61.6	57.5	60.2	57.6	57.1	58.9
2039	49.2	74.7	70.1	73.1	69.9	69.8	71.7	39.2	60.6	56.5	59.1	56.6	56.1	57.9
2040	48.9	74.3	69.6	72.6	69.5	69.4	71.3	38.5	59.6	55.5	58.1	55.6	55.1	56.9
2041	48.3	73.6	68.9	71.9	68.8	68.7	70.6	38.0	59.0	54.8	57.5	55.0	54.5	56.2
2042	47.8	72.9	68.2	71.2	68.2	68.0	70.0	37.5	58.3	54.2	56.8	54.4	53.9	55.6
2043	47.2	72.2	67.5	70.5	67.5	67.4	69.3	37.1	57.7	53.5	56.2	53.8	53.2	55.0
2044	46.6	71.5	66.8	69.8	66.8	66.7	68.6	36.6	57.0	52.9	55.6	53.2	52.6	54.4
2045	46.1	70.8	66.1	69.1	66.1	66.0	67.9	36.1	56.4	52.3	54.9	52.6	52.0	53.7
2046	45.5	70.1	65.4	68.4	65.5	65.3	67.2	35.7	55.8	51.6	54.3	52.0	51.4	53.1
2047	45.0	69.4	64.7	67.7	64.8	64.6	66.5	35.2	55.1	51.0	53.6	51.4	50.8	52.5
2048	44.4	68.7	63.9	67.0	64.1	63.9	65.9	34.8	54.5	50.4	53.0	50.8	50.1	51.9
2049	43.9	68.0	63.2	66.3	63.5	63.2	65.2	34.3	53.9	49.7	52.4	50.1	49.5	51.2
2050	43.3	67.3	62.5	65.6	62.8	62.6	64.5	33.8	53.2	49.1	51.7	49.5	48.9	50.6

4.5 Future battery technology mix and projected impacts

Technology share-weighted projections of LIB GHG emission intensity to 2050 are shown in **Figure 12A** indicating an overall reduction in the GHG intensity of LIB manufacture by up to nearly 50% by 2050 across the two scenarios considered. Projected future LIB GHG emissions are dependent on the assumed technology mix under both scenarios(**Table 12** and **Table 13**), on the depth of GHG reductions achieved in the electricity sectors of countries active in material and battery production (**Table 47**), as well as projected total battery capacity (**Table 48**).

Reliance on nickel-based batteries (denoted NCX, where X indicates either Al or Mn) results in the highest LIB emissions of the scenarios considered. Initially, to 2025, a small increase in GHG emissions is anticipated in this scenario as LFP batteries are replaced by more GHG-intensive nickel-based alternatives, a driver that exceeds the near-term reduction in electricity GHG intensity. Average GHG emissions subsequently decline to reach a minimum value in 2050, driven by the anticipated reduction of GHG emissions in the electricity sector, representing a reduction of 14% compared to current emissions under the SPS scenario (64.2 kgCO_2eq/kWh) and 32% under the SDS scenario (50.5 kgCO_2eq/kWh). The LFP scenario sees immediate GHG emission reductions due to the near-term reduction in electricity GHG intensity and the longer-term replacement of nickel-based batteries with the lower GHG LFP alternative. The combination of these two factors results in the lowest projected LIB GHG emissions of the scenarios considered, with technology-mix-weighted GHG emissions reducing to 51.8 kgCO_2eq/kWh and 40.6 kgCO_2/kWh (SPS and SDS scenarios, respectively). Detailed technology share-weighted GHG emissions projections to 2050 under SPS and SDS scenarios for NCX and LFP battery scenarios can be found in **Table 49** and **Table 50**, respectively.

Table 48. Projected total battery total capacity in GWh under both scenarios

Year	Stated Policies	Sustainable Development
2020	328	597
2021	332	565
2022	369	634
2023	419	730
2024	485	861
2025	573	1,042
2026	575	1,063
2027	694	1,304
2028	838	1,603
2029	1,013	1,972
2030	1,226	2,429
2031	1,369	2,590
2032	1,432	2,723
2033	1,499	2,868
2034	1,567	3,238
2035	1,736	3,628
2036	1,910	4,035
2037	2,094	4,459
2038	2,291	4,905
2039	2,506	5,381
2040	2,742	5,895
2041	3,000	6,448
2042	3,281	7,034
2043	3,584	7,654
2044	3,903	8,289
2045	4,230	8,927
2046	4,562	9,565
2047	4,897	10,199
2048	5,245	10,848
2049	5,613	11,520
2050	6,008	12,217

Considering the anticipated scale of BEV deployment, decisions on LIB chemistry and electricity sector decarbonisation have a significant influence on cumulative emissions to 2050. The IEA projects total LIB capacity will exceed 12,000 GWh by 2050 under the SDS as shown in **Table 48**; primary manufacturing to create this battery capacity would result in GHG emissions totalling 8.2 $GtCO_2eq$ under the NCX scenario where nickel-based battery chemistries dominate. Achieving the same capacity under the LFP scenario would result in 1.5 $GtCO_2$ fewer GHG emissions by 2050, a significant GHG emissions savings equivalent to ~3% of current global annual GHG emissions. These results are based on primary production only and do not consider a battery replacement. Battery replacement creates an opportunity for remanufacturing and recycling to reduce the GHG emissions burden compared to primary production, so in practice, the additional GHG emissions related to replacement can be less if a proper recycling ecosystem is in place. However, this must be balanced against declining ore quality that may drive up energy use, or the current trend towards larger battery sizes for longer range and/or larger (hence heavier) BEVs segments.

Interestingly, under the less aggressive decarbonisation trajectory (i.e. SPS scenario), the cumulative GHG emissions for both LIB scenarios are lower than the SDS scenario. Although the grid is cleaner and GHG emissions per unit of battery are lower under the SDS scenario, the demand for LIB is projected to increase significantly by 2050 (12,000 GWh), almost doubling the LIB demand in 2050 under the SPS scenario (6,000 GWh). This growth in battery capacity is the main driver in the future cumulative GHG emissions, and is shown in **Figure 12B**. Detailed annual and cumulative GHG emissions associated with LIB manufacture under the set of future scenarios for a NCX and LFP battery scenario, are shown in **Table 51** and **Table 52.**, respectively.

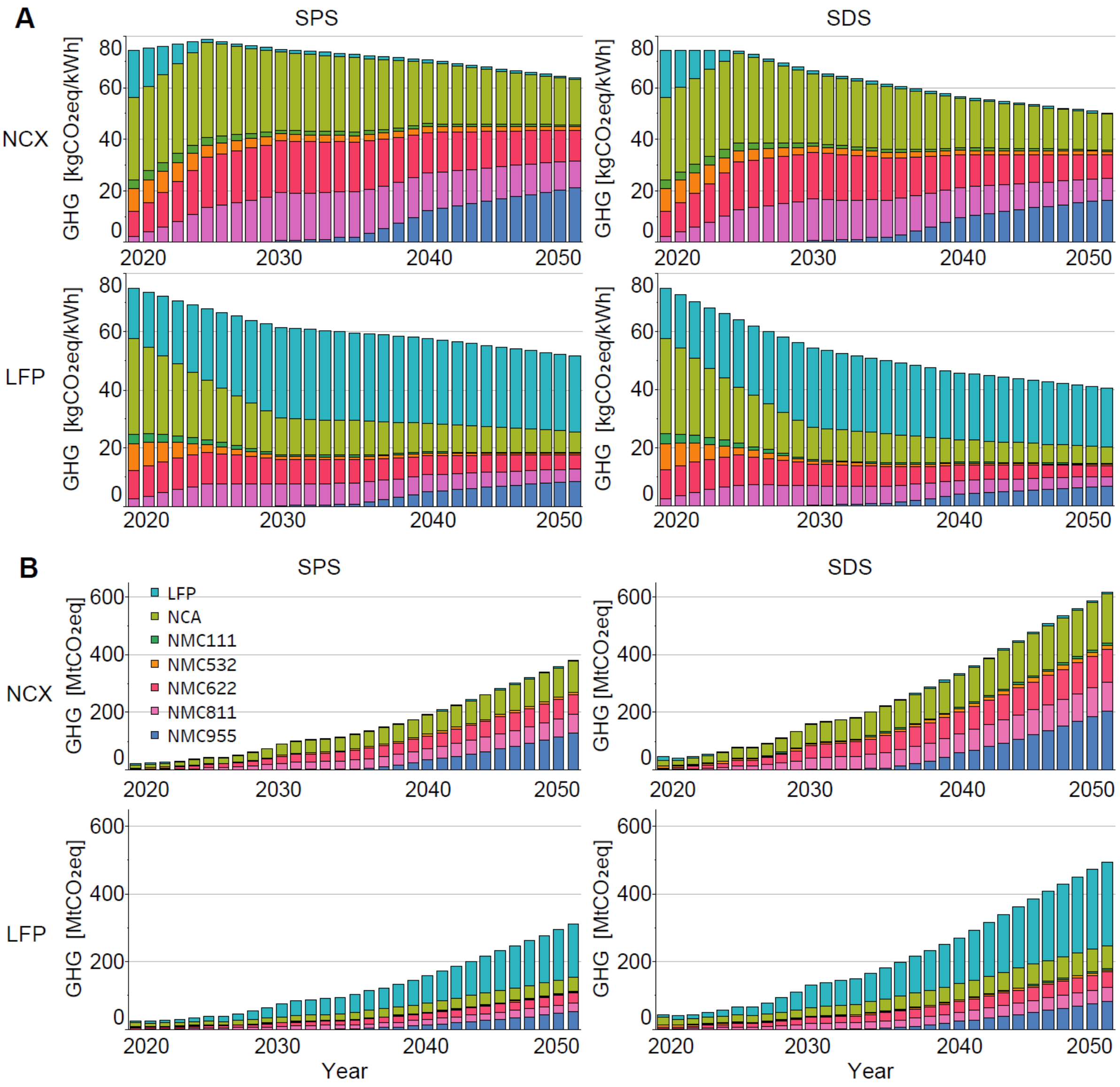

Figure 12. GHG emissions of LIB considering market shares by 2050 for the NCX and LFP battery scenarios coupled with the SPS and SDS electricity decarbonisation scenarios **(A)** Technology share-weighted projections of LIB GHG emissions intensity to 2050. GHG emissions expressed in $kgCO_2eq/kWh$ **(B)** Annual and cumulative GHG emissions from battery manufacturing of different market shares and LIB demand scenarios, excluding battery replacement. GHG emission expressed in $MtCO_2eq$.

Table 49. NCX scenario technology share-weighted GHG emissions projections of to 2050. GHG emissions expressed in $kgCO_2eq/kWh$.

	NCX battery Scenario - Stated Policies								**NCX battery Scenario - Sustainable Development**							
Year	LFP	NCA	NMC 111	NMC 523	NMC 622	NMC 811	NMC 955	TOTAL	LFP	NCA	NMC 111	NMC 523	NMC 622	NMC 811	NMC 955	TOTAL
2020	18.2	32.1	3.3	8.9	9.7	2.3	-	74.5	18.2	32.1	3.3	8.9	9.7	2.3	-	74.5
2021	14.6	3.0	3.4	8.8	11.5	3.9	-	75.4	14.5	32.7	3.4	8.7	11.4	3.9	-	74.6
2022	11.1	34.0	3.5	8.3	13.5	5.9	-	76.3	10.9	33.3	3.4	8.2	13.2	5.7	-	74.7
2023	7.7	35.0	3.4	7.5	5.4	8.1	-	77.1	7.5	33.8	3.3	7.3	15.0	7.8	-	74.6
2024	4.3	35.9	3.3	6.3	17.5	10.6	-	77.9	4.1	34.4	3.1	6.0	16.8	10.2	-	74.5
2025	1.0	36.8	3.0	4.7	9.7	13.5	-	78.7	1.0	34.8	2.8	4.5	18.6	2.7	-	74.4
2026	1.1	35.5	2.7	4.4	19.8	14.4	-	77.9	1.0	33.2	2.5	4.1	18.5	13.5	-	72.8
2027	1.1	34.3	2.4	4.0	20.0	15.5	-	77.2	1.0	31.6	2.2	3.7	8.5	14.2	-	71.3
2028	1.2	33.0	2.1	3.6	20.2	16.5	-	76.5	1.1	30.1	1.9	3.3	8.4	15.0	-	69.7
2029	1.3	31.8	1.7	3.2	20.3	17.5	-	75.8	1.1	28.6	1.6	2.9	18.3	15.7	-	68.1
2030	1.3	30.3	1.4	2.7	20.3	18.4	0.7	75.1	1.1	26.9	1.2	2.4	18.0	16.3	0.7	66.6
2031	1.3	30.1	1.4	2.7	20.1	18.3	0.8	74.7	1.1	26.5	1.2	2.4	17.7	16.0	0.7	65.6
2032	1.3	29.8	1.4	2.7	20.0	18.1	1.0	74.3	1.1	26.0	1.2	2.4	17.4	15.7	0.9	64.6
2033	1.3	29.6	1.3	2.7	19.8	17.9	1.3	3.8	1.1	25.5	1.2	2.3	17.1	15.4	1.1	63.6
2034	1.2	29.0	1.3	2.6	19.4	17.6	2.1	73.4	1.1	24.8	1.1	2.2	16.6	15.0	1.8	62.6
2035	1.2	28.9	1.3	2.6	19.3	17.5	2.1	3.0	1.0	24.4	1.1	2.2	16.3	14.7	1.8	61.7
2036	1.2	8.1	1.3	2.5	18.8	17.0	3.6	72.6	1.0	23.6	1.1	2.1	15.7	14.2	3.0	60.7
2037	1.2	7.2	1.2	2.5	18.2	16.5	5.4	72.2	0.9	22.6	1.0	2.0	15.1	13.6	4.5	59.7
2038	1.1	26.2	1.2	2.4	17.5	15.9	7.5	71.8	0.9	21.5	1.0	1.9	14.3	12.9	6.1	58.7
2039	1.1	25.1	1.1	2.3	16.8	15.2	9.9	71.4	0.9	20.3	0.9	1.8	13.6	12.2	8.0	57.7
2040	1.0	23.8	1.1	2.2	15.9	14.4	12.5	71.0	0.8	19.1	0.9	1.7	12.8	11.5	10.0	56.7
2041	1.0	3.2	1.1	2.1	15.5	14.0	13.4	70.3	0.8	18.6	0.8	1.7	12.4	11.1	10.7	56.1
2042	1.0	22.6	1.0	2.0	15.1	13.7	14.3	69.6	0.8	18.1	0.8	1.6	12.0	10.8	11.4	55.5
2043	0.9	21.9	1.0	2.0	14.6	13.3	15.3	69.0	0.7	17.5	0.8	1.6	11.7	10.5	12.1	54.9
2044	0.9	21.3	1.0	1.9	14.2	12.9	16.2	68.3	0.7	17.0	0.8	1.5	11.3	10.1	12.8	54.2
2045	0.9	20.6	0.9	1.9	13.8	12.5	17.1	67.6	0.7	16.4	0.7	1.5	10.9	9.8	13.5	53.6
2046	0.8	20.0	0.9	1.8	13.3	12.1	18.0	66.9	0.7	15.9	0.7	1.4	10.6	9.5	14.2	53.0
2047	0.8	19.4	0.9	1.7	12.9	11.7	18.9	66.2	0.6	15.4	0.7	1.4	10.2	9.2	14.9	52.4
2048	0.8	18.7	0.8	1.7	12.5	11.3	19.7	65.6	0.6	14.9	0.7	1.3	9.9	8.9	15.5	51.8
2049	0.8	8.1	0.8	1.6	12.1	10.9	20.5	64.9	0.6	14.4	0.6	1.3	9.6	8.6	16.1	51.1
2050	0.7	7.5	0.8	1.6	11.7	10.6	21.3	64.2	0.6	13.9	0.6	1.2	9.2	8.3	16.7	50.5

Table 50. LFP scenario technology share-weighted GHG emissions projections of to 2050. GHG emissions expressed in kgCO_2eq/kWh.

	LFP battery Scenario - Stated Policies								LFP battery Scenario - Sustainable Development							
Year	LFP	NCA	NMC 111	NMC 523	NMC 622	NMC 811	NMC 955	TOTAL	LFP	NCA	NMC 111	NMC 523	NMC 622	NMC 811	NMC 955	TOTAL
2020	17.2	32.8	3.4	9.2	9.9	2.4	-	74.9	17.2	32.8	3.4	9.2	9.9	2.4	-	74.9
2021	18.8	29.8	3.1	7.9	10.4	3.5	-	73.5	18.5	29.4	3.1	7.9	10.3	3.5	-	72.7
2022	20.2	27.0	2.8	6.6	10.7	4.7	-	72.0	19.8	26.5	2.7	6.5	10.5	4.6	-	70.5
2023	21.7	24.6	2.4	5.3	10.9	5.7	-	70.6	21.0	23.9	2.3	5.1	10.5	5.5	-	68.3
2024	23.2	22.5	2.0	3.9	11.0	6.7	-	69.3	22.1	21.5	1.9	3.8	10.5	6.4	-	66.2
2025	24.6	20.5	1.7	2.6	11.0	7.5	-	67.9	23.1	19.4	1.6	2.5	10.4	7.1	-	64.1
2026	26.0	18.8	1.4	2.3	10.5	7.6	-	66.6	24.1	17.5	1.3	2.2	9.8	7.1	-	62.1
2027	27.4	17.1	1.2	2.0	10.0	7.7	-	65.3	25.1	15.8	1.1	1.8	9.2	7.1	-	60.1
2028	28.7	15.5	1.0	1.7	9.5	7.7	-	64.1	25.9	14.1	0.9	1.5	8.6	7.0	-	58.2
2029	30.0	14.0	0.8	1.4	8.9	7.7	-	62.8	26.7	12.6	0.7	1.3	8.0	6.9	-	56.2
2030	31.3	12.4	0.6	1.1	8.3	7.5	0.3	61.6	27.5	11.0	0.5	1.0	7.4	6.7	0.3	54.3
2031	31.1	12.3	0.6	1.1	8.3	7.5	0.3	61.2	27.1	10.9	0.5	1.0	7.3	6.6	0.3	53.5
2032	30.9	12.2	0.6	1.1	8.2	7.4	0.4	60.8	26.6	10.7	0.5	1.0	7.1	6.4	0.4	52.7
2033	30.7	12.1	0.6	1.1	8.1	7.4	0.5	60.5	26.2	10.5	0.5	0.9	7.0	6.3	0.4	51.8
2034	30.5	11.9	0.5	1.1	8.0	7.2	0.9	60.1	25.7	10.2	0.5	0.9	6.8	6.1	0.7	51.0
2035	30.3	11.8	0.5	1.1	7.9	7.2	0.9	59.7	25.3	10.0	0.5	0.9	6.7	6.0	0.7	50.1
2036	30.1	11.5	0.5	1.0	7.7	7.0	1.5	59.4	24.8	9.7	0.4	0.9	6.4	5.8	1.2	49.3
2037	29.9	11.1	0.5	1.0	7.5	6.8	2.2	59.0	24.4	9.2	0.4	0.8	6.2	5.6	1.8	48.5
2038	29.7	10.7	0.5	1.0	7.2	6.5	3.1	58.6	24.0	8.8	0.4	0.8	5.9	5.3	2.5	47.6
2039	29.5	10.3	0.5	0.9	6.9	6.2	4.0	58.3	23.5	8.3	0.4	0.8	5.6	5.0	3.3	46.8
2040	29.3	9.7	0.4	0.9	6.5	5.9	5.1	57.9	23.1	7.8	0.4	0.7	5.2	4.7	4.1	45.9
2041	29.0	9.5	0.4	0.9	6.3	5.7	5.5	57.3	22.8	7.6	0.3	0.7	5.1	4.5	4.4	45.4
2042	28.7	9.2	0.4	0.8	6.2	5.6	5.9	56.7	22.5	7.4	0.3	0.7	4.9	4.4	4.7	44.9
2043	28.3	8.9	0.4	0.8	6.0	5.4	6.2	56.1	22.2	7.1	0.3	0.6	4.8	4.3	4.9	44.3
2044	28.0	8.7	0.4	0.8	5.8	5.2	6.6	55.5	22.0	6.9	0.3	0.6	4.6	4.1	5.2	43.8
2045	27.7	8.4	0.4	0.8	5.6	5.1	7.0	54.9	21.7	6.7	0.3	0.6	4.5	4.0	5.5	43.3
2046	27.3	8.1	0.4	0.7	5.4	4.9	7.3	54.3	21.4	6.5	0.3	0.6	4.3	3.9	5.8	42.7
2047	27.0	7.9	0.4	0.7	5.3	4.8	7.7	53.7	21.1	6.3	0.3	0.6	4.2	3.7	6.1	42.2
2048	26.7	7.6	0.3	0.7	5.1	4.6	8.0	53.0	20.9	6.1	0.3	0.5	4.0	3.6	6.3	41.7
2049	26.3	7.4	0.3	0.7	4.9	4.4	8.4	52.4	20.6	5.8	0.3	0.5	3.9	3.5	6.6	41.2
2050	26.0	7.1	0.3	0.6	4.8	4.3	8.7	51.8	20.3	5.6	0.3	0.5	3.8	3.4	6.8	40.6

Table 51. NCX scenario - Annual and cumulative GHG of different market shares and LIB demand scenarios. GHG emissions in MtCO2eq.

	NCX battery scenario - Stated policies								**NCX battery scenario - Sustainable Development**							
Year	LFP	NCA	NMC 111	NMC 523	NMC 622	NMC 811	NMC 955	TOTAL	LFP	NCA	NMC 111	NMC 523	NMC 622	NMC 811	NMC 955	TOTAL
2020	5.96	10.52	1.09	2.93	3.19	0.76	-	24.45	10.84	19.14	1.98	5.33	5.80	1.38	-	44.47
2021	4.85	10.96	1.14	2.93	3.83	1.30	-	25.01	8.18	18.49	1.93	4.94	6.46	2.19	-	42.18
2022	4.12	12.55	1.28	3.08	4.97	2.16	-	28.16	6.91	21.12	2.16	5.18	8.36	3.63	-	47.37
2023	3.23	14.64	1.43	3.14	6.47	3.39	-	32.30	5.44	24.70	2.41	5.30	10.91	5.71	-	54.46
2024	2.10	17.40	1.58	3.05	8.49	5.15	-	37.78	3.56	29.58	2.68	5.19	14.44	8.75	-	64.19
2025	0.58	21.08	1.72	2.72	11.26	7.71	-	45.07	0.99	36.29	2.96	4.67	19.39	13.24	-	77.54
2026	0.62	20.43	1.55	2.51	11.41	8.31	-	44.83	1.06	35.31	2.68	4.34	19.72	14.33	-	77.44
2027	0.79	23.76	1.66	2.77	13.88	10.72	-	53.58	1.36	41.28	2.87	4.80	24.10	18.56	-	92.97
2028	1.01	27.66	1.73	3.01	16.90	13.81	-	64.13	1.74	48.26	3.01	5.25	29.47	24.00	-	111.73
2029	1.28	32.20	1.76	3.23	20.60	17.75	-	76.82	2.21	56.42	3.07	5.66	36.06	30.96	-	134.40
2030	1.60	37.09	1.70	3.37	24.84	22.53	0.90	92.03	2.78	65.30	2.98	5.92	43.71	39.47	1.59	161.76
2031	1.77	41.16	1.88	3.74	27.56	25.00	1.09	102.21	2.92	68.57	3.12	6.22	45.88	41.42	1.81	169.94
2032	1.84	42.72	1.95	3.88	28.60	25.94	1.42	106.34	3.01	70.83	3.22	6.42	47.37	42.75	2.35	175.95
2033	1.91	44.29	2.02	4.02	29.65	26.89	1.89	110.66	3.11	73.21	3.33	6.63	48.96	44.16	3.11	182.51
2034	1.96	45.50	2.08	4.13	30.46	27.61	3.36	115.10	3.41	80.38	3.65	7.28	53.73	48.44	5.91	202.81
2035	2.15	50.12	2.29	4.55	33.53	30.41	3.69	126.73	3.75	88.70	4.02	8.03	59.26	53.41	6.50	223.68
2036	2.30	53.69	2.45	4.87	35.92	32.57	6.92	138.72	4.01	95.03	4.31	8.60	63.48	57.18	12.19	244.79
2037	2.44	56.99	2.60	5.17	38.12	34.56	11.34	151.22	4.24	100.62	4.56	9.10	67.18	60.49	19.92	266.11
2038	2.57	60.04	2.73	5.44	40.15	36.39	17.19	164.53	4.43	105.44	4.77	9.53	70.38	63.33	30.02	287.91
2039	2.69	62.84	2.86	5.69	42.01	38.08	24.75	178.92	4.60	109.51	4.95	9.90	73.07	65.71	42.88	310.60
2040	2.79	65.35	2.97	5.92	43.68	39.59	34.36	194.66	4.72	112.76	5.09	10.18	75.20	67.60	58.91	334.47
2041	2.97	69.60	3.16	6.30	46.51	42.14	40.30	210.99	5.01	119.87	5.41	10.82	79.92	71.82	68.96	361.81
2042	3.15	73.99	3.36	6.70	49.44	44.78	47.06	228.48	5.30	126.97	5.72	11.46	84.63	76.02	80.21	390.32
2043	3.33	78.52	3.56	7.10	52.45	47.50	54.72	247.19	5.59	134.00	6.03	12.09	89.30	80.18	92.75	419.94
2044	3.51	82.96	3.76	7.50	55.40	50.16	63.22	266.51	5.86	140.62	6.33	12.68	93.68	84.09	106.41	449.66
2045	3.69	87.19	3.95	7.88	58.21	52.69	72.36	285.96	6.10	146.66	6.59	13.22	97.67	87.64	120.85	478.74
2046	3.85	91.14	4.12	8.24	60.83	55.05	82.09	305.33	6.32	152.09	6.83	13.71	101.26	90.82	135.98	507.00
2047	3.99	94.78	4.28	8.56	63.24	57.21	92.36	324.44	6.50	156.85	7.04	14.13	104.40	93.60	151.72	534.24
2048	4.13	98.28	4.44	8.88	65.56	59.30	103.36	343.94	6.68	161.28	7.23	14.52	107.30	96.17	168.32	561.50
2049	4.26	101.76	4.59	9.19	67.86	61.36	115.23	364.26	6.84	165.45	7.41	14.89	110.04	98.58	185.88	589.10
2050	4.40	105.31	4.75	9.50	70.21	63.47	128.14	385.79	6.99	169.39	7.58	15.24	112.63	100.86	204.47	617.15
Cumulative	**85.83**	**1,634.55**	**80.44**	**159.98**	**1,065.24**	**944.28**	**905.78**	**4,876.10**	**144.5**	**2,774.1**	**135.9**	**271.3**	**1,803.8**	**1,586.5**	**1,500.7**	**8,216.74**

Table 52. LFP scenario - Annual and cumulative GHG of different market shares and LIB demand scenarios. GHG emissions in MtCO2eq.

	LFP Scenario - Stated policies								**LFP Scenario - Sustainable Development**							
Year	LFP	NCA	NMC 111	NMC 523	NMC 622	NMC 811	NMC 955	TOTAL	LFP	NCA	NMC 111	NMC 523	NMC 622	NMC 811	NMC 955	TOTAL
2020	5.65	10.78	1.12	3.00	3.26	0.77	-	24.59	10.29	19.61	2.03	5.46	5.94	1.41	-	44.73
2021	6.22	9.87	1.03	2.64	3.45	1.17	-	24.37	10.48	16.65	1.74	4.45	5.81	1.97	-	41.10
2022	7.47	9.98	1.02	2.45	3.95	1.72	-	26.59	12.55	16.80	1.72	4.12	6.65	2.89	-	44.72
2023	9.10	10.32	1.01	2.21	4.56	2.39	-	29.58	15.30	17.41	1.70	3.73	7.69	4.02	-	49.86
2024	11.23	10.90	0.99	1.91	5.32	3.23	-	33.58	19.02	18.53	1.68	3.25	9.04	5.48	-	57.00
2025	14.09	11.76	0.96	1.51	6.28	4.30	-	38.90	24.12	20.24	1.65	2.61	10.81	7.39	-	66.82
2026	14.94	10.79	0.82	1.33	6.03	4.39	-	38.30	25.66	18.66	1.42	2.30	10.42	7.57	-	66.02
2027	18.98	11.86	0.83	1.38	6.93	5.35	-	45.32	32.71	20.60	1.43	2.40	12.03	9.26	-	78.42
2028	24.05	12.99	0.81	1.41	7.94	6.48	-	53.69	41.58	22.66	1.41	2.47	13.84	11.27	-	93.23
2029	30.42	14.17	0.77	1.42	9.06	7.81	-	63.66	52.75	24.83	1.35	2.49	15.87	13.62	-	110.91
2030	38.38	15.22	0.70	1.38	10.19	9.24	0.37	75.48	66.78	26.79	1.22	2.43	17.93	16.19	0.65	132.00
2031	42.59	16.89	0.77	1.53	11.31	10.26	0.45	83.79	70.07	28.13	1.28	2.55	18.82	16.99	0.74	138.59
2032	44.27	17.52	0.80	1.59	11.73	10.64	0.58	87.14	72.46	29.06	1.32	2.63	19.43	17.54	0.96	143.40
2033	46.02	18.17	0.83	1.65	12.16	11.03	0.78	90.64	75.06	30.03	1.37	2.72	20.08	18.11	1.28	148.65
2034	47.82	18.66	0.85	1.69	12.49	11.32	1.38	94.22	83.29	32.96	1.50	2.99	22.03	19.87	2.42	165.06
2035	52.61	20.55	0.94	1.86	13.75	12.47	1.51	103.70	91.74	36.37	1.65	3.29	24.30	21.90	2.66	181.92
2036	57.53	22.01	1.00	2.00	14.72	13.35	2.84	113.44	100.24	38.95	1.77	3.52	26.02	23.43	4.99	198.92
2037	62.65	23.34	1.06	2.12	15.61	14.15	4.65	123.58	108.80	41.21	1.87	3.73	27.52	24.77	8.16	216.05
2038	68.08	24.57	1.12	2.23	16.43	14.90	7.04	134.37	117.52	43.15	1.95	3.90	28.80	25.92	12.29	233.54
2039	73.96	25.70	1.17	2.33	17.18	15.57	10.12	146.02	126.57	44.78	2.02	4.05	29.88	26.87	17.53	251.70
2040	80.37	26.70	1.21	2.42	17.84	16.17	14.04	158.75	136.05	46.06	2.08	4.16	30.72	27.61	24.06	270.76
2041	86.96	28.42	1.29	2.57	18.99	17.21	16.46	171.90	147.02	48.95	2.21	4.42	32.64	29.33	28.16	292.72
2042	94.00	30.20	1.37	2.73	20.18	18.28	19.21	185.98	158.42	51.83	2.34	4.68	34.55	31.03	32.74	315.58
2043	101.51	32.04	1.45	2.90	21.40	19.38	22.33	201.01	170.25	54.68	2.46	4.93	36.44	32.72	37.84	339.32
2044	109.24	33.84	1.53	3.06	22.60	20.46	25.78	216.51	182.09	57.36	2.58	5.17	38.21	34.30	43.40	363.10
2045	116.99	35.55	1.61	3.21	23.73	21.48	29.50	232.07	193.63	59.80	2.69	5.39	39.82	35.73	49.27	386.33
2046	124.67	37.15	1.68	3.36	24.79	22.44	33.46	247.54	204.81	61.98	2.78	5.59	41.27	37.01	55.42	408.86
2047	132.21	38.61	1.75	3.49	25.76	23.31	37.63	262.76	215.54	63.90	2.87	5.76	42.53	38.13	61.81	430.53
2048	139.88	40.02	1.81	3.61	26.70	24.15	42.09	278.25	226.25	65.67	2.94	5.91	43.70	39.16	68.54	452.18
2049	147.83	41.42	1.87	3.74	27.62	24.98	46.90	294.37	237.06	67.34	3.02	6.06	44.79	40.13	75.66	474.07
2050	156.24	42.85	1.93	3.87	28.57	25.82	52.14	311.42	248.02	68.92	3.08	6.20	45.83	41.04	83.19	496.28
Cumulative	**1,966.0**	**702.8**	**36.1**	**72.6**	**450.5**	**394.2**	**369.2**	**3,991.51**	**3,276.1**	**1,193.9**	**61.1**	**123.4**	**763.4**	**662.7**	**611.8**	**6,692.38**

4.6 Summary

Given the global decarbonisation challenge and the scaled-up production required for LIBs, it is critical that the environmental impacts of LIB technologies are properly understood. In this thesis chapter, the current and future life cycle environmental impacts of LIB manufacture are characterised spatially and temporally to better understand the role of electricity decarbonisation and battery technology in a globalised LIB supply chain. It is demonstrated how GHG emissions can be shifted globally for a technology that is aimed at addressing a national GHG emission target (e.g., as developed countries, mainly in the west, target BEVs to achieve 100% of new car sales as part of their national targets, GHG emissions from LIB could increase elsewhere, especially in the developing world in the east). Currently, China dominates the downstream battery supply chain, accounting for the largest share of supply chain GHG emissions, followed by Australia and Indonesia, depending on the battery technology type. However, this may change as LIB manufacturers emerge in different regions, and it is crucial that decisions on LIB productions also consider the overall life cycle emissions to minimise supply chain emissions. To achieve a net zero future, it is key to track upstream GHG emissions, or scope 3 emissions, throughout a global supply chain, and to identify measures to reduce them. It is found that decarbonising electricity generation could substantially reduce battery production emissions towards 2050 as electricity consumption contributes over a third of the total GHG emissions of LIB manufacture today. Technology-share-weighted projections of LIB GHG emissions intensity to 2050 indicate an overall reduction in the GHG intensity of LIB manufacture of up to around 50% by 2050 across the two scenarios considering different technology mixes. The depth of GHG reductions achieved in both scenarios also depends on the decarbonisation rate of the electricity sector in countries active in the material and battery production supply chain.

CHAPTER 5 Battery Recycling

Given the rapid growth of BEVs and the high risk of material supply for battery production, the recovery and recycling of materials from end-of-life batteries have become attractive. Recycling can alleviate the environmental burdens of batteries associated with production from the primary resources (e.g., mining and refining), by supplying secondary materials and integrating them back into the battery supply chain. Therefore, this chapter presents the GHG emissions of different LIB chemistries produced with secondary materials via different recycling technologies, exploring different recycling scenarios, and a further potential emission reduction by decarbonising the electricity grid in the future. This chapter describes three assessments 1) cathode active materials, 2) total battery, and 3) future battery. Similar to Chapter 4, for simplicity, the discussion focuses primarily on NMC811 and LFP battery chemistries throughout the chapter, however, numerical data for all chemistries are presented. The modelling does not consider a country-specific level of analysis as it is uncertain where battery recycling infrastructure will exist in the future. Therefore, the recycling of battery materials and battery assembly are assumed to take place in Europe.

5.1 Secondary materials impacts

Environmental impacts from secondary materials are calculated based on the recovered materials (**Table 17**) and efficiencies (**Table 16**) from Everbatt (ANL, 2020b). **Table 53** and **Table 54** show the GHG emissions and PED, respectively, of virgin and secondary materials for the different recycling techniques and different battery chemistries. Pyrometallurgical is the most GHG emission-intensive, thus, emissions offset from recovered materials are expected to be smaller compared to hydro and direct recycling. For lithium and manganese, the lowest emission factor (EF) comes from hydrometallurgical; pyrometallurgical does not recover lithium or manganese. For nickel and cobalt, the lowest EF comes from hydrometallurgical and the highest from pyrometallurgical. For graphite and aluminium, the lowest EF comes from direct recycling and the highest from hydrometallurgical; pyrometallurgical does not recover graphite or aluminium. For copper, the lowest EF is from direct recycling and the highest from pyrometallurgical, copper can be recovered from all recycling techniques. The quantity of materials recovered via different recycling technologies for various battery chemistries is presented in **Table 17.**

Table 53. Summary of GHG emissions related to recovered materials on a mass allocation factor. Values expressed in kgCO$_2$eq per kg material.

Recycling technique	Cathode	Li	Ni	Co	Mn	Gr	Al	Cu	Cathode
Virgin	**All**	13.08	18.53	7.33	1.43	4.45	15.64	3.35	0
Pyro	**NMC111**	0	10.73	10.73	0	0	0	10.73	0
	NMC532	0	10.30	10.30	0	0	0	10.30	0
	NMC622	0	9.75	9.75	0	0	0	9.75	0
	NMC811	0	9.78	9.78	0	0	0	9.78	0
	NCA	0	8.82	8.82	0	0	0	8.82	0
	LFP	0	0	0	0	0	0	31.85	0
Hydro	**NMC111**	2.22	2.22	2.22	2.22	2.22	2.22	2.22	0
	NMC532	2.19	2.19	2.19	2.19	2.19	2.19	2.19	0
	NMC622	2.20	2.20	2.20	2.20	2.20	2.20	2.20	0
	NMC811	2.28	2.28	2.28	2.28	2.28	2.28	2.28	0
	NCA	2.22	2.22	2.22	0	2.22	2.22	2.22	0
	LFP	3.92	0	0	0	3.92	3.92	3.92	0
Direct	**NMC111**	0	0	0	0	1.21	1.21	1.21	1.21
	NMC532	0	0	0	0	1.20	1.20	1.20	1.20
	NMC622	0	0	0	0	1.20	1.20	1.20	1.20
	NMC811	0	0	0	0	1.25	1.25	1.25	1.25
	NCA	0	0	0	0	1.20	1.20	1.20	1.20
	LFP	0	0	0	0	1.25	1.25	1.25	1.25

Table 54. Summary of PED related to recovered materials on a mass allocation factor. Values expressed in MJ per kg material.

Recycling technique	Cathode	Li	Ni	Co	Mn	Gr	Al	Cu	Cathode
Virgin	**All**	124.78	120.23	104.15	153.37	89.41	200.84	47.24	0
Pyro	**NMC111**	0	82.40	82.40	0	0	0	82.40	0

	NMC532	0	79.07	79.07	0	0	0	79.07	0
	NMC622	0	74.90	74.90	0	0	0	74.90	0
	NMC811	0	75.10	75.10	0	0	0	75.10	0
	NCA	0	67.70	67.70	0	0	0	67.70	0
	LFP	0	0	0	0	0	0	244.58	0
Hydro	**NMC111**	25.31	25.31	25.31	25.31	25.31	25.31	25.31	0
	NMC532	25.00	25.00	25.00	25.00	25.00	25.00	25.00	0
	NMC622	25.09	25.09	25.09	25.09	25.09	25.09	25.09	0
	NMC811	26.05	26.05	26.05	26.05	26.05	26.05	26.05	0
	NCA	25.29	25.29	25.29	0	25.29	25.29	25.29	0
	LFP	44.77	0	0	0	44.77	44.77	44.77	0
Direct	**NMC111**	0	0	0	0	11.00	11.00	11.00	11.00
	NMC532	0	0	0	0	10.86	10.86	10.86	10.86
	NMC622	0	0	0	0	10.89	10.89	10.89	10.89
	NMC811	0	0	0	0	11.30	11.30	11.30	11.30
	NCA	0	0	0	0	10.89	10.89	10.89	10.89
	LFP	0	0	0	0	11.32	11.32	11.32	11.32

5.2 Current cathode active material production impacts from secondary materials

Figure 13 and **Figure 14** show the GHG emissions and PED associated with cathode active material production using secondary materials from pyrometallurgical and hydrometallurgical recycling techniques (hereinafter referred to as pyro and hydro, respectively) for Europe’s average electricity grid under the circular battery scenario, i.e., using maximum secondary materials complemented by virgin materials. This scenario does not consider the availability of secondary materials, meaning that this mix of secondary and virgin materials is unrealistic and is not predicting what will happen in the future. However, it provides a comprehensive perspective on the potential GHG emission reduction from employing secondary materials. Direct recycling is not included here since active materials, e.g., lithium, nickel, manganese and cobalt, are not recovered via direct recycling. However, direct recycling is included and discussed in the next section for total battery production from secondary materials.

Under the circular battery scenario, secondary nickel-based cathode materials range from 18 $kgCO_2eq/kWh$ (NMC111 and NMC811 via hydro) to up to 37 $kgCO_2eq/kWh$ (NCA via pyro). GHG emissions for these chemistries follow the same trend that cathode production from primary materials, i.e., GHG emissions are dominated by the active materials (predominantly nickel, lithium/carbonate hydroxide, and cobalt for cobalt-rich chemistries) and the cathode production process.

For the NCX battery chemistries (i.e., NMC or NCA), under the circular battery scenario, when using pyro, secondary materials provide 98% of the supply for nickel and cobalt, while relying on primary supply for lithium and manganese, since these are not recoverable by pyro. On a per kWh battery basis, for the NMC811 cathode chemistry, secondary cobalt from pyro (1.67 $kgCO_2eq/kWh$) results in slightly higher emissions compared to primary production (1.25 $kgCO_2eq/kWh$). However, secondary nickel via pyro (13.62 $kgCO_2eq/kWh$) results in emission reductions compared to primary nickel (25.18 $kgCO_2eq/kWh$). For hydro, even more emission reductions are expected since all cathode materials are recovered. Secondary lithium is providing 90% of the supply, while the remaining is provided by primary lithium. Nickel, cobalt, and manganese provide 98% of the supply. Secondary materials via hydro can provide 3.63, 0.42, 0.38, and 1.22 $kgCO_2eq/kWh$ for nickel, cobalt, manganese, and lithium, respectively. Overall, final NMC811 cathode GHG emissions are reduced by 60% via hydro and 25% via pyro (from primary production of 45.4 $kgCO_2eq/kWh$ to secondary production of 18.25 $kgCO_2eq/kWh$ via hydro and 34.5 $kgCO_2eq/kWh$ via pyro). It is worth noting that a key driver is the electricity emission intensity considered for recycling (0.335 gCO_2eq/kWh for Europe) is considerably lower than the primary production from a mix of countries (0.838 gCO_2eq/kWh).

For LFP cathodes, the majority of emissions come from lithium input and the cathode production process. GHG emissions are reduced by 50% via hydro (from primary production of 17 kgCO_2eq/kWh to secondary production of 8.3 kgCO_2eq/kWh). Using pyro does not reduce GHG emissions in LFP cathodes because lithium is not recoverable, hence primary lithium is used, and the cathode production process does not make use of electricity. PED results for both cathode chemistries follow a similar trend to GHG emissions results. Detailed numerical data for all chemistries on GHG emissions and PED under the 50-50 and circular battery scenarios are displayed in **Table 55, Table 56**, **Table 57** and **Table 58**, respectively. The 50-50 scenario assumes that 50% of the battery materials are secondary, and the circular battery scenario assumes a maximum share of secondary materials.

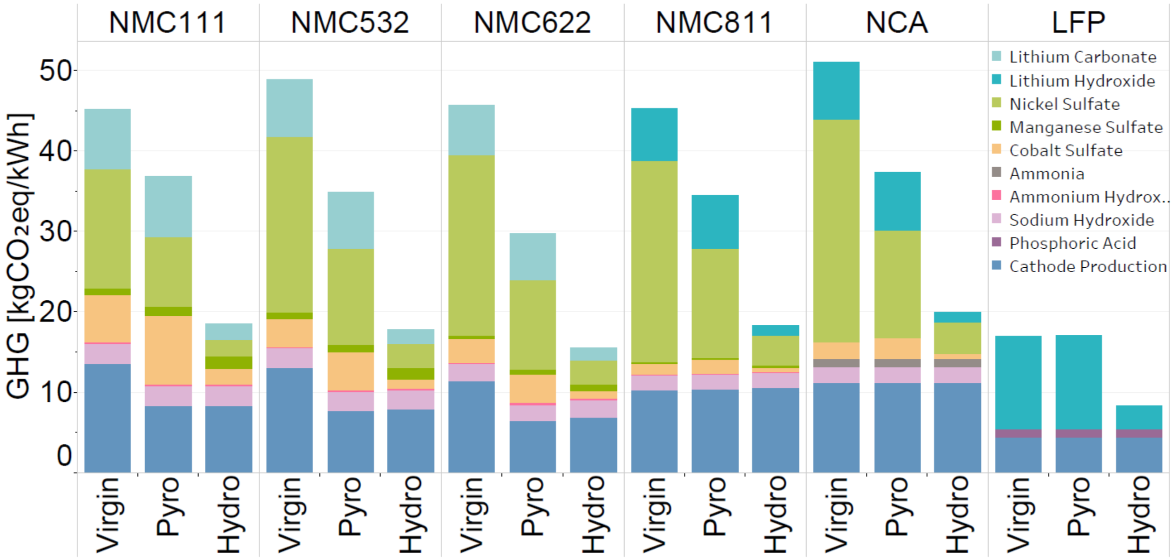

Figure 13. GHG emissions of cathode materials and production process for different battery chemistries and different recycling technologies under the circular battery scenario. The cathode production process includes precursor co-precipitation and cathode production via calcination as indicated in **Table 56**.

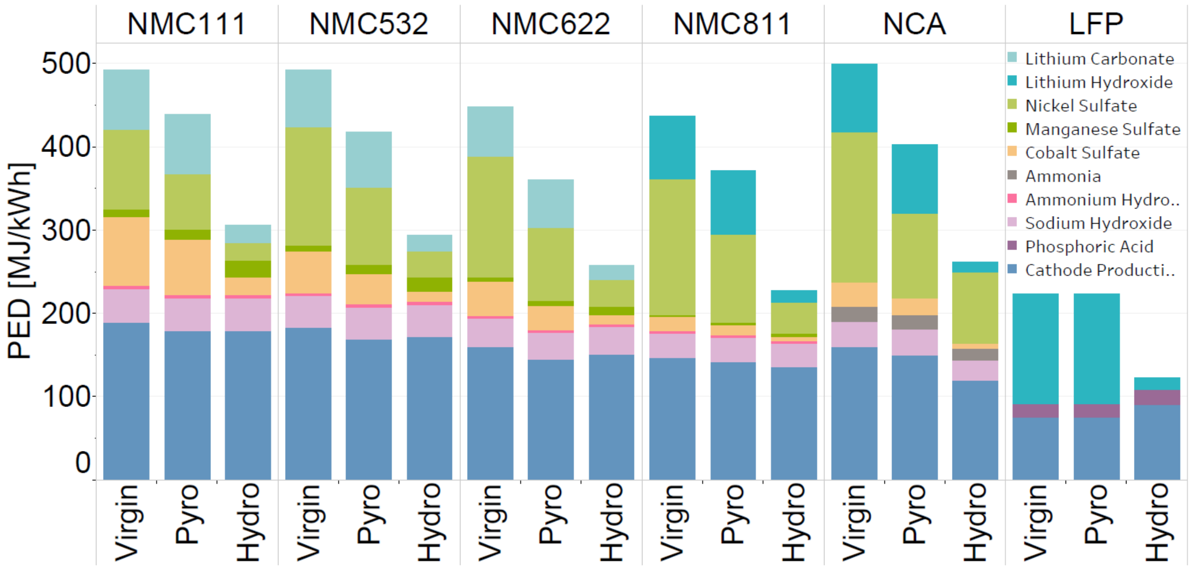

Figure 14. PED of cathode materials and production process for different battery chemistries and different recycling technologies under the circular battery scenario. The cathode production process includes precursor co-precipitation and cathode production via calcination as indicated in **Table 58**.

Table 55. 50-50 battery scenario - GHG emissions of virgin and secondary production of cathode active materials. Emissions expressed in $kgCO_2eq/kWh$ battery.

Materials	NMC111			NMC532			NMC622			NMC811			NCA			LFP		
	Virgin	Pyro	Hydro	Virgin	Pyro	Hydro	Virgin	Pyro	Hydro	Virgin	Pyro	Hydro	Virgin	Pyro	Hydro	Virgin	Pyro	Hydro
Nickel Sulfate	14.78	11.67	8.27	21.89	15.68	11.17	22.34	14.81	10.83	25.18	17.52	12.52	27.68	20.43	15.50	0.0	0.0	0.0
Cobalt Sulfate	5.85	7.21	3.81	3.49	3.87	2.07	2.95	2.99	1.66	1.25	1.33	0.72	2.09	2.31	1.36	0.0	0.0	0.0
Manganese Sulfate	1.11	1.11	1.42	0.96	0.88	1.11	0.56	0.49	0.62	0.24	0.22	0.27	0.0	0.0	0.0	0.0	0.0	0.0
Lithium Carbonate	7.47	7.47	4.37	7.18	6.61	3.82	6.27	5.45	3.18	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Lithium Hydroxide	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	6.52	5.94	3.15	7.17	7.17	3.90	11.53	11.53	6.68
Sodium Hydroxide	2.53	2.53	2.53	2.43	2.24	2.22	2.13	1.85	1.85	1.81	1.65	1.60	1.94	1.94	1.94	0.0	0.0	0.0
Ammonium Hydroxide	0.22	0.22	0.22	0.21	0.20	0.19	0.19	0.16	0.16	0.16	0.14	0.14	0.00	0.00	0.00	0.0	0.0	0.0
Ammonia	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.06	1.06	1.06	0.0	0.0	0.0
Aluminium sulfate	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.01	0.01	0.01	0.0	0.0	0.0
Phosphoric Acid	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.07	1.07	1.07
Precursor Co-precipitation	4.41	4.41	4.41	4.24	3.91	3.87	3.73	3.24	3.23	3.16	2.88	2.80	3.43	3.43	3.43	0.0	0.0	0.0
Cathode Production	9.09	3.85	3.85	8.77	3.42	3.39	7.67	2.82	2.81	7.16	6.52	6.34	7.75	7.75	7.75	4.40	4.40	4.40
Total	45.5	38.5	28.9	49.2	36.8	27.8	45.8	31.8	24.3	45.5	36.2	27.5	51.1	44.1	35.0	17.0	17.0	12.1

Table 56. Circular battery scenario - GHG emissions of virgin and secondary production of cathode active materials. Emissions expressed in $kgCO_2eq/kWh$ battery.

Materials	NMC111			NMC532			NMC622			NMC811			NCA			LFP		
	Virgin	Pyro	Hydro	Virgin	Pyro	Hydro	Virgin	Pyro	Hydro	Virgin	Pyro	Hydro	Virgin	Pyro	Hydro	Virgin	Pyro	Hydro
Nickel Sulfate	14.78	8.68	2.03	21.89	11.98	2.95	22.34	11.13	3.02	25.18	13.62	3.63	27.68	13.46	3.80	0.00	0.00	0.00
Cobalt Sulfate	5.85	8.52	1.85	3.49	4.73	1.08	2.95	3.63	0.92	1.25	1.67	0.42	2.09	2.51	0.66	0.00	0.00	0.00
Manganese Sulfate	1.11	1.11	1.71	0.96	0.93	1.45	0.56	0.52	0.85	0.24	0.24	0.38	0.00	0.00	0.00	0.00	0.00	0.00
Lithium Carbonate	7.47	7.47	1.89	7.18	6.95	1.78	6.27	5.83	1.56	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Lithium Hydroxide	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	6.52	6.56	1.22	7.17	7.17	1.29	11.53	11.53	2.80
Sodium Hydroxide	2.53	2.53	2.53	2.43	2.35	2.41	2.13	1.98	2.11	1.81	1.82	1.86	1.94	1.94	1.94	0.00	0.00	0.00
Ammonium Hydroxide	0.22	0.22	0.22	0.21	0.21	0.21	0.19	0.17	0.19	0.16	0.16	0.16	0.00	0.00	0.00	0.00	0.00	0.00
Ammonia	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.06	1.06	1.06	0.00	0.00	0.00
Aluminium sulfate	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.01	0.00	0.00	0.00
Phosphoric Acid	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.07	1.07	1.07
Precursor Co-precipitation	4.41	4.41	4.41	4.24	4.11	4.21	3.73	3.47	3.69	3.16	3.18	3.24	3.43	3.43	3.43	0.00	0.00	0.00
Cathode Production	9.09	3.85	3.85	8.77	3.60	3.68	7.67	3.02	3.22	7.16	7.21	7.34	7.75	7.75	7.75	4.40	4.40	4.40
Total	45.5	36.8	18.5	49.2	34.9	17.8	45.8	29.8	15.6	45.5	34.5	18.3	51.1	37.3	20.0	17.0	17.0	8.3

Table 57. 50-50 battery scenario - Energy of virgin and secondary production of cathode active materials. PED expressed in MJ/kWh battery

Materials	NMC111			NMC532			NMC622			NMC811			NCA			LFP		
	Virgin	Pyro	Hydro	Virgin	Pyro	Hydro	Virgin	Pyro	Hydro	Virgin	Pyro	Hydro	Virgin	Pyro	Hydro	Virgin	Pyro	Hydro
Nickel Sulfate	95.9	80.8	58.0	142.1	114.6	83.9	144.9	110.9	83.6	163.3	131.4	95.9	179.6	140.4	108.7	0.0	0.0	0.0
Cobalt Sulfate	83.2	74.5	51.7	49.6	42.5	30.1	41.9	34.0	24.8	17.7	15.1	10.7	29.7	24.5	18.5	0.0	0.0	0.0
Manganese Sulfate	12.2	12.2	16.0	10.6	10.3	13.4	6.2	5.8	7.6	2.6	2.6	3.3	0.0	0.0	0.0	0.0	0.0	0.0
Lithium Carbonate	71.3	71.3	42.9	68.5	66.6	40.2	59.9	56.4	34.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Lithium Hydroxide	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	74.9	74.2	39.5	82.4	82.4	44.8	132.5	132.5	11.5
Sodium Hydroxide	40.4	40.4	40.4	38.9	37.8	38.0	34.1	32.2	32.6	28.9	28.7	27.9	31.0	31.0	31.0	0.0	0.0	0.0
Ammonium Hydroxide	3.6	3.6	3.6	3.5	3.4	3.4	3.0	2.9	2.9	2.6	2.5	2.5	0.0	0.0	0.0	0.0	0.0	0.0
Ammonia	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	17.2	17.2	17.2	0.0	0.0	0.0
Aluminium sulfate	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.1	0.0	0.0	0.0
Phosphoric Acid	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	15.7	15.7	27.0
Precursor Co-precipitation	75.3	75.3	75.3	72.4	70.5	70.8	63.6	59.9	60.7	53.9	53.4	52.1	58.4	58.4	58.4	0.0	0.0	0.0
Cathode Production	113.9	103.2	103.2	109.9	97.1	97.5	96.1	82.2	83.2	93.2	83.7	81.6	100.9	91.5	91.5	75.0	75.0	128.9
Total	495.7	461.3	391.1	495.3	442.8	377.1	449.7	384.3	329.8	437.2	391.6	313.5	499.6	445.7	370.4	223.3	223.3	167.4

Table 58. Circular battery scenario - Energy of virgin and secondary production of cathode active materials. PED expressed in MJ/kWh battery.

Materials	NMC111			NMC532			NMC622			NMC811			NCA			LFP		
	Virgin	Pyro	Hydro	Virgin	Pyro	Hydro	Virgin	Pyro	Hydro	Virgin	Pyro	Hydro	Virgin	Pyro	Hydro	Virgin	Pyro	Hydro
Nickel Sulfate	95.9	66.3	21.7	142.1	92.8	31.7	144.9	87.6	32.5	163.3	105.4	37.3	179.6	102.7	86.3	0.0	0.0	0.0
Cobalt Sulfate	83.2	66.2	21.5	49.6	37.2	12.6	41.9	29.1	10.7	17.7	13.1	4.6	29.7	19.5	6.1	0.0	0.0	0.0
Manganese Sulfate	12.2	12.2	19.5	10.6	10.4	16.6	6.2	5.9	9.7	2.6	2.7	4.2	0.0	0.0	0.0	0.0	0.0	0.0
Lithium Carbonate	71.3	71.3	20.1	68.5	67.3	19.1	59.9	57.4	16.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Lithium Hydroxide	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	74.9	76.5	13.4	82.4	82.4	11.8	132.5	132.5	13.8
Sodium Hydroxide	40.4	40.4	40.4	38.9	38.2	38.8	34.1	32.7	34.1	28.9	29.6	28.5	31.0	31.0	24.6	0.0	0.0	0.0
Ammonium Hydroxide	3.6	3.6	3.6	3.5	3.4	3.4	3.0	2.9	3.0	2.6	2.6	2.5	0.0	0.0	0.0	0.0	0.0	0.0
Ammonia	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	17.2	17.2	13.6	0.0	0.0	0.0
Aluminium sulfate	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.1	0.0	0.0	0.0
Phosphoric Acid	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	15.7	15.7	18.9
Precursor Co-precipitation	75.3	75.3	75.3	72.4	71.1	72.2	63.6	60.9	63.4	53.9	55.1	53.0	58.4	58.4	46.4	0.0	0.0	0.0
Cathode Production	113.9	103.2	103.2	109.9	98.0	99.4	96.1	83.6	87.0	93.2	86.3	83.1	100.9	91.5	72.6	75.0	75.0	90.0
Total	495.7	438.5	305.4	495.3	418.3	294.0	449.7	360.2	257.2	437.2	371.3	226.7	499.6	403.0	261.5	223.3	223.3	122.8

5.3 The role of secondary materials in battery manufacture

This section presents the GHG emissions of different LIB chemistries produced with secondary materials via different recycling technologies, exploring different recycling scenarios. Key battery materials are recycled and put back into the closed-loop battery supply chain to lessen the environmental impacts caused by primary production, thus aiming towards circularity. Materials not considered in the recycled process are assumed to be taken from primary production. This study assumes two distinct recycling scenarios that look at a range of potential outcomes, comparing production from all materials with a maximum secondary material scenario (Circular Battery Scenario) and a slightly more realistic scenario with 50% from virgin materials and 50% from secondary materials (50-50 scenario) for Europe's average electricity grid.

Generally, the use of secondary materials in battery manufacture reduces overall GHG emissions by avoiding the use of key battery materials coming from primary production. However, these materials are recovered depending on the recycling technology used. Cathode materials (i.e., lithium, nickel, manganese, and cobalt) and their recoverability from different recycling technologies were discussed in the previous section. In addition to cathode materials, this section describes the use of battery secondary materials such as graphite (anode material), copper, and aluminium in battery manufacture. Among the different recycling methods, direct recycling has the lowest impact, followed by hydrometallurgical and pyrometallurgical. The total battery recycling analysis from using secondary materials reveals similar GHG emissions for all nickel-based chemistries ranging from ~ 30 kgCO_2eq/kWh for direct recycling, to 39 kgCO_2eq/kWh for hydro, to a maximum of 69 kgCO_2eq/kWh for pyro.

For the NMC811 battery, in the circular battery scenario via direct recycling (best case), the battery assembly (taking place in Europe) contributes the largest GHG emissions share, accounting for over 40% of the total (12.5 $kgCO_2eq/kWh$). The manufacturing of the cathode represents about 38% of the total GHG emissions (11.7 $kgCO_2eq/kWh$). In comparison, for primary production, the cathode represented nearly 60% of the total (45.5$kgCO_2eq/kWh$) – this denotes a 33.7 $kgCO_2eq/kWh$ reduction (see **section 4.2** Total battery production). This reduction is due to direct recycling physically recovering the cathode with all its main constituents (i.e., lithium, nickel, cobalt, and manganese) with low emissions in the process, thus avoiding supply from these key materials.

Materials such as aluminium, graphite and copper can be recovered with direct recycling, providing 90% of the supply. Secondary aluminium contributes approximately 5% of the total emissions (1.7 $kgCO_2eq/kWh$), resulting in emissions reductions compared to primary aluminium (9.7 $kgCO_2eq/kWh$). Graphite and copper contribute 4% (1.3 $kgCO_2eq/kWh$) and 1% (0.36 $kgCO_2eq/kWh$) of the battery emissions via direct recycling. The battery management system (BMS) or electronic components is responsible for 6% of the total emissions, and although it contributes a minor share of emissions for primary production and is not included in the recycling scope of this analysis (BMS coming from primary production), there is an opportunity for recycling and treating electronic waste from BMS. **Figure 15** reports the GHG emission resulting from battery manufacturing using primary and secondary materials via pyro, hydro and direct recycling processes. The GHG emissions reductions for the NMC811 battery using secondary materials via direct recycling compared to production from primary battery materials (79.61 $kgCO_2eq/kWh$) are 17% for pyrometallurgical (65.86 $kgCO_2eq/kWh$), 51% for hydrometallurgical (38.89 $kgCO_2eq/kWh$) and 61% for direct recycling (30.77 $kgCO_2eq/kWh$). The recycling of transition materials (including lithium, nickel and cobalt) in the active cathode material provides the largest GHG emissions reductions.

The LFP battery presents the lowest GHG emissions across all the batteries analysed under the circular battery scenario via direct recycling with 27 kgCO$_2$eq/kWh. Mainly due to avoiding the burden of materials involved in cathode production. Battery assembly and the active material contribute 46% and 22%, respectively, to the total GHG emissions. Interestingly, the pyrometallurgical recycling process results in net increases in GHG emissions by 10%. Primarily due to accounting for the emissions from incinerating copper alone, being the only recovered material in the pyro recycling process. This means that the copper used in LFP batteries is more efficient to mine (virgin copper) and emits lower GHGs per kWh. However, these increases are only significant to the pyrometallurgical recycling process, whereas the hydro and direct recycling processes show reductions in GHG emissions, similar to NMC and NCA batteries. The GHG emissions and PED of all battery chemistries under the circular battery recycling scenario for different recycling techniques are given from **Table 59** to **Table 64.**

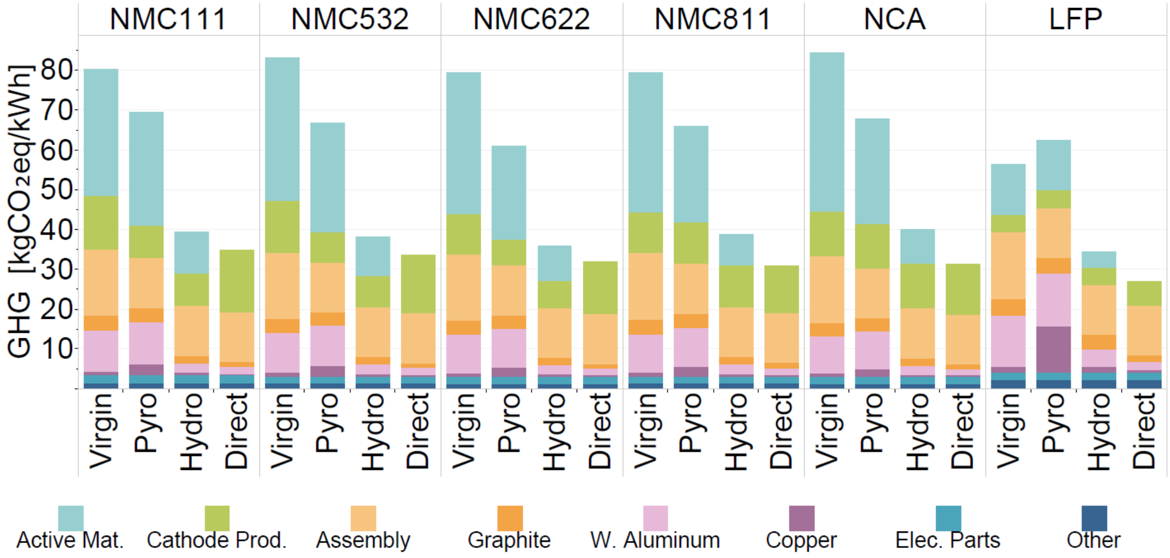

Figure 15. Battery manufacturing GHG emissions from virgin and different recycling technologies under the circular battery scenario. Numerical data can be found in subsequent tables from **Table 59** to **Table 64.**

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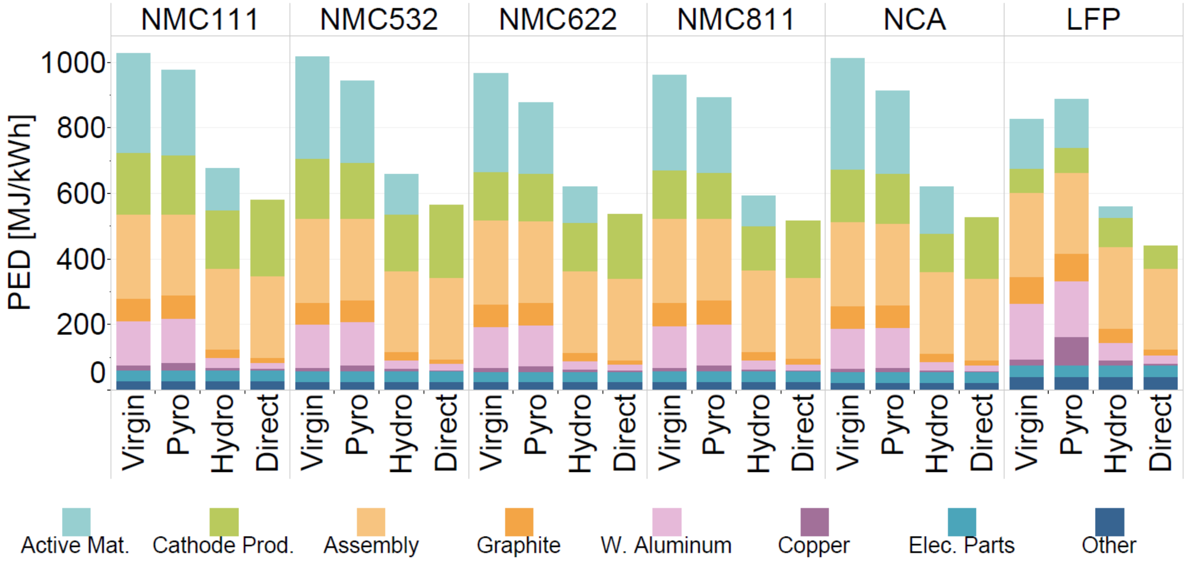

Figure 16. Battery manufacturing PED from virgin and different recycling technologies under the circular battery scenario. Numerical data can be found in subsequent tables from **Table 59** to **Table 64.**

Table 59. GHG emissions and PED of virgin and secondary production of NMC111 battery for different recycling techniques under the 50-50 and circular battery scenarios. GHG emissions are expressed in kgCO$_2$eq/kWh battery and is PED expressed in MJ/kWh.

NMC111	**Virgin**		**Pyro**				**Hydro**				**Direct**			
Materials			**50-50**		**Circular Battery**		**50-50**		**Circular Battery**		**50-50**		**Circular Battery**	
	Energy	**GHG**	**Energy**	**GHG**	**Energy**	**GHG**	**Energy**	**GHG**	**Energy**	**GHG**	**Energy**	**GHG**	**Energy**	**GHG**
Active Material	495.69	45.47	461.29	38.47	438.48	36.79	391.06	28.88	305.37	18.49	255.26	18.19	231.34	15.58
Graphite	70.45	3.68	70.45	3.50	70.45	3.50	45.19	2.62	24.99	1.92	39.56	2.23	14.84	1.21
Binder	2.06	0.13	2.06	0.12	2.06	0.12	2.06	0.12	2.06	0.12	2.06	0.12	2.06	0.12
Copper	13.30	0.82	18.25	1.98	22.22	2.81	10.21	0.78	7.74	0.66	8.20	0.64	4.12	0.40
Wrought Aluminum	135.37	9.75	135.37	10.54	135.37	10.54	76.21	6.02	28.89	2.40	71.39	5.68	20.21	1.79
Electrolyte: LiPF6	12.68	0.64	12.68	0.74	12.68	0.74	12.68	0.74	12.68	0.74	12.68	0.74	12.68	0.74
Electrolyte: EC	1.51	0.05	1.51	0.06	1.51	0.06	1.51	0.06	1.51	0.06	1.51	0.06	1.51	0.06
Electrolyte: DMC	5.56	0.18	5.56	0.21	5.56	0.21	5.56	0.21	5.56	0.21	5.56	0.21	5.56	0.21
Plastic: PP	2.01	0.06	2.01	0.06	2.01	0.06	2.01	0.06	2.01	0.06	2.01	0.06	2.01	0.06
Plastic: PET	0.57	0.02	0.57	0.02	0.57	0.02	0.57	0.02	0.57	0.02	0.57	0.02	0.57	0.02
Plastic: PET	0.56	0.02	0.56	0.02	0.56	0.02	0.56	0.02	0.56	0.02	0.56	0.02	0.56	0.02
Steel	0.72	0.05	0.72	0.06	0.72	0.06	0.72	0.06	0.72	0.06	0.72	0.06	0.72	0.06
Thermal Insulation	0.34	0.02	0.34	0.02	0.34	0.02	0.34	0.02	0.34	0.02	0.34	0.02	0.34	0.02
Coolant: Glycol	2.00	0.17	2.00	0.18	2.00	0.18	2.00	0.18	2.00	0.18	2.00	0.18	2.00	0.18
Electronic Parts	33.33	1.87	33.33	1.94	33.33	1.94	33.33	1.94	33.33	1.94	33.33	1.94	33.33	1.94
Battery Assembly	256.36	16.68	247.90	12.51	247.90	12.51	247.90	12.51	247.90	12.51	247.90	12.51	247.90	12.51
Total per battery	**1024.1**	**79.61**	**994.62**	**70.43**	**975.76**	**69.58**	**831.93**	**54.24**	**676.24**	**39.40**	**683.66**	**42.68**	**579.75**	**34.91**

Table 60. GHG emissions and PED of virgin and secondary production of NMC532 battery for different recycling techniques under the 50-50 and circular battery scenarios. GHG emissions are expressed in kgCO$_2$eq/kWh battery, and PED is expressed in MJ/kWh.

NMC532	**Virgin**		**Pyro**				**Hydro**				**Direct**			
Materials			**50-50**		**Circular Battery**		**50-50**		**Circular Battery**		**50-50**		**Circular Battery**	
	Energy	**GHG**	**Energy**	**GHG**	**Energy**	**GHG**	**Energy**	**GHG**	**Energy**	**GHG**	**Energy**	**GHG**	**Energy**	**GHG**
Active Material	495.33	49.18	442.81	36.80	418.32	34.86	377.13	27.84	293.98	17.77	246.17	19.11	223.00	14.56
Graphite	68.65	3.41	68.65	3.41	68.65	3.41	43.92	2.55	24.14	1.85	43.92	2.17	14.37	1.17
Binder	1.31	0.08	1.31	0.08	1.31	0.08	1.31	0.08	1.31	0.08	1.31	0.08	1.31	0.08
Copper	12.62	0.89	16.88	1.82	20.28	2.57	9.65	0.74	7.27	0.62	7.76	0.61	3.87	0.38
Wrought Aluminum	129.99	10.12	129.99	10.12	129.99	10.12	73.08	5.77	27.56	2.29	68.51	5.46	19.32	1.71
Electrolyte: LiPF6	11.51	0.67	11.51	0.67	11.51	0.67	11.51	0.67	11.51	0.67	11.51	0.67	11.51	0.67
Electrolyte: EC	1.37	0.05	1.37	0.05	1.37	0.05	1.37	0.05	1.37	0.05	1.37	0.05	1.37	0.05
Electrolyte: DMC	5.05	0.19	5.05	0.19	5.05	0.19	5.05	0.19	5.05	0.19	5.05	0.19	5.05	0.19
Plastic: PP	2.30	0.07	2.30	0.07	2.30	0.07	2.30	0.07	2.30	0.07	2.30	0.07	2.30	0.07
Plastic: PET	0.66	0.02	0.66	0.02	0.66	0.02	0.66	0.02	0.66	0.02	0.66	0.02	0.66	0.02
Plastic: PET	0.53	0.02	0.53	0.02	0.53	0.02	0.53	0.02	0.53	0.02	0.53	0.02	0.53	0.02
Steel	0.66	0.06	0.66	0.06	0.66	0.06	0.66	0.06	0.66	0.06	0.66	0.06	0.66	0.06
Thermal Insulation	0.34	0.02	0.34	0.02	0.34	0.02	0.34	0.02	0.34	0.02	0.34	0.02	0.34	0.02
Coolant: Glycol	1.99	0.17	1.99	0.17	1.99	0.17	1.99	0.17	1.99	0.17	1.99	0.17	1.99	0.17
Electronic Parts	32.06	1.87	32.06	1.87	32.06	1.87	32.06	1.87	32.06	1.87	32.06	1.87	32.06	1.87
Battery Assembly	256.36	16.68	247.90	12.51	247.90	12.51	247.90	12.51	247.90	12.51	247.90	12.51	247.90	12.51
Total per battery	**1020.7**	**83.51**	**963.99**	**67.89**	**942.91**	**66.69**	**809.45**	**52.63**	**658.63**	**38.26**	**672.03**	**43.07**	**566.23**	**33.55**

Table 61. GHG emissions and PED of virgin and secondary production of NMC622 battery for different recycling techniques under the 50-50 and circular battery scenarios. GHG emissions are expressed in kgCO$_2$eq/kWh battery, and PED is expressed in MJ/kWh.

NMC622	**Virgin**		**Pyro**				**Hydro**				**Direct**			
Materials			**50-50**		**Circular Battery**		**50-50**		**Circular Battery**		**50-50**		**Circular Battery**	
	Energy	**GHG**	**Energy**	**GHG**	**Energy**	**GHG**	**Energy**	**GHG**	**Energy**	**GHG**	**Energy**	**GHG**	**Energy**	**GHG**
Active Material	449.70	45.84	384.29	31.81	360.18	29.76	329.79	24.35	257.21	15.56	215.27	15.33	195.03	13.12
Graphite	68.80	3.42	68.80	3.42	68.80	3.42	44.05	2.56	24.25	1.86	44.05	2.17	14.42	1.17
Binder	1.20	0.07	1.20	0.07	1.20	0.07	1.20	0.07	1.20	0.07	1.20	0.07	1.20	0.07
Copper	11.66	0.83	15.08	1.62	17.81	2.25	8.93	0.68	6.74	0.57	7.18	0.56	3.59	0.35
Wrought Aluminum	124.96	9.73	124.96	9.73	124.96	9.73	70.28	5.55	26.54	2.20	65.87	5.24	18.59	1.65
Electrolyte: LiPF6	11.18	0.65	11.18	0.65	11.18	0.65	11.18	0.65	11.18	0.65	11.18	0.65	11.18	0.65
Electrolyte: EC	1.33	0.05	1.33	0.05	1.33	0.05	1.33	0.05	1.33	0.05	1.33	0.05	1.33	0.05
Electrolyte: DMC	4.90	0.18	4.90	0.18	4.90	0.18	4.90	0.18	4.90	0.18	4.90	0.18	4.90	0.18
Plastic: PP	1.71	0.05	1.71	0.05	1.71	0.05	1.71	0.05	1.71	0.05	1.71	0.05	1.71	0.05
Plastic: PET	0.51	0.02	0.51	0.02	0.51	0.02	0.51	0.02	0.51	0.02	0.51	0.02	0.51	0.02
Plastic: PET	0.50	0.02	0.50	0.02	0.50	0.02	0.50	0.02	0.50	0.02	0.50	0.02	0.50	0.02
Steel	0.64	0.05	0.64	0.05	0.64	0.05	0.64	0.05	0.64	0.05	0.64	0.05	0.64	0.05
Thermal Insulation	0.33	0.02	0.33	0.02	0.33	0.02	0.33	0.02	0.33	0.02	0.33	0.02	0.33	0.02
Coolant: Glycol	2.02	0.18	2.02	0.18	2.02	0.18	2.02	0.18	2.02	0.18	2.02	0.18	2.02	0.18
Electronic Parts	32.06	1.87	32.06	1.87	32.06	1.87	32.06	1.87	32.06	1.87	32.06	1.87	32.06	1.87
Battery Assembly	256.36	16.68	247.90	12.51	247.90	12.51	247.90	12.51	247.90	12.51	247.90	12.51	247.90	12.51
Total per battery	**967.85**	**79.66**	**897.4**	**62.25**	**876.02**	**60.83**	**757.34**	**48.81**	**619.03**	**35.87**	**636.64**	**38.98**	**535.91**	**31.97**

Table 62. GHG emissions and PED of virgin and secondary production of NMC811 battery for different recycling techniques under the 50-50 and circular battery scenarios. GHG emissions are expressed in $kgCO_2eq/kWh$ battery, and PED is expressed in MJ/kWh.

NMC811	**Virgin**		**Pyro**				**Hydro**				**Direct**			
Materials			**50-50**		**Circular Battery**		**50-50**		**Circular Battery**		**50-50**		**Circular Battery**	
	Energy	**GHG**	**Energy**	**GHG**	**Energy**	**GHG**	**Energy**	**GHG**	**Energy**	**GHG**	**Energy**	**GHG**	**Energy**	**GHG**
Active Material	437.18	45.47	391.60	36.19	371.26	34.47	313.52	27.54	226.70	18.25	217.74	15.60	173.14	11.72
Graphite	73.96	3.68	73.96	3.68	73.96	3.68	47.76	2.78	26.79	2.07	47.76	2.35	15.81	1.30
Binder	2.18	0.13	2.18	0.13	2.18	0.13	2.18	0.13	2.18	0.13	2.18	0.13	2.18	0.13
Copper	11.56	0.82	14.96	1.61	17.69	2.24	8.96	0.69	6.89	0.58	7.16	0.56	3.64	0.36
Wrought Aluminum	125.17	9.75	125.17	9.75	125.17	9.75	70.70	5.59	27.13	2.26	66.10	5.25	18.85	1.67
Electrolyte: LiPF6	11.04	0.64	11.04	0.64	11.04	0.64	11.04	0.64	11.04	0.64	11.04	0.64	11.04	0.64
Electrolyte: EC	1.32	0.05	1.32	0.05	1.32	0.05	1.32	0.05	1.32	0.05	1.32	0.05	1.32	0.05
Electrolyte: DMC	4.84	0.18	4.84	0.18	4.84	0.18	4.84	0.18	4.84	0.18	4.84	0.18	4.84	0.18
Plastic: PP	2.02	0.06	2.02	0.06	2.02	0.06	2.02	0.06	2.02	0.06	2.02	0.06	2.02	0.06
Plastic: PET	0.58	0.02	0.58	0.02	0.58	0.02	0.58	0.02	0.58	0.02	0.58	0.02	0.58	0.02
Plastic: PET	0.51	0.02	0.51	0.02	0.51	0.02	0.51	0.02	0.51	0.02	0.51	0.02	0.51	0.02
Steel	0.64	0.05	0.64	0.05	0.64	0.05	0.64	0.05	0.64	0.05	0.64	0.05	0.64	0.05
Thermal Insulation	0.33	0.02	0.33	0.02	0.33	0.02	0.33	0.02	0.33	0.02	0.33	0.02	0.33	0.02
Coolant: Glycol	1.98	0.17	1.98	0.17	1.98	0.17	1.98	0.17	1.98	0.17	1.98	0.17	1.98	0.17
Electronic Parts	32.06	1.87	32.06	1.87	32.06	1.87	32.06	1.87	32.06	1.87	32.06	1.87	32.06	1.87
Battery Assembly	256.36	16.68	247.90	12.51	247.90	12.51	247.90	12.51	247.90	12.51	247.90	12.51	247.90	12.51
Total per battery	**961.72**	**79.61**	**911.09**	**66.95**	**893.48**	**65.86**	**746.34**	**52.33**	**592.90**	**38.89**	**644.15**	**39.49**	**516.84**	**30.77**

Table 63. GHG emissions and PED of virgin and secondary production of NCA battery for different recycling techniques under the 50-50 and circular battery scenarios. GHG emissions are expressed in kgCO$_2$eq/kWh battery, and PED is expressed in MJ/kWh.

NCA	**Virgin**		**Pyro**				**Hydro**				**Direct**			
Materials			**50-50**		**Circular Battery**		**50-50**		**Circular Battery**		**50-50**		**Circular Battery**	
	Energy	**GHG**	**Energy**	**GHG**	**Energy**	**GHG**	**Energy**	**GHG**	**Energy**	**GHG**	**Energy**	**GHG**	**Energy**	**GHG**
Active Material	499.57	51.14	445.69	44.10	403.03	37.34	370.43	34.96	261.51	19.95	235.19	16.82	186.75	12.61
Graphite	70.05	3.48	70.05	3.48	70.05	3.48	44.93	2.61	24.84	1.91	44.93	2.21	14.68	1.20
Binder	1.15	0.07	1.15	0.07	1.15	0.07	1.15	0.07	1.15	0.07	1.15	0.07	1.15	0.07
Copper	10.78	0.76	13.11	1.39	14.98	1.89	8.27	0.63	6.27	0.53	6.63	0.52	3.31	0.32
Wrought Aluminum	120.90	9.42	120.90	9.42	120.90	9.42	68.06	5.38	25.79	2.14	63.73	5.07	17.99	1.59
Electrolyte: LiPF6	10.68	0.62	10.68	0.62	10.68	0.62	10.68	0.62	10.68	0.62	10.68	0.62	10.68	0.62
Electrolyte: EC	1.27	0.05	1.27	0.05	1.27	0.05	1.27	0.05	1.27	0.05	1.27	0.05	1.27	0.05
Electrolyte: DMC	4.68	0.17	4.68	0.17	4.68	0.17	4.68	0.17	4.68	0.17	4.68	0.17	4.68	0.17
Plastic: PP	1.56	0.05	1.56	0.05	1.56	0.05	1.56	0.05	1.56	0.05	1.56	0.05	1.56	0.05
Plastic: PET	0.47	0.02	0.47	0.02	0.47	0.02	0.47	0.02	0.47	0.02	0.47	0.02	0.47	0.02
Plastic: PET	0.48	0.02	0.48	0.02	0.48	0.02	0.48	0.02	0.48	0.02	0.48	0.02	0.48	0.02
Steel	0.61	0.05	0.61	0.05	0.61	0.05	0.61	0.05	0.61	0.05	0.61	0.05	0.61	0.05
Thermal Insulation	0.33	0.02	0.33	0.02	0.33	0.02	0.33	0.02	0.33	0.02	0.33	0.02	0.33	0.02
Coolant: Glycol	2.09	0.18	2.09	0.18	2.09	0.18	2.09	0.18	2.09	0.18	2.09	0.18	2.09	0.18
Electronic Parts	32.13	1.87	32.13	1.87	32.13	1.87	32.13	1.87	32.13	1.87	32.13	1.87	32.13	1.87
Battery Assembly	256.36	16.68	247.90	12.51	247.90	12.51	247.90	12.51	247.90	12.51	247.90	12.51	247.90	12.51
Total per battery	**1013.1**	**84.61**	**953.1**	**74.02**	**912.30**	**67.75**	**795.04**	**59.21**	**621.77**	**40.17**	**653.83**	**40.26**	**526.08**	**31.35**

Table 64. GHG emissions and PED of virgin and secondary production of LFP battery for different recycling techniques under the 50-50 and circular battery scenarios. GHG emissions are expressed in $kgCO_2eq/kWh$ battery, and PED is expressed in MJ/kWh.

LFP	**Virgin**		**Pyro**				**Hydro**				**Direct**			
Materials			**50-50**		**Circular Battery**		**50-50**		**Circular Battery**		**50-50**		**Circular Battery**	
	Energy	**GHG**	**Energy**	**GHG**	**Energy**	**GHG**	**Energy**	**GHG**	**Energy**	**GHG**	**Energy**	**GHG**	**Energy**	**GHG**
Active Material	223.30	17.00	223.30	17.00	223.30	17.00	167.44	12.15	122.76	8.26	112.04	9.92	67.36	6.03
Graphite	82.35	4.09	82.35	4.09	82.35	4.09	61.79	3.85	45.35	3.66	61.79	2.62	17.62	1.45
Binder	1.57	0.09	1.57	0.09	1.57	0.09	1.57	0.09	1.57	0.09	1.57	0.09	1.57	0.09
Copper	18.80	1.33	58.07	7.00	89.48	11.54	18.31	1.45	17.92	1.54	11.65	0.92	5.94	0.58
Wrought Aluminum	169.51	13.20	169.51	13.20	169.51	13.20	103.65	8.26	50.96	4.30	89.53	7.13	25.55	2.27
Electrolyte: LiPF6	20.15	1.17	20.15	1.17	20.15	1.17	20.15	1.17	20.15	1.17	20.15	1.17	20.15	1.17
Electrolyte: EC	2.40	0.09	2.40	0.09	2.40	0.09	2.40	0.09	2.40	0.09	2.40	0.09	2.40	0.09
Electrolyte: DMC	8.84	0.33	8.84	0.33	8.84	0.33	8.84	0.33	8.84	0.33	8.84	0.33	8.84	0.33
Plastic: PP	2.99	0.09	2.99	0.09	2.99	0.09	2.99	0.09	2.99	0.09	2.99	0.09	2.99	0.09
Plastic: PET	0.81	0.03	0.81	0.03	0.81	0.03	0.81	0.03	0.81	0.03	0.81	0.03	0.81	0.03
Plastic: PET	0.74	0.03	0.74	0.03	0.74	0.03	0.74	0.03	0.74	0.03	0.74	0.03	0.74	0.03
Steel	0.98	0.08	0.98	0.08	0.98	0.08	0.98	0.08	0.98	0.08	0.98	0.08	0.98	0.08
Thermal Insulation	0.40	0.03	0.40	0.03	0.40	0.03	0.40	0.03	0.40	0.03	0.40	0.03	0.40	0.03
Coolant: Glycol	2.55	0.22	2.55	0.22	2.55	0.22	2.55	0.22	2.55	0.22	2.55	0.22	2.55	0.22
Electronic Parts	33.75	1.96	33.75	1.96	33.75	1.96	33.75	1.96	33.75	1.96	33.75	1.96	33.75	1.96
Battery Assembly	256.36	16.68	247.90	12.51	247.90	12.51	247.90	12.51	247.90	12.51	247.90	12.51	247.90	12.51
Total per battery	**825.51**	**56.44**	**856.33**	**57.94**	**887.74**	**62.48**	**674.29**	**42.34**	**560.08**	**34.40**	**598.12**	**37.22**	**439.57**	**26.97**

5.4 Electricity decarbonisation and impacts on future LIB recycling

Projected decarbonisation in the European electricity grid favours the battery recycling processes and thus the life cycle GHG emissions of battery manufacturing to 2050. For simplicity, the results will focus on the circular battery scenario for the SPS and SDS decarbonisation scenarios to 2050. **Figure 17** shows the circular battery GHG emissions of NMC811 battery production from pyro, hydro and direct recycling technologies for both decarbonisation scenarios to 2050. Under the SPS scenario, the GHG emissions of the NMC811 are reduced by 34%, 64%, and 70% for pyro, hydro and direct recycling, respectively; achieving a 24.4 $kgCO_2eq/kWh$ for direct recycling compared to virgin production of 79.6 $kgCO_2eq/kWh$. The findings are driven by reductions in the GHG intensity of several components including the active material (80%), wrought aluminium (88%), graphite (73%), and copper (66%) Under the more enthusiastic scenario (SDS), various key materials see significant changes as a result of electricity decarbonisation coupled with recycling. Via hydro recycling, nickel and lithium reduce to 3.5 and 1.1 $kgCO_2eq/kWh$, a decrease of 86% and 83% respectively. GHG emissions of the cathode production process can be reduced to around 4 $kgCO_2eq/kW$, over a 60% reduction. Battery assembly, assuming takes place in Europe, would reduce by 38% under the SDS scenario.

Moreover, GHG emissions for whole battery production would reduce to 27.2 $kgCO_2eq/kWh$ (66% reduction) for hydro recycling and 23.6 $kgCO_2eq/kWh$ (72% reduction) for direct recycling. The latter is 26.3 $kgCO_2eq/kWh$ less than the sole electricity decarbonised NMC811 battery production in SDS by 2050. This points out the potential environmental benefits of recycling. For LFP, as portrayed in **Figure 18**, GHG emissions are reduced to 22.4 $kgCO_2eq/kWh$ (72% reduction) and ~20.4 $kgCO_2eq/kWh$ (74% reduction) respectively under the SPS and SDS scenarios to 2050 via direct recycling.

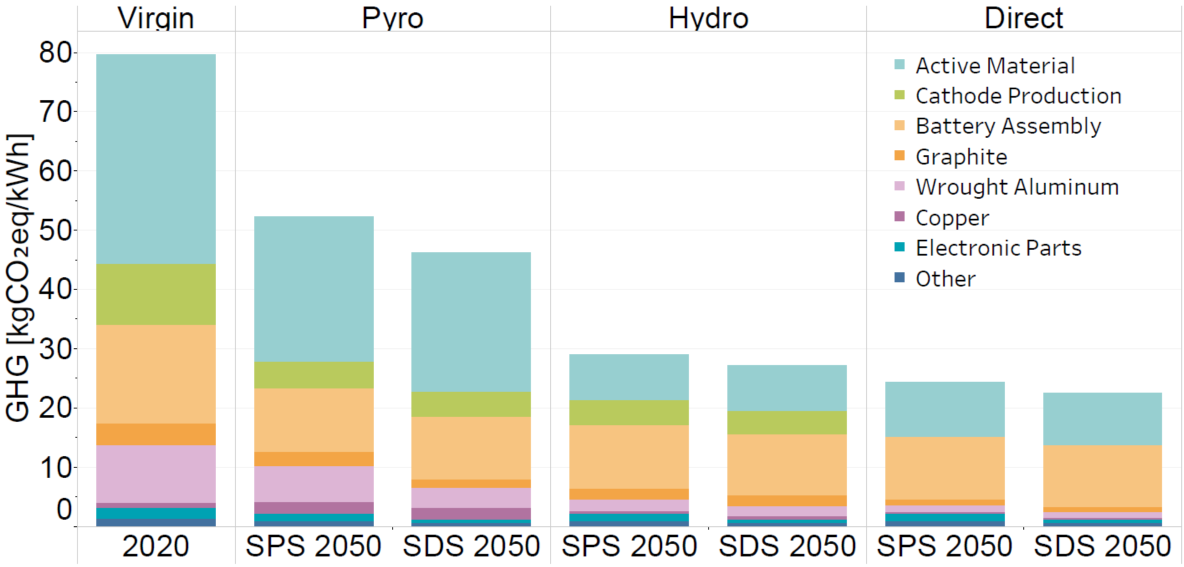

Figure 17. GHG emissions of NMC811 battery chemistry considering the decarbonisation of the electricity sector to 2050 in SPS and SDS scenarios for pyro, hydro and direct recycling technologies.

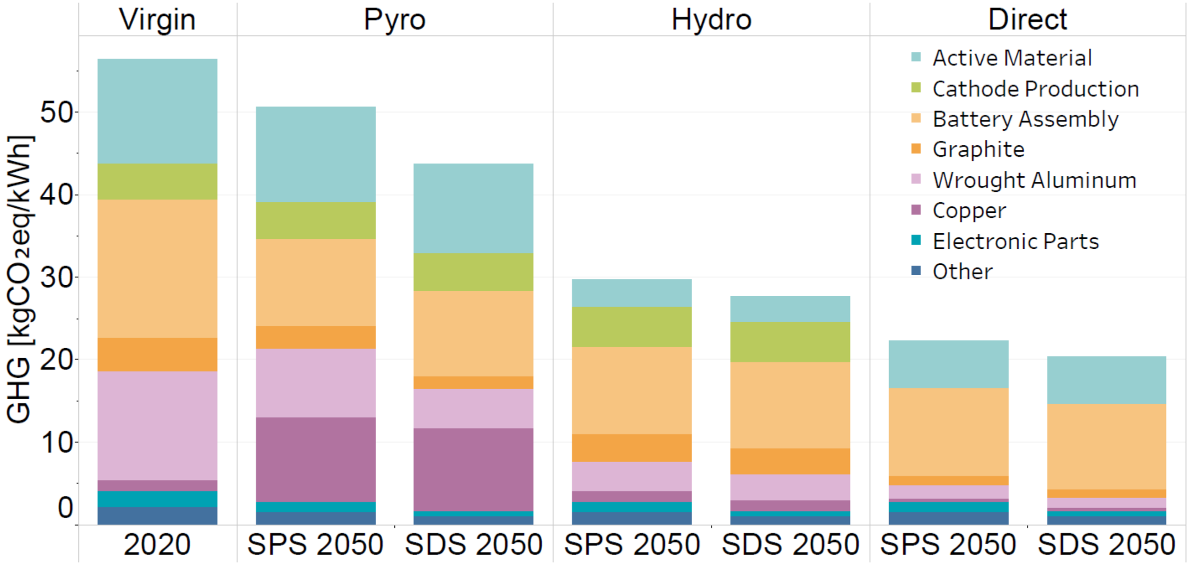

Figure 18. GHG emissions of LFP battery chemistry considering the decarbonisation of the electricity sector to 2050 in SPS and SDS scenarios for pyro, hydro and direct recycling technologies.

Europe’s electricity decarbonisation is on track to meeting climate goals, thus contributing to a significant GHG reduction in battery production. Europe’s GHG electricity intensity sees a reduction from 0.336 kgCO_2eq/kWh in 2020 to 0.081 kgCO_2eq/kWh of electricity in 2050, under the SDS scenario. The total battery GHG emissions would be 46.3 kgCO_2eq/kWh, 27.2 kgCO_2eq/kWh, and 22.6 kgCO_2eq/kWh, for pyro, hydro, and direct recycling by 2050, respectively. If a less ambitious GHG reduction is achieved in the electricity sector under the SPS scenario, e.g., 0.109 kgCO_2eq/kWh, then a moderate reduction in LIB production emissions would be achieved: 52.2 kgCO_2eq/kWh, 29 kgCO_2eq/kWh, and 24.4 kgCO_2eq/kWh, for pyro, hydro and direct recycling, respectively. Detailed numerical data for the different recycling technologies under the different recycling and decarbonisation scenarios are found from **Table 65** to **Table 70.**

Table 65. GHG emissions of virgin and secondary production of NMC111 for different recycling techniques under the 50-50 and circular battery (CB) scenarios coupled with the Stated Policies and Sustainable Development scenarios to 2050. Emissions expressed in kgCO$_2$eq/kWh battery.

NMC111 Materials	**Virgin**	**Stated Policies Scenario**						**Sustainable Development Scenario**					
		Pyro		**Hydro**		**Direct**		**Pyro**		**Hydro**		**Direct**	
		50-50	**CB**	**50-50**	**CB**	**50-50**	**CB**	**50-50**	**CB**	**50-50**	**CB**	**50-50**	**CB**
Active Material	45.47	33.17	31.50	24.81	15.57	15.54	13.07	31.19	30.48	23.16	15.19	15.14	12.75
Graphite	3.68	2.32	2.32	2.02	1.77	1.55	0.93	1.36	1.36	1.53	1.67	1.06	0.82
Binder	0.13	0.07	0.07	0.07	0.07	0.07	0.07	0.02	0.02	0.02	0.02	0.02	0.02
Copper	0.82	1.68	2.50	0.63	0.61	0.46	0.31	1.57	2.45	0.54	0.60	0.37	0.29
Wrought Aluminium	9.75	6.61	6.61	4.04	1.98	3.64	1.26	3.71	3.71	2.58	1.69	2.18	0.95
Electrolyte: LiPF6	0.64	0.38	0.38	0.38	0.38	0.38	0.38	0.09	0.09	0.09	0.09	0.09	0.09
Electrolyte: EC	0.05	0.06	0.06	0.06	0.06	0.06	0.06	0.05	0.05	0.05	0.05	0.05	0.05
Electrolyte: DMC	0.18	0.21	0.21	0.21	0.21	0.21	0.21	0.20	0.20	0.20	0.20	0.20	0.20
Plastic: PP	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06
Plastic: PET	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Plastic: PET	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Steel	0.05	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06
Thermal Insulation	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Coolant: Glycol	0.17	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18
Electronic Parts	1.87	1.21	1.21	1.21	1.21	1.21	1.21	0.62	0.62	0.62	0.62	0.62	0.62
Battery Assembly	16.68	10.63	10.63	10.63	10.63	10.63	10.63	10.39	10.39	10.39	10.39	10.39	10.39
Total per battery	**79.61**	**56.693**	**55.84**	**44.40**	**32.85**	**34.10**	**28.49**	**49.57**	**49.74**	**39.56**	**30.89**	**30.49**	**26.56**

Table 66. GHG emissions of virgin and secondary production of NMC532 for different recycling techniques under the 50-50 and circular battery (CB) scenarios coupled with the Stated Policies and Sustainable Development scenarios to 2050. Emissions expressed in kgCO$_2$eq/kWh battery.

NMC532	**Virgin**	**Stated Policies Scenario**						**Sustainable Development Scenario**					
Materials		**Pyro**		**Hydro**		**Direct**		**Pyro**		**Hydro**		**Direct**	
		50-50	**CB**	**50-50**	**CB**	**50-50**	**CB**	**50-50**	**CB**	**50-50**	**CB**	**50-50**	**CB**
Active Material	49.18	34.60	30.85	26.34	15.10	14.71	12.46	32.28	29.87	24.33	14.72	14.32	12.14
Graphite	3.41	2.26	2.26	1.95	1.71	1.51	0.90	1.33	1.33	1.48	1.61	1.03	0.79
Binder	0.08	0.04	0.04	0.04	0.04	0.04	0.04	0.02	0.02	0.02	0.02	0.02	0.02
Copper	0.89	1.54	2.28	0.59	0.58	0.44	0.30	1.44	2.23	0.51	0.56	0.35	0.27
Wrought Aluminium	10.12	6.35	6.35	3.87	1.88	3.49	1.20	3.56	3.56	2.47	1.60	2.09	0.91
Electrolyte: LiPF6	0.67	0.35	0.35	0.35	0.35	0.35	0.35	0.08	0.08	0.08	0.08	0.08	0.08
Electrolyte: EC	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
Electrolyte: DMC	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.19
Plastic: PP	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07
Plastic: PET	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Plastic: PET	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Steel	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06
Thermal Insulation	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Coolant: Glycol	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17
Electronic Parts	1.87	1.17	1.17	1.17	1.17	1.17	1.17	0.59	0.59	0.59	0.59	0.59	0.59
Battery Assembly	16.68	10.63	10.63	10.63	10.63	10.63	10.63	10.39	10.39	10.39	10.39	10.39	10.39
Total per battery	**83.51**	**57.535**	**54.53**	**45.54**	**32.06**	**32.93**	**27.64**	**50.29**	**48.67**	**40.48**	**30.17**	**29.47**	**25.79**

Table 67. GHG emissions of virgin and secondary production of NMC622 for different recycling techniques under the 50-50 and circular battery (CB) scenarios coupled with the Stated Policies and Sustainable Development scenarios to 2050. Emissions expressed in kgCO_2eq/kWh battery.

NMC622 Materials	**Virgin**	**Stated Policies Scenario**						**Sustainable Development Scenario**					
		Pyro		**Hydro**		**Direct**		**Pyro**		**Hydro**		**Direct**	
		50-50	**CB**	**50-50**	**CB**	**50-50**	**CB**	**50-50**	**CB**	**50-50**	**CB**	**50-50**	**CB**
Active Material	45.84	31.74	27.46	24.25	13.18	12.90	10.93	29.58	26.65	22.33	12.83	12.56	10.66
Graphite	3.42	2.27	2.27	1.96	1.72	1.51	0.90	1.33	1.33	1.49	1.62	1.03	0.79
Binder	0.07	0.04	0.04	0.04	0.04	0.04	0.04	0.01	0.01	0.01	0.01	0.01	0.01
Copper	0.83	1.36	2.00	0.55	0.53	0.40	0.27	1.27	1.96	0.47	0.52	0.32	0.25
Wrought Aluminium	9.73	6.10	6.10	3.72	1.82	3.35	1.16	3.42	3.42	2.38	1.54	2.01	0.87
Electrolyte: LiPF6	0.65	0.34	0.34	0.34	0.34	0.34	0.34	0.08	0.08	0.08	0.08	0.08	0.08
Electrolyte: EC	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
Electrolyte: DMC	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18
Plastic: PP	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
Plastic: PET	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Plastic: PET	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Steel	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
Thermal Insulation	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Coolant: Glycol	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18
Electronic Parts	1.87	1.17	1.17	1.17	1.17	1.17	1.17	0.59	0.59	0.59	0.59	0.59	0.59
Battery Assembly	16.68	10.63	10.63	10.63	10.63	10.63	10.63	10.39	10.39	10.39	10.39	10.39	10.39
Total per battery	**79.66**	**54.211**	**50.57**	**43.23**	**29.99**	**30.91**	**26.01**	**47.25**	**45.01**	**38.32**	**28.16**	**27.57**	**24.22**

Table 68. GHG emissions of virgin and secondary production of NMC811 for different recycling techniques under the 50-50 and circular battery (CB) scenarios coupled with the Stated Policies and Sustainable Development scenarios to 2050. Emissions expressed in $kgCO_2eq/kWh$ battery.

NMC811	**Virgin**	**Stated Policies**						**Sustainable Development**					
Materials		**Pyro**		**Hydro**		**Direct**		**Pyro**		**Hydro**		**Direct**	
		50-50	**CB**	**50-50**	**CB**	**50-50**	**CB**	**50-50**	**CB**	**50-50**	**CB**	**50-50**	**CB**
Active Material	45.47	33.97	28.89	24.99	11.95	11.28	9.15	31.37	27.79	22.79	11.57	10.88	8.89
Graphite	3.68	2.44	2.44	2.14	1.91	1.64	1.00	1.43	1.43	1.64	1.80	1.12	0.88
Binder	0.13	0.07	0.07	0.07	0.07	0.07	0.07	0.03	0.03	0.03	0.03	0.03	0.03
Copper	0.82	1.35	1.99	0.55	0.55	0.40	0.28	1.26	1.94	0.47	0.53	0.32	0.26
Wrought Aluminium	9.75	6.11	6.11	3.75	1.87	3.37	1.18	3.43	3.43	2.41	1.59	2.02	0.90
Electrolyte: LiPF6	0.64	0.33	0.33	0.33	0.33	0.33	0.33	0.08	0.08	0.08	0.08	0.08	0.08
Electrolyte: EC	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
Electrolyte: DMC	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18
Plastic: PP	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06
Plastic: PET	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Plastic: PET	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Steel	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
Thermal Insulation	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Coolant: Glycol	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17
Electronic Parts	1.87	1.17	1.17	1.17	1.17	1.17	1.17	0.59	0.59	0.59	0.59	0.59	0.59
Battery Assembly	16.68	10.63	10.63	10.63	10.63	10.63	10.63	10.39	10.39	10.39	10.39	10.39	10.39
Total per battery	**79.61**	**56.642**	**52.20**	**44.21**	**29.05**	**29.47**	**24.39**	**49.16**	**46.26**	**38.97**	**27.17**	**26.02**	**22.59**

Table 69. GHG emissions of virgin and secondary production of NCA for different recycling techniques under the 50-50 and circular battery (CB) scenarios coupled with the Stated Policies and Sustainable Development scenarios to 2050. Emissions expressed in kgCO_2eq/kWh battery.

NCA Materials	**Virgin**	**Stated Policies**						**Sustainable Development**					
		Pyro		**Hydro**		**Direct**		**Pyro**		**Hydro**		**Direct**	
		50-50	**CB**	**50-50**	**CB**	**50-50**	**CB**	**50-50**	**CB**	**50-50**	**CB**	**50-50**	**CB**
Active Material	51.14	34.53	28.29	26.50	13.00	14.39	10.60	31.94	27.36	24.19	12.61	13.84	10.30
Graphite	3.48	2.31	2.31	2.00	1.76	1.54	0.92	1.35	1.35	1.53	1.66	1.05	0.81
Binder	0.07	0.04	0.04	0.04	0.04	0.04	0.04	0.01	0.01	0.01	0.01	0.01	0.01
Copper	0.76	1.16	1.68	0.51	0.50	0.37	0.25	1.08	1.64	0.43	0.48	0.30	0.23
Wrought aluminium	9.42	5.90	5.90	3.60	1.77	3.25	1.12	3.31	3.31	2.31	1.50	1.94	0.85
Electrolyte: LiPF6	0.62	0.32	0.32	0.32	0.32	0.32	0.32	0.07	0.07	0.07	0.07	0.07	0.07
Electrolyte: EC	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
Electrolyte: DMC	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17
Plastic: PP	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
Plastic: PET	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Plastic: PET	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Steel	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
Thermal Insulation	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Coolant: Glycol	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18
Electronic Parts	1.87	1.17	1.17	1.17	1.17	1.17	1.17	0.60	0.60	0.60	0.60	0.60	0.60
Battery Assembly	16.68	10.63	10.63	10.63	10.63	10.63	10.63	10.39	10.39	10.39	10.39	10.39	10.39
Total per battery	**84.61**	**56.622**	**50.89**	**45.33**	**29.74**	**32.26**	**25.61**	**49.31**	**45.30**	**40.09**	**27.89**	**28.76**	**23.82**

Table 70. GHG emissions of virgin and secondary production of LFP for different recycling techniques under the 50-50 and circular battery (CB) scenarios coupled with the Stated Policies and Sustainable Development scenarios to 2050. Emissions expressed in kgCO_2eq/kWh battery.

LFP Materials	**Virgin**	**Stated Policies**						**Sustainable Development**					
		Pyro		**Hydro**		**Direct**		**Pyro**		**Hydro**		**Direct**	
		50-50	**CB**	**50-50**	**CB**	**50-50**	**CB**	**50-50**	**CB**	**50-50**	**CB**	**50-50**	**CB**
Active Material	17.00	15.93	15.93	11.54	8.02	9.31	5.79	15.31	15.31	11.22	7.95	8.99	5.71
Graphite	4.09	2.71	2.71	3.02	3.26	1.83	1.11	1.59	1.59	2.44	3.11	1.25	0.98
Binder	0.09	0.05	0.05	0.05	0.05	0.05	0.05	0.02	0.02	0.02	0.02	0.02	0.02
Copper	1.33	6.14	10.32	1.17	1.38	0.66	0.46	5.93	10.14	1.04	1.34	0.52	0.42
Wrought aluminium	13.20	8.27	8.27	5.66	3.57	4.57	1.60	4.64	4.64	3.83	3.17	2.74	1.21
Electrolyte: LiPF6	1.17	0.60	0.60	0.60	0.60	0.60	0.60	0.14	0.14	0.14	0.14	0.14	0.14
Electrolyte: EC	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09
Electrolyte: DMC	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33
Plastic: PP	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09
Plastic: PET	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
Plastic: PET	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
Steel	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08
Thermal Insulation	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
Coolant: Glycol	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.22
Electronic Parts	1.96	1.23	1.23	1.23	1.23	1.23	1.23	0.63	0.63	0.63	0.63	0.63	0.63
Battery Assembly	16.68	10.63	10.63	10.63	10.63	10.63	10.63	10.39	10.39	10.39	10.39	10.39	10.39
Total per battery	**56.44**	**46.468**	**50.65**	**34.80**	**29.64**	**29.77**	**22.37**	**39.55**	**43.76**	**30.59**	**27.65**	**25.57**	**20.40**

5.5 Summary

By and large, secondary supply, via recycling, can help reduce primary supply requirements and alleviate the environmental burdens associated with the mining and refining of materials from primary sources, which are known to be highly energy intensive. The driver of recycling is to guarantee supply for cobalt and lithium, which are considered more economically viable and current supply chain markets are either very complex or in the need of massive expansion. Lithium is hardly recycled. The recycling scenarios assumed in this chapter are not predicting what will happen in the future but are putting into context how recycling could reduce impacts in the future, which will most likely be after 2030 when LIBs reach their EoL (considering 15-20 years of battery lifetimes). Therefore, these recycling scenarios look at the range of potential outcomes, comparing production from all materials with a maximum secondary material scenario (circular battery scenario) and a slightly more realistic scenario with 50% from virgin materials and 50% from secondary materials (50-50 scenario). Secondary materials will never meet the rising demand for batteries, meaning that although recycling provides useful complementary resources, it can only provide a tiny fraction of the total demand (Bloodworth, 2014). However, the proposed recycling scenarios provide a full picture of the possible outcomes of recycling, where direct recycling offers the lowest impacts, followed by hydrometallurgical and pyrometallurgical, reducing GHG emissions by 61%, 51% and 17%, respectively. This chapter follows the framework proposal emitted by the European Commission on battery recycling and battery carbon footprint regulations. Therefore, highlighting the significance of strategic legislation that battery stakeholders must comply with. As the BEVs market grows, so does the relevance of effective EoL handling and the environmental issues of LIBs. Future work should assess the future material requirements for the BEV market and to what extent recycling can provide suitable solutions to the whole LIB value chain.

CHAPTER 6 Conclusions

A potential effective short-term solution for decarbonising the transport sector is to transition from ICEVs towards BEVs. The rise of BEVs, currently dominated by LIBs, is expected to exponentially grow driving demand for critical raw materials. Reducing GHG emissions associated with global LIB production is essential to decarbonise transport. Therefore, it is significant to qualitatively understand the sustainability concerns of batteries for BEVs from a life cycle perspective. This could be achieved by taking into account varying production impacts in different geographical locations, and their change over time as the market share of competing for battery chemistries evolve, transitions towards more renewable energy intensive electricity mixes take place, and recycling technologies are deployed at a commercial scale, providing a source of secondary materials to battery manufacture.

This thesis provides a dynamic LCA of lithium-ion batteries for electric vehicles that includes: the environmental impacts (i.e., primary energy demand and GHG emissions) of current batteries with various chemistries across the global supply chain; the prospective variability of impacts over time due to decarbonising the electricity supply, the anticipated battery technology development, and the use of secondary materials from waste recycling.

Chapter 3 presents the novel framework and the LCI used throughout the dynamic LCA model for the evaluation of the environmental impacts of LIBs manufacturing and LIBs recycling. The foreground data is based on the GREET 2 model for the materials and energy inputs of LIB production, the EverBatt model for the closed-loop battery, and Xu, et al (2020) for the battery technology scenarios. The background data was taken from the BGS for material sourcing, the IEA for the current and future electricity mix scenarios, ecoinvent 3.7 for the electricity generation emission factors, and Statista for battery assembly. The model operates for different geographical locations, and scenarios for battery chemistries, electricity decarbonisation and recycling technology. Material compositions of the battery chemistries are assumed to be representative of current and future battery manufacture, while the background systems are changing.

Chapter 4 presents the LCA results in quantifying the GHG emissions for geographical locations, electricity mix scenarios, and different battery chemistries, to answer the overall research questions: **1)** what are the GHG emissions associated with lithium-ion battery manufacturing and different battery chemistries?; **2)** in which geographical locations are these emissions expected to occur?; **3)** how are the future global GHG emissions expected to change towards 2050? Results and discussion are focused mainly on NMC811 and LFP battery chemistries. NMC811 was chosen because it offers higher energy density and uses minimum cobalt, being attractive to BEV manufacturers; and LFP because it has regained market share over the last two years and is expected to contribute a significant share in the future. However, numerical data for all battery chemistries are provided.

Regarding **research question 1**, the GHG emissions for different chemistries are 80.5 $kgCO_2eq/kWh$ for NMC111, 83.5 $kgCO_2eq/kWh$ for NMC532, 79.6 $kgCO_2eq/kWh$ for NMC622, 79.6 $kgCO_2eq/kWh$ for NMC811, 84.6 $kgCO_2eq/kWh$ for NCA, and 56.4 $kgCO_2eq/kWh$ for LFP. All nickel-based chemistries show similar results, but for NMC811 the cathode manufacturing contributes around 60% of the total GHG emissions. This is primarily driven by nickel sulfate (NiSO4) production, which contributes almost a third of the total battery emissions (32%). Also, the battery assembly contributes an important share of emissions (21%). In comparison, the largest contributors to the LFP battery are the battery assembly and lithium hydroxide (LiOH) production, with 30% and 20% of total emissions, respectively. This analysis identifies opportunities to decarbonise batteries by analysing the abovementioned emission-intensive activities, such as raw material extraction and refining of active materials (e.g., nickel and lithium) and manufacturing of cells and battery packs. The emissions are directly proportional to the energy sources used in the manufacturing processes and to the battery manufacturing regions.

Research question 2 is assessed with a spatial LCA model that describes where the GHG emissions are taking place in the global supply chain by looking at the geographical locations of mining and refining of materials, and battery manufacturing. Currently, around two thirds of the total global emissions associated with battery production are highly concentrated in three countries: China (45%), Indonesia (13%) and Australia (9%). China's dominance in the battery materials supply chain can be explained by the over 80% of global raw materials refining and around 78% of cell and pack battery manufacturing. Moreover, the country has a GHG-intensive electricity mix of 0.941 kgCO_2eq/kWh that is dominated by fossil fuels. Indonesia's emissions contributions are due to being the largest nickel supplier in the world (38% of global production) and to its highly emission-intensive electricity mix of 1.16 kgCO_2eq/kWh (fossil fuel dominated). Australia has a relatively lower GHG emission of 0.79 kgCO_2eq/kWh electricity mix but produces around half of the lithium globally. This level of detail, which is not found in any other literature, is significant to understanding which activities and which countries in the supply chain are accounting for the battery GHG emissions and thus is critical to provide insight to policymakers seeking net-zero mining and refining operations to reduce the overall emissions of the battery supply chain For example, the battery's total GHG emissions could be reduced by using materials from regions with the lowest GHG emissions in their mining, refining, and manufacturing activities. This would entail mining nickel in Canada and refining it in Norway; mining lithium in Brazil and refining it in the USA, and battery assembly taking place in Hungary; overall a reduction of 28% in emissions could be achieved by selecting the lowest impact locations for mining, refining, and manufacturing activities. This analysis encourages organisations to comply with the latest regulations on calculating the carbon footprint of each battery model produced for its entire life cycle by reporting reliable data on material provenance. This need to consider supply chain specific impacts of battery materials and manufacturing will bring new levels of transparency and will effectively reduce the risk of materials supply and environmental concerns that may occur throughout a global supply chain.

Research question 3 is addressed by quantifying the GHG emissions of battery production over time by looking at potential scenarios of battery chemistry market shares coupled with the decarbonisation of the electricity mix. Given that electricity consumption plays an important role in the battery life cycle, grid decarbonisation shows to reduce emissions by about 21% in the Stated Policies Scenario (SPS) and up to 38% in the Sustainable Development Scenario (SDS) by 2050. In addition, decarbonising the grid could demonstrate even greater emission reductions in the battery use phase (which is not within the scope of this thesis). On the battery technology mix side, two main scenarios are evaluated considering the most typical LIBs that are expected to dominate the market in the future: NCX scenario (X indicating either Mn or Al) and LFP scenario. GHG emissions for the technology share-weighted projections of the NCX scenario to 2050 would reduce by 14% and 32% under the SPS and SDS respectively. For the LFP scenario, greater reductions in the order of 31% and 46% would be seen in the SPS and SDS, respectively. Furthermore, the IEA estimates battery capacity to be over 12 TWh by 2050 under the SDS, where global cumulative emissions would be 8.2 GtCO2eq for the nickel-based chemistries scenario and 6.6 GtCO2eq for the LFP-based chemistry scenario. Decarbonising the grid significantly helps but will not be enough if the rapidly scaling supply chain of materials does not track their upstream GHG emissions.

Chapter 5 addresses **research question 4** by developing a dynamic LCA of closed-loop recycling and battery manufacture using secondary materials, coupled with future electricity grid decarbonisation. Recycling allows to recover critical materials at different rates, however, recycling efficiencies highly rely on the technical limitations of the different recycling technologies and the desired battery chemistry to recycle. To properly assess the environmental benefits of recycling, this thesis includes the most common recycling techniques: pyrometallurgical, hydrometallurgical and direct recycling. While assessing the future supply of secondary materials by these recycling methods is outside of the scope of the thesis, two recycling scenarios are considered to quantify the potential GHG emissions impacts of battery recycling: a "circular battery scenario" that assumes maximum uptake of secondary materials based on material-specific recovery rates for each recycling technology; and a "50-50 scenario" with batteries produced from 50% secondary materials and 50% primary materials. Recycling is assumed to occur in Europe, as it is uncertain where battery recycling infrastructure will exist in the future, and to be consistent with the new EU regulatory framework for batteries, which supports the scaling up of battery recycling in Europe (European Commission, 2020a). Generally, secondary materials, through recycling, shows GHG emissions reductions by avoiding the use of emission-intensive primary materials that undergo mining and refining. On a per kWh battery basis, for NMC811 battery chemistry, for the circular battery scenario, via hydrometallurgical, the GHG emissions of secondary nickel, lithium, and cobalt production would be reduced by 86%, 81%, and 67%, respectively. The total NMC811 battery GHG emission reductions by using secondary materials for different recycling technologies would be 17 % via pyrometallurgical, 51% via hydrometallurgical, and 61% direct recycling. Lastly, if Europe decarbonises its electricity grid to 2050 as proposed in the SDS (most ambitious scenario) the total NMC811 battery emission reductions by using secondary materials from recycling would be 42% via pyrometallurgical, 66% via hydrometallurgical, and 72% via direct recycling, compared to primary production in 2020. While the thesis does not consider the future availability of secondary materials, the results already provide a comprehensive perspective on the potential GHG emission reduction from employing secondary materials in future battery manufacture.

6.1 Implications of novel results of this thesis to stakeholders

The recent breakthroughs in lithium-ion battery research could have significant implications for stakeholders in the electric vehicle industry, particularly with regards to GHG emissions. Electric vehicles are often touted as more environmentally friendly than traditional gasoline-powered vehicles, but their environmental impacts depend largely on the resource consumption, the mining and refining practices, and on the energy sources used to perform these activities. Therefore, it is important to consider the emissions associated with the production of key battery materials, the supply chain complexity, and the end-of-life of LIBs.

This thesis provides novel results in the battery life cycle assessment field. First, iron-based batteries show lower GHG emissions compared to nickel-based batteries, because they avoid the burden of using high carbon intensity materials such as nickel and cobalt. This suggest that a transition to iron-based batteries would positively influence the environmental impacts of LIB production. Second, the supply chain for LIBs is complex, involving a variety of raw materials and manufacturing processes across the world that contribute to emissions. China's dominance in the battery materials supply chain and battery manufacturing, is a main driver in the overall battery life cycle emissions; meaning that the country's industrial decarbonisation becomes vital to reducing emissions, especially if a battery passport is applied and required for all batteries manufactured. Third, decarbonising the grid could demonstrate significant emissions reduction in the future, as well as switching to a LFP-based scenario, which could reduce cumulative emissions by over 1.5 $GtCO_2eq$ to 2050. In this case, a Sustainable Development Scenario (SDS) does not necessarily mean emissions reduction. This is because SDS would need to double up its battery capacity to over 12TWh by 2050 to meet the ambitious demand. Forth, secondary materials via recycling could alleviate the resource consumption and emissions coming from primary materials production. Among the three recycling techniques, direct recycling offers the best solution, however, this technique is not yet commercially available and is still under development. Therefore, hydrometallurgical recycling will be the preferred option due to offering the highest emissions reductions, high recovery rates, and recovery of many key materials. However, a hybrid approach that start with pyrometallurgical treatment followed by a hydrometallurgical post-processing, can recover the most materials and be a suitable solution to battery recycling.

6.2 Main limitations and uncertainties

While LCA is a valuable tool for evaluating the environmental impacts, there are several limitations and uncertainties associated with its application to LIBs that were experienced during this analysis such as limited data availability, regional variability, supply chain complexity, rapidly evolving technological advancement, and end-of-life considerations.

- *Limited data availability.* LCA relies on accurate and comprehensive data to assess the environmental impacts at each stage of the battery life cycle. However, data availability can be limited, particularly for emerging battery technologies and specific geographical regions. This introduced uncertainties and affected the accuracy of the assessment.
- *Future Technological advancements.* The LCA results for LIB can change significantly with future technological advancements, new materials, manufacturing processes, and recycling methods are being developed, which can significantly impact the environmental performance of batteries. For example, the development of next-generation batteries may render current LCA obsolete or inaccurate. Conducting LCAs for emerging technologies becomes challenging as data may be scarce or outdated.
- *Regional variability.* The environmental impacts associated with LIB production can vary significantly depending on the geographic location and the energy mix used

during manufacturing. The energy sources utilised, such as fossil fuels or renewables, can affect the overall carbon footprint and other environmental indicators.

- *Supply chain complexity*. LIB have a complex and globally distributed supply chains. Obtaining accurate data on raw material extraction, transportation, and processing can be challenging. Supply chain uncertainties, including changes in material sources and mining practices can affect the environmental performance of batteries.
- *End-of-life considerations.* Proper disposal and recycling of LIBs is crucial to minimise environmental impacts. However, the availability and effectiveness of recycling infrastructure can vary across regions. Predicting the future performance and efficiency of recycling technologies and their associated environmental benefits is challenging, therefore various assumptions were made for this analysis.

To address these limitations and uncertainties, ongoing research and data collection efforts are necessary to improve the accuracy and relevance of LCA studies of LIBs. Additionally, collaborative efforts among researchers, industry stakeholders, and policymakers can help establish standardised methodologies and data sharing practices, enabling more robust, realistic, and consistent LCA analyses.

6.3 Future Work

This section discusses the recommendations for future work in the following studied areas: battery production, battery supply chain, battery technology development, and battery recycling. **Table 71** summarises the research questions addressed in this thesis along with the related methods, data sources, and the final relevant contributions.

Battery production. This thesis evaluated the environmental impacts of batteries by considering country-level data on the electricity grid and its potential decarbonisation over time through the adoption of more low-carbon technologies. The analysis showed that efforts to decarbonise the electricity sector reduce the overall GHG emissions of battery manufacture. Future work should evaluate the role of other decarbonisation measures involving non-electricity energy inputs such as fuel switching and energy efficiency improvements in different life cycle stages of the battery. In addition, the thesis only considered two environmental indicators, PED and GHG emissions. Future research could include other relevant metrics such as water consumption as it is a scarce resource and sometimes availability is limited.

Battery supply chain. The supply chain of battery materials is distinguished by highly global trade, with energy and resource-intensive activities taking place across a wide range of locations globally. This research highlighted the location specific GHG emissions of battery manufacture based on the current material sourcing location. However, future material availability and material demand are not included in the study. It is expected that the European Union alone will require up to 15 times more cobalt and around 60 times more lithium by 2050, indicating a potential significant supply constraint. Future work can evaluate possible material supply disruptions and material needed for the BEV transition, and although some studies have approached this issue, assessments of specific markets (e.g., Europe, China, and North America) to avoid potential supply bottlenecks are required. As the market grows, so does the importance of the optimisation of global battery supply chains and their sustainability.

Battery technology development. This thesis incorporated three main battery chemistries NMC, NCA and LFP, and two global battery scenarios NCX and LFP. However, battery size and requirements differ depending on each government’s policies and environmental targets. LFP batteries are most common in China, while NCA and NMC are typically favoured in Europe and North America. Therefore, future work can focus on improving the accuracy of forecasting battery environmental impacts and demand for materials by considering the analysis of competing battery chemistry scenarios on a country level. Moreover, as technology evolves, new-generation batteries will become attractive for BEVs. Further work could evaluate these promising breakthrough battery chemistries such as lithium-sulphur, lithium-silicon, lithium-air, solid-state batteries, and sodium-ion batteries.

Battery recycling. It is found that the use of secondary materials via recycling can reduce the future GHG emissions of batteries. However, this thesis does not consider the future availability of secondary materials, which opens up an opportunity for future research for evaluating the role of potential material supply risk. Even though closed-loop recycling for battery materials would effectively reduce the supply risk, the current amount of secondary materials used for battery remanufacture is minimal. Future work can evaluate the integration of mandatory minimum levels of recycled content by 2035: 20% cobalt, 10% lithium, and 12% nickel, as required by the recently published EU regulatory framework for batteries (European Commission, 2020a). The pioneering efforts in regulations like this for battery remanufacture/recycling/repurposing will enable a sustainable and circular LIB economy for the future in a rapidly growing industry.

Table 71. Summary of research questions, methods used, and main data sources that resulted in main findings.

Research Question	Methods	Data Source	Main results
Which battery chemistry provides the least GHG emissions and which materials contribute the highest GHG emissions to the overall cradle-to-gate manufacturing process?	Dynamic LCA model includes 8 materials and 7 battery chemistries	**Direct Energy inputs.** ANL GREET2 model (2020)	**For NMCs:** ~ 80 kgCO_2eq/kWh **For NCA:** 84 kgCO_2eq/kWh **For LFP:** 56 kgCO_2eq/kWh
In which geographical locations are these emissions expected to occur for different battery chemistries?	Dynamic LCA model includes 41 mining countries, 26 refining countries, and 5 leading manufacturing countries under the 2% global production threshold.	**Mineral sourcing.** BGS– World Mineral Production (2015-2019) **Battery Assembly 2020.** Statista **Electricity generation inputs.** IEA – Electricity generation (2020) **Electricity generation emission factors.** ecoinvent 2020 **Electricity T&D losses.** The World Bank	**For NMC811.** China contributes 45% of total battery emissions due to battery assembly and refining, Indonesia 13% due to nickel, and Australia 9% mainly due to lithium. **For LFP.** China contributes 57% due to battery assembly and refining, Australia 17%, and Chile 5% due to lithium.
How are the future global GHG emissions expected to change towards 2050 by decarbonising the electricity sector and considering various battery technology scenarios?	The prospective LCA model looks at 2 electricity decarbonisation scenarios. The prospective LCA model considers 2 battery chemistry scenarios	**Electricity generation.** IEA World Energy Outlook 2020 & 2021 **Battery Assembly.** The battery Report 2020 **Battery Technology Scenarios.** Xu, et al (2020)	GHG emissions reduce by up to 21% in the SPS and 38% in the SDS by 2050 per kWh of battery due to electricity decarbonisation. Global cumulative emissions of 8.2 GtCO_2eq by 2050 for nickel-based chemistries scenario and 6.6 GtCO_2eq for LFP-based chemistry scenario

What are the GHG emission reductions of battery manufacture using secondary materials via different recycling technologies?	Dynamic and prospective LCA model including 3 recycling techniques and 2 recycling scenarios	**Battery recycling fractions.** ANL – Everbatt model (2020)	For NMC811, secondary nickel, lithium, and cobalt emissions reductions via hydro of 86%, 81% and 67%, compared to primary production, respectively. Total NMC811 battery GHG emission reductions of 17 % via pyro, 51% via hydro, and 61% direct recycling, by using secondary materials from recycling. GHG emission reductions by 2050 using secondary materials from recycling coupled with electricity decarbonisation via pyro 42%, hydro 66%, and direct recycling 72%.

ANNEX

This annexe provides global data used in this thesis regarding material production per country as provided by (Sun *et al.*, 2019; USGS, 2020; Brown *et al.*, 2021). Countries below the thick border indicate the 2% cut-off, meaning that are not considered in this analysis. Values given in metric ktons of material (material content).

Global Warming Potential Values

The emission factors are converted from gCH_4 and gN_2O to gCO_2eq using the 100-year Global Warming Potential (GWP) given below. For comparability with international data submission guidelines, the factors from the 5th Assessment report of the IPCC are used (AR5) (IPCC, 2014).

Designation or Name	***Chemical formula***	***100-Year GWP***
Carbon dioxide	CO_2	1
Methane	CH_4	28
Nitrous oxide	N_2O	265

Table A 1. Nickel production per country – 2020 (Brown *et al.*, 2021).

Mining			**Refining**		
Country	**Production**	**Share**	**Country**	**Production**	**Share**
Indonesia	1,036.20	38.34%	China	806.00	32.35%
Philippines	323.33	11.96%	Indonesia	409.00	16.41%
Russia	226.00	8.36%	Russia	226.30	9.08%
New Caledonia	209.55	7.75%	Japan	182.70	7.33%
Canada	180.90	6.69%	Canada	124.74	5.01%
Australia	158.75	5.87%	Australia	106.47	4.27%
China	104.67	3.87%	Norway	92.13	3.70%
Brazil	55.70	2.06%	Finland	90.15	3.62%
Guatemala	55.00	2.04%	New Caledonia	87.92	3.53%
Cuba	45.30	1.68%	Brazil	54.30	2.18%
South Africa	43.44	1.61%	Korea (Rep. of)	41.07	1.65%
Colombia	40.57	1.50%	Colombia	40.57	1.63%
Finland	38.53	1.43%	United Kingdom	39.63	1.59%
Madagascar	33.73	1.25%	South Africa	39.10	1.57%
Papua New Guinea	33.09	1.22%	Madagascar	33.73	1.35%
Dominican Republic	28.45	1.05%	Guatemala	20.32	0.82%
Zimbabwe	16.28	0.60%	Burma	16.00	0.64%
Burma	16.00	0.59%	North Macedonia	15.30	0.61%
Greece	13.70	0.51%	Cuba	14.80	0.59%
USA	13.49	0.50%	Ukraine	14.20	0.57%
Turkey	11.00	0.41%	Dominican Republic	13.36	0.54%
Ivory Coast	9.10	0.34%	Greece	11.97	0.48%
Kosovo	3.31	0.12%	France	6.90	0.28%
Albania	2.80	0.10%	Kosovo	3.60	0.14%
Zambia	2.50	0.09%	Austria	0.70	0.03%
Poland	0.72	0.03%	Poland	0.70	0.03%
Norway	0.20	0.01%	India	0.05	0.00%

Table A 2. Lithium production per country – 2020. Mining (USGS, 2020), Refining (Sun *et al.*, 2019).

Mining			**Refining**		
Country	**Production**	**Share**	**Country**	**Production**	**Share**
Australia	45.00	52.26%	China	10.80	34.29%
Chile	19.30	22.42%	Chile	9.80	31.11%
China	10.80	12.54%	Australia	5.80	18.41%
Argentina	6.30	7.32%	Argentina	3.60	11.43%
Brazil	2.40	2.79%	USA	1.10	3.49%
Zimbabwe	1.20	1.39%	Portugal	0.20	0.63%
Portugal	0.90	1.05%	Brazil	0.20	0.63%
Canada	0.20	0.23%			

Table A 3. Manganese production per country – 2020. Mining (Brown *et al.*, 2021), Refining (Sun *et al.*, 2019).

Mining			**Refining**		
Country	**Production**	**Share**	**Country**	**Production**	**Share**
South Africa	17,008.95	30.06%	China	12.87	56.86%
Gabon	7,186.00	12.70%	India	2.09	9.23%
Australia	6,649.43	11.75%	South Africa	1.09	4.81%
China	6,500.00	11.49%	Japan	0.82	3.61%
Ghana	5,383.01	9.51%	Korea	0.71	3.15%
Brazil	3,200.00	5.65%	Gabon	0.62	2.74%
India	2,956.18	5.22%	Russia	0.59	2.61%
Ukraine	1,854.24	3.28%	Malaysia	0.43	1.91%
Ivory Coast	1,200.00	2.12%	USA	0.39	1.74%
Malaysia	1,130.75	2.00%	Ukraine	0.39	1.73%
Burma	982.00	1.74%	Norway	0.34	1.50%
Kazakhstan	970.10	1.71%	Brazil	0.28	1.22%
Mexico	534.04	0.94%	Germany	0.24	1.08%
Georgia (a)	350.00	0.62%	France	0.21	0.93%
Iran (e)	130.00	0.23%	Spain	0.19	0.83%
Zambia	100.00	0.18%	Italy	0.16	0.69%
Turkey	85.00	0.15%	Australia	0.13	0.57%
Morocco	80.00	0.14%	Argentina	0.11	0.50%
Vietnam	76.11	0.13%	Uruguay	0.10	0.43%
Romania	45.00	0.08%	Singapore	0.07	0.33%
Peru	41.80	0.07%	United Arab Emirates	0.07	0.32%
Oman	33.00	0.06%	China Taiwan	0.07	0.29%
Namibia	32.15	0.06%	Latvia	0.06	0.28%
Egypt (c)	30.00	0.05%	Poland	0.06	0.26%
Bolivia	17.10	0.03%	Saudi Arabia	0.06	0.25%
DRC	4.94	0.01%	Mexico	0.05	0.22%
Thailand	4.80	0.01%	Belgium	0.04	0.18%
Sudan	4.00	0.01%	Netherlands	0.04	0.16%

Table A 4. Cobalt production per country – 2020 (Brown *et al.*, 2021).

Mining			Refining		
Country	**Production**	**Share**	**Country**	**Production**	**Share**
DRC	77.96	63.32%	China	86.00	63.29%
Philippines	6.70	5.44%	Finland	12.53	9.22%
Australia	5.69	4.62%	Belgium	6.50	4.78%
Russia	5.50	4.47%	Canada	6.08	4.47%
Cuba	5.20	4.22%	Japan	5.90	4.34%
Canada	5.13	4.17%	Norway	4.35	3.20%
Madagascar	2.93	2.38%	Australia	3.70	2.72%
Papua New Guinea	2.92	2.37%	Madagascar	2.90	2.13%
Morocco	2.40	1.95%	Morocco	2.40	1.76%
China	2.00	1.62%	Russia	2.00	1.47%
New Caledonia	1.70	1.38%	Zambia	1.27	0.94%
Finland	1.45	1.18%	New Caledonia	1.24	0.91%
Zambia	1.27	1.03%	South Africa	1.03	0.76%
South Africa	1.03	0.83%			
USA	0.50	0.41%			
Zimbabwe	0.40	0.32%			
Indonesia	0.35	0.28%			

Table A 5. Graphite production per country – 2020 (Brown *et al.*, 2021).

Production		
Country	**Production**	**Share**
China	700.00	61.82%
Mozambique	113.80	10.05%
Brazil	96.00	8.48%
Madagascar	53.40	4.72%
Korea, Dem. P.R. of	40.00	3.53%
India	32.94	2.91%
Austria	20.00	1.77%
Turkey	16.80	1.48%
Russia	16.60	1.47%
Ukraine	15.00	1.32%
Canada	11.00	0.97%
Norway	9.60	0.85%
Sri Lanka	3.70	0.33%
Mexico	3.18	0.28%
Germany	0.21	0.02%
Zimbabwe	0.10	0.01%

Table A 6. Phosphate production per country – 2020 (Brown *et al.*, 2021).

Production		
Country	**Production**	**Share**
China	93,324.00	41.12%
Morocco	35,300.00	15.55%
USA	23,300.00	10.27%
Russia	13,800.00	6.08%
Peru	11,091.50	4.89%
Jordan	9,223.35	4.06%
Saudi Arabia	6,200.00	2.73%
Brazil	5,300.00	2.34%
Vietman	4,651.63	2.05%
Tunisia	4,108.80	1.81%
Israel	2,649.80	1.17%
Senegal	2,391.90	1.05%
Syria	2,000.00	0.88%
Kazakhstan	1,830.00	0.81%
South Africa	1,825.72	0.80%
India	1,441.63	0.64%
Algeria	1,338.40	0.59%
Egypt	1,300.00	0.57%
Finland	994.57	0.44%
Iran	866.00	0.38%
Mexico	830.00	0.37%
Australia	720.62	0.32%
Togo	703.57	0.31%
Uzbekistan	700.00	0.31%
Christmas Island	486.00	0.21%
Iraq	140.00	0.06%
Pakistan	83.04	0.04%
Nauru	81.50	0.04%
Colombia	77.91	0.03%
Venezuela	70.00	0.03%
Sri Lanka	47.44	0.02%
Mali	46.00	0.02%
Zimbabwe	9.00	0.00%
Chile	3.41	0.00%
Philippines	3.00	0.00%
Malawi	1.75	0.00%
Burkina Faso	1.00	0.00%
Laos	0.64	0.00%

Table A 7. Aluminium production per country – 2020 (Brown *et al.*, 2021).

Bauxite Mining			Alumina Refining			Primary Aluminium		
Country	**Production**	**Share**	**Country**	**Production**	**Share**	**Country**	**Production**	**Share**
Australia	105,543.79	30.41%	China	71,474.17	54.49%	China	35,043.60	55.76%
Guinea	70,173.33	20.22%	Australia	20,239.20	15.43%	Russia	3,637.00	5.79%
China	62,000.00	17.86%	Brazil	9,170.80	6.99%	India	3,628.83	5.77%
Brazil	31,937.90	9.20%	India	6,706.50	5.11%	Canada	2,853.77	4.54%
India	22,073.40	6.36%	Russia	2,755.00	2.10%	UAE	2,600.00	4.14%
Indonesia	16,592.74	4.78%	Jamaica	2172.97	1.66%	Australia	1,569.59	2.50%
Jamaica	9,022.29	2.60%	Ireland	1860.97	1.42%	Bahrain	1,365.01	2.17%
Russia	5,574.00	1.61%	Saudi Ara	1798.34	1.37%	Norway	1,300.00	2.07%
Saudi Arabia	4,780.80	1.38%	Ukraine	1690.00	1.29%	USA	1,126.03	1.79%
Kazakhstan	3,811.70	1.10%	Spain	1595.00	1.22%	Saudi Arabi	967.00	1.54%
Vietnam	3,200.00	0.92%	Canada	1522.00	1.16%	Malaysia	760.00	1.21%
Sierra Leone	1,962.50	0.57%	USA	1410.00	1.08%	South Africa	717.00	1.14%
Guyana	1,919.75	0.55%	Kazakhsta	1403.65	1.07%	Ireland	690.00	1.10%
Greece	1,492.00	0.43%	Vietnam	1382.10	1.05%	Brazil	650.20	1.03%
Solomon Islan	1,234.00	0.36%	Indonesia	1148.42	0.88%	Qatar	645.00	1.03%
Ghana	1,116.33	0.32%	UAE	1100.00	0.84%	Mozambiqu	569.00	0.91%
Bosnia & Herz	1,043.34	0.30%	Germany	1000.00	0.76%	Germany	507.93	0.81%
Malaysia	900.56	0.26%	Greece	672.40	0.51%	Argentina	438.20	0.70%
Iran	805.20	0.23%	France	500.00	0.38%	Oman	391.00	0.62%
Montenegro	774.73	0.22%	Romania	460.91	0.35%	France	390.00	0.62%
Turkey	700.00	0.20%	Guinea	368.00	0.28%	New Zealan	351.00	0.56%
USA	154.87	0.04%	Turkey	260.00	0.20%	Romania	280.33	0.45%
Pakistan	93.31	0.03%	Iran	233.27	0.18%	Iran	275.72	0.44%
France	70.00	0.02%	Bosnia &	213.52	0.16%	Kazakhstan	264.90	0.42%
Venezuela	50.00	0.01%	Japan	25.00	0.02%	Egypt	260.00	0.41%
Croatia	14.34	0.00%				Indonesia	250.39	0.40%
Colombia	13.53	0.00%				Spain	230.00	0.37%
Mozambique	8.02	0.00%				Greece	182.10	0.29%
						Slovakia	174.79	0.28%
						Sweden	120.00	0.19%
						Takikistan	100.80	0.16%
						Netherlands	81.10	0.13%
						Turkey	78.10	0.12%
						Slovenia	68.26	0.11%
						Bosnia & H	67.69	0.11%
						Cameroon	54.00	0.09%
						Ghana	43.20	0.07%
						UK	39.40	0.06%
						Montenegro	36.52	0.06%
						Azerbaijan	32.69	0.05%
						Venezuela	10.00	0.02%

Table A 8. Copper production per country – 2020 (Brown *et al.*, 2021).

Copper Mining			Copper Smelting			Copper Refining		
Country	**Prod**	**Share**	**Country**	**Prod.**	**Shar**	**Country**	**Prod.**	**Shar**
Chile	5787.4	27.9%	China	7082.7	43.4%	China	9784.2	40.5%
Peru	2455.4	11.88%	Japan	1169.6	7.17%	Chile	2269.1	9.40%
China	1683.7	8.14%	Chile	1011.2	6.20%	Japan	1495.3	6.19%
DRC	1420.3	6.87%	Russia	790.50	4.85%	DRC	1160.2	4.81%
USA	1260.00	6.09%	Zambia	638.50	3.92%	USA	1030.0	4.27%
Australia	934.06	4.52%	Korea	520.00	3.19%	Russia	1028.0	4.26%
Russia	813.60	3.93%	Poland	489.24	3.00%	Korea	659.00	2.73%
Zambia	797.52	3.86%	USA	466.00	2.86%	Germany	629.70	2.61%
Mexico	768.54	3.72%	Australia	401.28	2.46%	Poland	565.59	2.34%
Kazakhstan	608.00	2.94%	India	342.30	2.10%	Kazakhstan	477.01	1.98%
Canada	560.78	2.71%	Kazakhstan	295.00	1.81%	Mexico	428.00	1.77%
Poland	449.00	2.17%	Peru	294.32	1.81%	Australia	425.68	1.76%
Brazil	363.30	1.76%	Canada	290.00	1.78%	India (a)	407.24	1.69%
Indonesia	351.00	1.70%	Germany	288.60	1.77%	Spain	386.70	1.60%
Iran	310.00	1.50%	Mexico	277.65	1.70%	Belgium	356.60	1.48%
Mongolia	297.50	1.44%	Bulgaria	255.20	1.57%	Peru	307.86	1.28%
Burma	219.00	1.06%	Indonesia	246.10	1.51%	Canada	281.18	1.16%
Spain	170.56	0.82%	Spain	245.80	1.51%	Zambia	264.50	1.10%
Panama	147.48	0.71%	Philippines	217.80	1.34%	Indonesia	257.98	1.07%
Uzbekistan	141.00	0.68%	Iran	201.10	1.23%	Iran (b)	250.13	1.04%
Laos	140.94	0.68%	Uzbekistan	147.30	0.90%	Burma	218.00	0.90%
Papua New Guinea	99.40	0.48%	Sweden	135.90	0.83%	Philippines	217.30	0.90%
Sweden	99.33	0.48%	Finland	120.37	0.74%	Bulgaria	207.20	0.86%
Armenia	91.20	0.44%	Brazil	110.90	0.68%	Sweden	201.35	0.83%
Turkey	73.50	0.36%	Serbia	82.40	0.51%	Brazil	174.00	0.72%
Philippines	71.89	0.35%	Turkey	46.00	0.28%	Austria	128.20	0.53%
Bulgaria	70.93	0.34%	Namibia	45.95	0.28%	Turkey	116.00	0.48%
Saudi Arabia	67.30	0.33%	South Africa	26.00	0.16%	Uzbekistan	100.00	0.41%
South Africa	52.50	0.25%	Norway	21.96	0.13%	Serbia	74.00	0.31%
Serbia	44.00	0.21%	Vietnam	19.20	0.12%	Laos	71.65	0.30%
Portugal	41.55	0.20%	Pakistan	13.05	0.08%	South Africa	35.60	0.15%
Morocco	34.00	0.16%	Tanzania	10.00	0.06%	Norway	21.96	0.09%
Finland	32.59	0.16%	DRC	2.00	0.01%	Ukraine	20.41	0.08%
Vietnam	30.55	0.15%				Vietnam	19.20	0.08%
India (a)	30.47	0.15%				Namibia	15.74	0.07%
Mauritania	29.62	0.14%				Argentina	14.00	0.06%
Namibia	16.11	0.08%				Finland	13.01	0.05%
Eritrea	16.01	0.08%				Mongolia	11.76	0.05%
Pakistan	13.05	0.06%				Italy	9.80	0.04%
Tanzania	10.00	0.05%				Egypt	4.00	0.02%
Romania	9.20	0.04%				Bolivia	3.10	0.01%
Zimbabwe	8.70	0.04%				North Macedonia	0.72	0.00%
Tajikistan	8.50	0.04%				Cyprus	0.70	0.00%
Colombia	7.64	0.04%						
North Macedonia	7.10	0.03%						
Kyrgyzstan	7.00	0.03%						
Ecuador	6.10	0.03%						
Dominican Republic	6.05	0.03%						

Bolivia	4.48	0.02%		
Albania	3.00	0.01%		
Azerbaijan	2.21	0.01%		
Korea, Dem. P.R. of	2.00	0.01%		
Georgia	0.90	0.00%		
Cyprus	0.70	0.00%		
Slovakia	0.02	0.00%		

REFERENCES

Abdul-Manan, A.F.N. *et al.* (2022) ‘Electrifying passenger road transport in India requires near-term electricity grid decarbonisation’, *Nature Communications 2022 13:1*, 13(1), pp. 1–13. Available at: https://doi.org/10.1038/s41467-022-29620-x.

Aguirre, K. *et al.* (2012) ‘Lifecycle analysis comparison of a battery electric vehicle and a conventional gasoline vehicle’, *Calif Air Resour Board* [Preprint]. Available at: https://www.ioes.ucla.edu/wp-content/uploads/ev-vs-gasoline-cars-practicum-final-report.pdf (Accessed: 18 January 2023).

Amarakoon, S., Smith, J. and Segal, B.G. (2013) ‘Application of Life-Cycle Assessment to Nanoscale Technology: Lithium-ion Batteries for Electric Vehicles’, *United States Environmental Protection Agency* [Preprint].

Ambrose, H. and Kendall, A. (2016) ‘Effects of battery chemistry and performance on the life cycle greenhouse gas intensity of electric mobility’, *Transportation Research Part D: Transport and Environment*, 47, pp. 182–194. Available at: https://doi.org/10.1016/J.TRD.2016.05.009.

ANL (2020a) *Argonne National Laboratory GREET Model*. Available at: https://greet.es.anl.gov/ (Accessed: 19 October 2020).

ANL (2020b) *EverBatt | Argonne National Laboratory*. Available at: https://www.anl.gov/amd/everbatt (Accessed: 17 November 2022).

ANL (2021) *The Greenhouse Gases, Regulated Emissions, and Energy Use in Technologies (GREET) Model, Argonee National Laboratory*. Available at: https://greet.es.anl.gov/ (Accessed: 21 February 2022).

Bauer, C. *et al.* (2015) ‘The environmental performance of current and future passenger vehicles: Life Cycle Assessment based on a novel scenario analysis framework’, *Applied Energy*, 157, pp. 871–883. Available at: https://doi.org/10.1016/j.apenergy.2015.01.019.

BEIS (2020) *Government takes historic step towards net-zero with end of sale of new petrol and diesel cars by 2030*. Available at: https://www.gov.uk/government/news/government-takes-historic-step-towards-net-zero-with-end-of-sale-of-new-petrol-and-diesel-cars-by-2030 (Accessed: 10 January 2023).

Benveniste, G. *et al.* (2018) ‘Comparison of the state of Lithium-Sulphur and lithium-ion batteries applied to electromobility’, *Journal of Environmental Management*, 226, pp. 1–12. Available at: https://doi.org/10.1016/J.JENVMAN.2018.08.008.

Berkeley, N. *et al.* (2017) ‘Assessing the transition towards Battery Electric Vehicles: A Multi-Level Perspective on drivers of, and barriers to, take up’, *Transportation Research Part A: Policy and Practice*, 106, pp. 320–332. Available at: https://doi.org/10.1016/j.tra.2017.10.004.

Bloodworth, A. (2014) ‘Track flows to manage technology-metal supply: Recycling cannot meet the demand for rare metals used in digital and green technologies’, *Nature 2013 505:7481*, 505(7481), pp. 19–20. Available at: https://doi.org/10.1038/505019a.

Bobba, S. *et al.* (2020) ‘Bridging tools to better understand environmental performances and raw materials supply of traction batteries in the future EU fleet’, *Energies*, 13(10), pp. 1–27. Available at: https://doi.org/10.3390/en13102513.

Brown, T.J. *et al.* (2021) *World Mineral Production 2015-2019. British Geological Survey, BGS*.

Chen, Q. *et al.* (2022) 'Investigating carbon footprint and carbon reduction potential using a cradle-to-cradle LCA approach on lithium-ion batteries for electric vehicles in China', *Journal of Cleaner Production*, 369, p. 133342. Available at: https://doi.org/10.1016/J.JCLEPRO.2022.133342.

Ciez, R.E. and Whitacre, J.F. (2019) 'Examining different recycling processes for lithium-ion batteries', *Nature Sustainability*, 2(2), pp. 148–156. Available at: https://doi.org/10.1038/s41893-019-0222-5.

CNBC (2021) *Tesla switching to LFP batteries in all standard-range cars*. Available at: https://www.cnbc.com/2021/10/20/tesla-switching-to-lfp-batteries-in-all-standard-range-cars.html (Accessed: 15 December 2021).

Costa, C.M. *et al.* (2021) 'Recycling and environmental issues of lithium-ion batteries: Advances, challenges and opportunities', *Energy Storage Materials*, 37(January), pp. 433–465. Available at: https://doi.org/10.1016/j.ensm.2021.02.032.

Cozzi, L. *et al.* (2020) *International Energy Agency, World Energy Outlook 2020*. Available at: https://www.oecd-ilibrary.org/energy/world-energy-outlook-2020_557a761b-en.

Cozzi, L. and Gould, T. (2021) *International Energy Agency, World Energy Outlook 2021*. Available at: www.iea.org/weo.

Dai, Q. *et al.* (2019) 'EverBatt: A Closed-loop Battery Recycling Cost and Environmental Impacts Model', *Argonne National Laboratory*, pp. 1–88.

Dai, Q. *et al.* (2019) 'EverBatt: A Closed-loop Battery Recycling Cost and Environmental Impacts Model Energy Systems Division', *Argonne National Laboratory* [Preprint]. Available at: https://publications.anl.gov/anlpubs/2019/07/153050.pdf (Accessed: 17 November 2022).

Dai, Q., Kelly, J.C., *et al.* (2019a) 'Life cycle analysis of lithium-ion batteries for automotive applications', *Batteries*, 5(2). Available at: https://doi.org/10.3390/batteries5020048.

Dai, Q., Kelly, J.C., *et al.* (2019b) 'Life Cycle Analysis of Lithium-Ion Batteries for Automotive Applications', *Batteries 2019, Vol. 5, Page 48*, 5(2), p. 48. Available at: https://doi.org/10.3390/BATTERIES5020048.

Dai, Q. and Winjobi, O. (2019) 'Updates for Battery Recycling and Materials in GREET 2019', (October), pp. 1–9.

Dils, E. (2019) *Ae we losing resources when managing Europe's waste?* Available at: https://www.eionet.europa.eu/etcs/etc-wmge/products/etc-wmge-reports/are-we-losing-resources-when-managing-europes-waste-1 (Accessed: 8 January 2023).

Dunn, J.B. *et al.* (2012) 'Impact of recycling on cradle-to-gate energy consumption and greenhouse gas emissions of automotive lithium-ion batteries', *Environmental Science and Technology*, 46(22), pp. 12704–12710. Available at: https://doi.org/10.1021/ES302420Z.

Dunn, J.B. *et al.* (2015) 'The significance of Li-ion batteries in electric vehicle life-cycle energy and emissions and recycling's role in its reduction', *Energy and Environmental Science*, 8(1), pp. 158–168. Available at: https://doi.org/10.1039/c4ee03029j.

Dunn, J.B., Gaines, L. and Sullivan, J. (2014) *Material and Energy Flows in the Materials*

Production, Assembly, and End-of-Life Stages of the Automotive Lithium-Ion Battery Life Cycle, *Argonne GREET Publication*. Available at: https://greet.es.anl.gov/publication-li-ion (Accessed: 3 October 2019).

Ecoinvent (2020) *Ecoinvent 3.7*. Available at: https://ecoinvent.org/ (Accessed: 24 January 2022).

EEA (2021) *Reducing loss of resources from waste management is key to strengthening the circular economy in Europe.*, *European Environment Agency*.

Ellingsen, L.A.W. *et al.* (2014) 'Life Cycle Assessment of a Lithium-Ion Battery Vehicle Pack', *Journal of Industrial Ecology*, 18(1), pp. 113–124. Available at: https://doi.org/10.1111/jiec.12072.

Ellingsen, L.A.W., Singh, B. and Strømman, A.H. (2016) 'The size and range effect: lifecycle greenhouse gas emissions of electric vehicles', *Environmental Research Letters*, 11(5), p. 054010. Available at: https://doi.org/10.1088/1748-9326/11/5/054010.

Engel, H., Hertzke, P. and Siccardo, G. (2019) *Second-life EV batteries: The newest value pool in energy storage*. Available at: https://www.mckinsey.com/industries/automotive-and-assembly/our-insights/second-life-ev-batteries-the-newest-value-pool-in-energy-storage#/ (Accessed: 4 May 2023).

EPRS (2022) *EU Legislation in Progress New EU regulatory framework for batteries Setting sustainability requirements*.

Erriquez, M. *et al.* (2021) 'Building better batteries: Insights on chemistry and design from China', *McKinsey&Company* [Preprint].

European Commission (2019) 'Report from the Commission on the Implementation of the Strategic Action Plan on Batteries: Building a Strategic Battery Value Chain in Europe', *European Commission*, p. 17. Available at: https://ec.europa.eu/transparency/regdoc/rep/1/2019/EN/COM-2019-176-F1-EN-MAIN-PART-1.PDF.

European Commission (2020a) *Proposal for a Regulation of the European Parliament and of the Council concerning batteries and waste batteries, repealing Directive 2006/66/EC and amending Regulation (EU) 2019/1020*. Available at: https://eur-lex.europa.eu/resource.html?uri=cellar:5ee7d299-3ad8-11eb-b27b-01aa75ed71a1.0001.02/DOC_1&format=PDF#page=21 (Accessed: 8 January 2023).

European Commission (2020b) *Proposal for a Regulation of the European Parliament and of the Council concerning batteries and waste batteries, repealing Directive 2006/66/EC and amending Regulation (EU) 2019/1020*. Available at: https://eur-lex.europa.eu/resource.html?uri=cellar:5ee7d299-3ad8-11eb-b27b-01aa75ed71a1.0001.02/DOC_1&format=PDF#page=24 (Accessed: 8 January 2023).

European Commission (2020c) *The 2020 EU Critical Raw Materials List. Critical Raw Materials Resilience: Charting a Path towards greater Security and Sustainability*. Brusells. Available at: http://info.worldbank.org/governance/wgi/. (Accessed: 15 January 2023).

Faria, R. *et al.* (2013) 'Impact of the electricity mix and use profile in the life-cycle assessment of electric vehicles', *Renewable and Sustainable Energy Reviews*, pp. 271–287. Available at: https://doi.org/10.1016/j.rser.2013.03.063.

Field, K. (2018) *Yes, Tesla Recycles All Of Its Spent Batteries & Wants To Do More In The*

Future, CleanTechnica. Available at: https://cleantechnica.com/2018/06/07/yes-tesla-recycles-all-of-its-spent-batteries-wants-to-do-more-in-the-future/ (Accessed: 7 January 2023).

Gaines, L. *et al.* (2011) 'Life-Cycle Analysis of Production and Recycling of Lithium Ion Batteries', *Transportation Research Record: Journal of the Transportation Research Board*, 2252(1), pp. 57–65. Available at: https://doi.org/10.3141/2252-08.

Garcia-Ferrer, M. and Verbanac, R. (2022) *WTO panel rules against Indonesia's export limitations, European Commission*. Available at: https://ec.europa.eu/commission/presscorner/detail/en/ip_22_7314 (Accessed: 13 January 2023).

Green Car Congress (2021) *Walkabout Resources' Tanzanian graphite project moves to construction phase*. Available at: https://www.greencarcongress.com/2021/08/20210830-walkabout.html (Accessed: 13 January 2023).

Green Car Reports (2022) *CATL improves cell-to-pack tech, claims advantage over Tesla 4680 cells*. Available at: https://www.greencarreports.com/news/1135472_catl-improves-cell-to-pack-tech-claims-advantage-over-tesla-4680-cells (Accessed: 19 August 2022).

Hannan, M.A. *et al.* (2018) 'State-of-the-Art and Energy Management System of Lithium-Ion Batteries in Electric Vehicle Applications: Issues and Recommendations', *IEEE Access*, 6, pp. 19362–19378. Available at: https://doi.org/10.1109/ACCESS.2018.2817655.

Harper, G. *et al.* (2019) 'Recycling lithium-ion batteries from electric vehicles', *Nature 2019 575:7781*, 575(7781), pp. 75–86. Available at: https://doi.org/10.1038/s41586-019-1682-5.

Hasuchild, M.Z., Rosenbaum, R.K. and Olsen, S.I. (2018) *Life Cycle Assessment - Theory and Practice*. Edited by M. Hauschild, R.K. Rosenbaum, and S. Olsen. Springer Nature. Available at: http://link.springer.com/10.1007/978-3-319-56475-3.

Hawkins, T.R. *et al.* (2013) 'Comparative Environmental Life Cycle Assessment of Conventional and Electric Vehicles', *Journal of Industrial Ecology*, 17(1), pp. 53–64. Available at: https://doi.org/10.1111/j.1530-9290.2012.00532.x.

Hendrickson, T.C.J. *et al.* (2015) 'Life-cycle implications and supply chain logistics of electric vehicle battery recycling in California', *Environmental Research Letters*, 10(1), p. 014011. Available at: https://doi.org/10.1088/1748-9326/10/1/014011.

Hill, N. *et al.* (2019) 'Circular Economy Perspectives for the Management of Batteries used in Electric Vehicles'. Available at: https://doi.org/10.2760/537140.

HIR (2020) *The Lithium Triangle: Where Chile, Argentina, and Bolivia Meet, Harvard International Review*. Available at: https://hir.harvard.edu/lithium-triangle/ (Accessed: 13 January 2023).

Holman, J. (2022) *Infographic: Africa set for boom in graphite mining projects as EV battery demand surges | S&P Global Commodity Insights, S&P Global Commodity Insights*. Available at: https://www.spglobal.com/commodityinsights/en/market-insights/latest-news/energy-transition/051022-infographic-africa-boom-graphite-mining-projects-ev-battery-demand-surges (Accessed: 13 January 2023).

Holman, J. and Leech, J. (2022) *Feature: More projects needed globally to combat future graphite deficit | S&P Global Commodity Insights, &P Global Commodity Insights*. Available at: https://www.spglobal.com/commodityinsights/en/market-insights/latest-news/energy-transition/051022-feature-more-projects-needed-globally-to-combat-future-graphite-deficit (Accessed: 13 January 2023).

Horiba, T. (2014) ‘Lithium-ion battery systems’, *Proceedings of the IEEE,* 102(6). Available at: https://doi.org/10.1109/JPROC.2014.2319832.

ICCT (2021) *European Union CO2 Standards for new Passenger Cars and Vans*. Available at: https://theicct.org/wp-content/uploads/2021/12/eu-co2-FS5-jun2021.pdf.

IEA (2019) *Global EV Outlook 2019*. Available at: https://webstore.iea.org/download/direct/2807?fileName=Global_EV_Outlook_2019.pdf (Accessed: 2 October 2019).

IEA (2020a) *Electricity - Fuels & Technologies - IEA, International Energy Agency*. Available at: https://www.iea.org/fuels-and-technologies/electricity (Accessed: 21 October 2020).

IEA (2020b) *Global EV Outlook 2020 Entering the decade of electric drive?* Available at: http://www.iea.org/publications/freepublications/publication/name-37024-en.html%5Cnhttp://scholar.google.com/scholar?hl=en&btnG=Search&q=intitle:Global+EV+Outlook:+Understanding+the+Electric+Vehicle+Landscape+to+2020#0.

IEA (2021) ‘The Role of Critical Minerals in Clean Energy Transitions’, *The Role of Critical Minerals in Clean Energy Transitions* [Preprint]. Available at: https://doi.org/10.1787/f262b91c-en.

IEA (2022a) *Electricity Sector*. Available at: https://www.iea.org/reports/electricity-sector (Accessed: 16 January 2023).

IEA (2022b) *Global EV Outlook 2022 - Securing supplies for an electric future, Global EV Outlook 2022*. Available at: https://www.iea.org/reports/global-ev-outlook-2022%0Ahttps://iea.blob.core.windows.net/assets/ad8fb04c-4f75-42fc-973a-6e54c8a4449a/GlobalElectricVehicleOutlook2022.pdf.

IEA (2022c) *Global Supply Chains of EV Batteries*. Available at: https://www.iea.org/reports/global-supply-chains-of-ev-batteries (Accessed: 9 August 2022).

IEA (2022d) *Transport*. Paris. Available at: https://www.iea.org/reports/transport.

Imanishi, N. and Yamamoto, O. (2019) ‘Perspectives and challenges of rechargeable lithium–air batteries’, *Materials Today Advances,* 4, p. 100031. Available at: https://doi.org/10.1016/J.MTADV.2019.100031.

Insights, S.G.C. (2021) *Volkswagen’s plan on LFP use shifts hydroxide dominance narrative in EV sector | S&P Global Commodity Insights*. Available at: https://www.spglobal.com/commodityinsights/en/market-insights/latest-news/metals/031721-volkswagens-plan-on-lfp-use-shifts-hydroxide-dominance-narrative-in-ev-sector (Accessed: 9 August 2022).

International Energy Agency (2018) *Global EV Outlook 2018.*

International Energy Agency (2020a) *Stated Policies Scenario – World Energy Model – Analysis - IEA, International Energy Agency*. Available at: https://www.iea.org/weo/weomodel/steps/ (Accessed: 20 October 2021).

International Energy Agency (2020b) *Sustainable Development Scenario – World Energy*

Model – Analysis - IEA. Available at: https://www.iea.org/reports/world-energy-model/sustainable-development-scenario#abstract (Accessed: 20 October 2021).

International Energy Agency (2021) *Global EV Outlook 2021 Accelerating ambitions despite the pandemic*. Available at: www.iea.org/t&c/ (Accessed: 11 January 2022).

IPCC (2014) *IPCC. Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, IPCC: Geneva, Switzerland*. Gian-Kasper Plattner. Available at: http://www.ipcc.ch. (Accessed: 24 January 2022).

IRENA (2020) *Global Renewables outlook: Energy transformation 2050*. Available at: www.irena.org (Accessed: 11 January 2022).

ISO (2006) ‘14040: Environmental management–life cycle assessment—Principles and framework’, *International organization for standardization*, 2006.

Jin, H. and Lienert, P. (2023) *Tesla to use iron-based batteries in Semi electric trucks and affordable electric car | Reuters*, *Reuters*. Available at: https://www.reuters.com/business/autos-transportation/tesla-use-iron-based-batteries-semi-electric-trucks-affordable-electric-car-2023-04-06/ (Accessed: 22 April 2023).

Keshan, H., Thornburg, J. and Ustun, T.S. (2016) ‘Comparison of lead-Acid and lithium ion batteries for stationary storage in off-grid energy systems’, in *IET Conference Publications*. Institution of Engineering and Technology. Available at: https://doi.org/10.1049/cp.2016.1287.

Kim, H.C. *et al.* (2016) ‘Cradle-to-Gate Emissions from a Commercial Electric Vehicle Li-Ion Battery: A Comparative Analysis’, *Environmental Science and Technology*, 50(14), pp. 7715–7722. Available at: https://doi.org/10.1021/ACS.EST.6B00830/SUPPL_FILE/ES6B00830_SI_001.PDF.

Lastoskie, C.M. and Dai, Q. (2015) ‘Comparative life cycle assessment of laminated and vacuum vapor-deposited thin film solid-state batteries’, *Journal of Cleaner Production*, 91, pp. 158–169. Available at: https://doi.org/10.1016/J.JCLEPRO.2014.12.003.

Latini, D. *et al.* (2022) ‘A comprehensive review and classification of unit operations with assessment of outputs quality in lithium-ion battery recycling’, *Journal of Power Sources*, 546. Available at: https://doi.org/10.1016/j.jpowsour.2022.231979.

LeVine, S. (2015) *The powerhouse : inside the invention of a battery to save the world*. Viking.

Lu, Q. *et al.* (2016) ‘Life cycle assessment of electric vehicle power battery’, *Materials Science Forum*, 847, pp. 403–410. Available at: https://doi.org/10.4028/WWW.SCIENTIFIC.NET/MSF.847.403.

Majeau-Bettez, G., Hawkins, T.R. and StrØmman, A.H. (2011) ‘Life cycle environmental assessment of lithium-ion and nickel metal hydride batteries for plug-in hybrid and battery electric vehicles’, *Environmental Science and Technology*, 45(10), pp. 4548–4554. Available at: https://doi.org/10.1021/ES103607C/SUPPL_FILE/ES103607C_SI_001.PDF.

Månberger, A. (2023) ‘Critical Raw Material Supply Matters and the Potential of the Circular Economy to Contribute to Security’, *Intereconomics*, 2023(2), pp. 74–78. Available at: https://doi.org/10.2478/IE-2023-0016.

McKinsey (2023) *Building green businesses: How Finnish companies can accelerate the transition to net zero*. Available at: https://www.mckinsey.com/capabilities/sustainability/our-insights/sustainability-blog/building-green-businesses-how-finnish-companies-can-accelerate-the-transition-to-net-zero (Accessed: 28 April 2023).

McManus, M.C. (2012) 'Environmental consequences of the use of batteries in low carbon systems: The impact of battery production', *Applied Energy*, 93, pp. 288–295. Available at: https://doi.org/10.1016/J.APENERGY.2011.12.062.

Miao, Y. *et al.* (2019a) 'Current li-ion battery technologies in electric vehicles and opportunities for advancements', *Energies*. MDPI AG. Available at: https://doi.org/10.3390/en12061074.

Miao, Y. *et al.* (2019b) 'Current Li-Ion Battery Technologies in Electric Vehicles and Opportunities for Advancements', *Energies 2019, Vol. 12, Page 1074*, 12(6), p. 1074. Available at: https://doi.org/10.3390/EN12061074.

Mohr, M. *et al.* (2020) 'Toward a cell-chemistry specific life cycle assessment of lithium-ion battery recycling processes', *Journal of Industrial Ecology*, 24(6), pp. 1310–1322. Available at: https://doi.org/10.1111/JIEC.13021.

Nicholas., Y. *et al.* (2021) *State of Batteries Report 2020, BatteryBits 16 January 2021*. Available at: https://www.batterybrunch.org/battery-report.

Notter, D.A. *et al.* (2010) 'Contribution of Li-ion batteries to the environmental impact of electric vehicles', *Environmental Science and Technology*, 44(17), pp. 6550–6556. Available at: https://doi.org/10.1021/es903729a.

Our World in Data (2020) *Carbon intensity of electricity, 2020*, *Carbon electricity of electricity, 2020*. Available at: https://ourworldindata.org/grapher/carbon-intensity-electricity?time=2020&region=SouthAmerica (Accessed: 26 January 2023).

Peters, J.F. *et al.* (2017) 'The environmental impact of Li-Ion batteries and the role of key parameters – A review', *Renewable and Sustainable Energy Reviews*, 67, pp. 491–506. Available at: https://doi.org/10.1016/J.RSER.2016.08.039.

Porzio, J. and Scown, C.D. (2021) 'Life-Cycle Assessment Considerations for Batteries and Battery Materials', *Advanced Energy Materials*, 11(33), p. 2100771. Available at: https://doi.org/10.1002/AENM.202100771.

Rand, D.A.J. (David A.J., Woods, R. and Dell, R. (1998) *Batteries for electric vehicles*. Research Studies Press.

Richa, K., Babbitt, C.W. and Gaustad, G. (2017) 'Eco-Efficiency Analysis of a Lithium-Ion Battery Waste Hierarchy Inspired by Circular Economy', *Journal of Industrial Ecology*, 21(3), pp. 715–730. Available at: https://doi.org/10.1111/JIEC.12607.

Ritchie, H., Roser, M. and Rosado, P. (2020) 'Emissions by sector', *Our World in Data* [Preprint]. Available at: https://ourworldindata.org/co2-and-other-greenhouse-gas-emissions (Accessed: 16 January 2023).

Romare, M. and Dahllöf, L. (2017) *The Life Cycle Energy Consumption and Greenhouse Gas Emissions from Lithium-Ion Batteries A study with focus on Current Technology and batteries for ligh-duty vehicles.*, *IVL Swedish Environmental Research Institute*. Available at: http://www.ivl.se/download/18.5922281715bdaebede9559/1496046218976/C243+The+life+cycle+energy+consumption+and+CO2+emissions+from+lithium+ion+batteries+.pdf.

Ryu, H.H. *et al.* (2021) ‘Reducing cobalt from lithium-ion batteries for the electric vehicle era’, *Energy & Environmental Science,* 14(2), pp. 844–852. Available at: https://doi.org/10.1039/D0EE03581E.

Samaras, C. and Meisterling, K. (2008) ‘Life cycle assessment of greenhouse gas emissions from plug-in hybrid vehicles: Implications for policy’, *Environmental Science and Technology,* 42(9), pp. 3170–3176. Available at: https://doi.org/10.1021/ES702178S/SUPPL_FILE/ES702178S-FILE004.PDF.

Schill, W.P. (2020) ‘Electricity Storage and the Renewable Energy Transition’, *Joule,* 4(10), pp. 2059–2064. Available at: https://doi.org/10.1016/j.joule.2020.07.022.

Searcey, D. and Lipton, E. (2022) *Hunt for the ‘Blood Diamond of Batteries’ Impedes Green Energy Push, The New York Times*. Available at: https://www.nytimes.com/2021/11/29/world/congo-cobalt-albert-yuma-mulimbi.html (Accessed: 9 January 2023).

Simon, B. and Weil, M. (2013) ‘Analysis of materials and energy flows of different lithium ion traction batteries’, *Revue de Métallurgie,* 110(1), pp. 65–76. Available at: https://doi.org/10.1051/METAL/2013056.

Skeete, J.P. *et al.* (2020) ‘Beyond the EVent horizon: Battery waste, recycling, and sustainability in the United Kingdom electric vehicle transition’, *Energy Research and Social Science,* 69(May), p. 101581. Available at: https://doi.org/10.1016/j.erss.2020.101581.

Skidmore, Z. (2021) *The future of artisanal mining in the DRC, Mining Technology*. Available at: https://www.mining-technology.com/features/artisanal-mining-drc/ (Accessed: 13 January 2023).

Sovacool, B.K. *et al.* (2020) ‘Sustainable minerals and metals for a low-carbon future’, *Science*, 367(6473), pp. 30–33. Available at: https://doi.org/10.1126/SCIENCE.AAZ6003/SUPPL_FILE/AAZ6003_SOVACOOL_SM.PDF.

Statista (2021) *Projected global lithium-ion battery capacity between 2021 and 2025, by country (in gigawatt hours)*. Available at: https://www.statista.com/statistics/1246648/projected-global-lithium-ion-battery-capacity-by-country/ (Accessed: 15 November 2021).

Stockhead (2022) *BlackEarth’s new DFS reveals a Maniry Graphite Project primed to produce as the boom times begin, BlackEarth Minerals*. Available at: https://stockhead.com.au/resources/blackearths-new-dfs-reveals-a-maniry-graphite-project-primed-to-produce-as-the-boom-times-begin/ (Accessed: 13 January 2023).

Stringer, D. and Ma, J. (2018) *Where 3 Million Electric Vehicle Batteries Will Go When They Retire, Bloomberg*. Available at: https://www.bloomberg.com/news/features/2018-06-27/where-3-million-electric-vehicle-batteries-will-go-when-they-retire?leadSource=uverify wall (Accessed: 7 January 2023).

Sullivan, J.L., Burnham, A. and Wang, M. (2010) ‘Energy-Consumption and Carbon-Emission Analysis of Vehicle and Component Manufacturing Energy Systems Division’, *Argonee National Laboratory, Energy Systtems Division, Argonne, US, ANL/ESD/10-6* [Preprint]. Available at: www.anl.gov. (Accessed: 18 January 2023).

Sun, X. *et al.* (2019) ‘Supply risks of lithium-ion battery materials: An entire supply chain estimation', *Materials Today Energy*, 14, p. 100347. Available at: https://doi.org/10.1016/j.mtener.2019.100347.

Sun, X. *et al.* (2020) 'Life cycle assessment of lithium nickel cobalt manganese oxide (NCM) batteries for electric passenger vehicles', *Journal of Cleaner Production*, 273, p. 123006. Available at: https://doi.org/10.1016/J.JCLEPRO.2020.123006.

TechCrunch (2021) *What Tesla's bet on iron-based batteries means for manufacturers | TechCrunch*. Available at: https://techcrunch.com/2021/07/28/what-teslas-bet-on-iron-based-batteries-means-for-manufacturers/?guccounter=1&guce_referrer=aHR0cHM6Ly93d3cuZ29vZ2xlLmNvLnVrLw&guce_referrer_sig=AQAAANHBiRoA7HB6mICyWuO-IEIPlVICy8Ac6Dem-ypw6d3KJqnzZ36T-hhMKjkK5NIOir0incmc (Accessed: 31 August 2022).

The Investor (2020) *SK makes world's 1st NCM battery with 90% nickel, The Korea Herald*. Available at: http://www.theinvestor.co.kr/view.php?ud=20200810000820 (Accessed: 9 June 2022).

U.S. DOE (2020) *Battery Critical Materials Supply Chain Opportunities - Virtual Workshop, U.S. Department of Energy. Office of Energy Efficiency & Renewable Energy*. Available at: https://www.nrel.gov/transportation/assets/pdfs/battery-critical-materials-presentation.pdf (Accessed: 9 June 2022).

Usai, L. *et al.* (2022) 'Analysis of the Li-ion battery industry in light of the global transition to electric passenger light duty vehicles until 2050', *Environmental Research: Infrastructure and Sustainability*, 2(1), p. 011002. Available at: https://doi.org/10.1088/2634-4505/AC49A0.

USGS (2020) *Mineral commodity summaries 2020, U.S Department OF The Interior, U.S Geological Survey*. United States Geological Survey. Available at: https://pubs.usgs.gov/periodicals/mcs2020/mcs2020.pdf.

Wang, G. *et al.* (2019) 'New insights into Li diffusion in Li–Si alloys for Si anode materials: role of Si microstructures', *Nanoscale*, 11(29), pp. 14042–14049. Available at: https://doi.org/10.1039/C9NR03986D.

Wang, R. *et al.* (2020) 'Lithium metal anodes: Present and future', *Journal of Energy Chemistry*, 48, pp. 145–159. Available at: https://doi.org/10.1016/J.JECHEM.2019.12.024.

Wang, Y. *et al.* (2017) 'Quantifying the environmental impact of a Li-rich high-capacity cathode material in electric vehicles via life cycle assessment', *Environmental science and pollution research international*, 24(2), pp. 1251–1260. Available at: https://doi.org/10.1007/S11356-016-7849-9.

Wang, Y. *et al.* (2021) 'Recent progress on the recycling technology of Li-ion batteries', *Journal of Energy Chemistry*, 55, pp. 391–419. Available at: https://doi.org/10.1016/J.JECHEM.2020.05.008.

Winjobi, O., Dai, Q. and Kelly, J.C. (2020) 'Update of Bill-of-Materials and Cathode Chemistry addition for Lithium-ion Batteries in GREET 2020', (October), pp. 1–12.

Wood Mackenzie (2022) *Global lithium-ion battery capacity to rise five-fold by 2030 | Wood Mackenzie*. Available at: https://www.woodmac.com/press-releases/global-lithium-ion-battery-capacity-to-rise-five-fold-by-2030/ (Accessed: 19 August 2022).

World Bank (2014) *Electric power transmission and distribution losses (% of output)*. Available at: https://data.worldbank.org/indicator/EG.ELC.LOSS.ZS (Accessed: 4 November

2021).

Xu, C. *et al.* (2020) ‘Future material demand for automotive lithium-based batteries’, *Communications Materials*, 1(1). Available at: https://doi.org/10.1038/s43246-020-00095-x.

Yang, Y. *et al.* (2022) ‘Life Cycle Prediction Assessment of Battery Electrical Vehicles with Special Focus on Different Lithium-Ion Power Batteries in China’, *Energies*, 15(15). Available at: https://doi.org/10.3390/EN15155321.

Zackrisson, M. (2016) ‘Life cycle assessment of long life lithium electrode for electric vehicle batteries-5Ah cell’, *Swerea IVF, Mölndal, Sweden, Project Report 24603* [Preprint]. Available at: www.swereaivf.se (Accessed: 18 January 2023).

Zackrisson, M., Avellán, L. and Orlenius, J. (2010) ‘Life cycle assessment of lithium-ion batteries for plug-in hybrid electric vehicles – Critical issues’, *Journal of Cleaner Production*, 18(15), pp. 1519–1529. Available at: https://doi.org/10.1016/J.JCLEPRO.2010.06.004.