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Lithium-Ion Vehicle Battery Production

Status 2019 on Energy Use, CO_2 Emissions, Use of Metals, Products Environmental Footprint, and Recycling

Erik Emilsson, Lisbeth Dahllöf

In cooperation with the Swedish Energy Agency

Author: Erik Emilsson, Lisbeth Dahllöf, IVL Swedish Environmental Research Institute
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Photographer:
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IVL Swedish Environmental Research Institute Ltd.
P.O Box 210 60, S-100 31 Stockholm, Sweden
Phone +46-(0)10-7886500 // www.ivl.se

This report has been reviewed and approved in accordance with IVL's audited and approved management system.

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Summary

This report is an update of the previous report from 2017 by IVL: Life Cycle Energy Consumption and Greenhouse Gas Emissions from Lithium-Ion Batteries (C243). It has been financed by the Swedish Energy Agency.

A literature study on Life Cycle Assessments (LCAs) of lithium-ion batteries used in light-duty vehicles was done. The main question was the greenhouse gas (GHG) emissions from the production of the lithium-ion batteries for vehicles. A search for standardization of LCA methodology and new information regarding recycling, and information on the supply risks for important lithium-ion battery materials was also included in the literature study.

The data is presented as GHG emissions expressed as CO_2-equivalents, in relation to the batteries' storage capacity, expressed as kWh storage capacity. Based on the new and transparent data, an estimate of 61-106kg CO_2-eq/kWh battery capacity was calculated for the most common type, the NMC chemistry. The difference in the range depends mainly on varying the electricity mix for cell production. If less transparent data are included the maximum value is 146kg CO_2eq/kWh. The calculated range is substantially lower than the earlier 150-200kg CO_2-eq/kWh battery in the 2017 report. One important reason is that this report includes battery manufacturing with close-to 100 percent fossil free electricity in the range, which is not common yet, but likely will be in the future. The decrease in the higher end of the range is mainly due to new production data for cell production, including more realistic measurements of dry-room process energies for commercial-scale factories, and solvent-slurry evaporation estimates that are more in line with actual production. The former range also included emissions from recycling which was about 15kg CO_2-eq/kWh battery, which is not included in the new range.

Regarding standardization of LCA, Product Category Rules (PCRs) are published for their Product Environmental Footprint developed by the European Commission.

The average nickel-content is expected to increase and cobalt-content to decrease in newer batteries as the batteries that are produced are expected to move towards higher energy density and away from cobalt, which is at supply risk. The supply of nickel may in future also become at risk.

The PEF benchmark reports that twelve percent of the total GHG emissions for batteries is in the end of life stage in Europe.

There is still a need for more data, especially since the different production steps can be performed in different ways with different efficiencies. Also, data for electronics production still needs to become better. A standardized way for data collection is recommended, for example by using the Product Environmental Footprint Category Rules (PEFCR). Furthermore, more information on the metals supply chains is needed, as well as better traceability, so that sustainable production can be achieved and guaranteed.

Sammanfattning

Denna rapport är en uppdatering av den tidigare rapporten från 2017 från IVL: Life Cycle Energy Consumption and Greenhouse Gas Emission from Lithium-Ion Batteries (C243). Denna uppdatering har, liksom den tidigare, finansierats av Energimyndigheten.

En litteraturstudie av livscykelanalyser (LCA:er) av litiumjon-batterier som används i lätta fordon gjordes. Huvudfrågan var växthusgasutsläppen (GHG) från produktion av litiumjon-batterier för fordon. En sökning efter standardisering av LCA-metodik och ny information angående återvinning samt om försörjningsrisker för metallerna i litiumjon-batterierna ingick också i litteraturstudien.

Data rapporteras som växthusgasutsläpp uttryckt i CO_2-ekvivalenter, i förhållande till batteriernas lagringskapacitet, uttryckt som kWh lagringskapacitet. Baserat på de nya och transparenta data beräknades ett intervall på 61–106 kg CO_2-ekv / kWh batterikapacitet för den vanligaste typen, NMC-kemi. Intervallet beror främst på variationen i elmix för cellproduktion. Om mindre transparenta data ingår är maximivärdet 146 kg CO_2-ekv / kWh. Detta intervall är väsentligt lägre än det tidigare 150–200 kg CO_2-ekv / kWh-batteriet i 2017-rapporten. En viktig orsak till skillnaden är att vi inkluderat batteriproduktion med nära nog fossilfri el-användning i spannet. Att den övre gränsen sjunkit beror främst på nya produktionsdata för cellproduktion, vilket inkluderar mer realistiska mätningar av energiförbrukningen i fabrikernas ”dry-rooms” i kommersiell skala samt en mer verklighetstrogen modellering av energin som går åt för att indunsta lösningsmedlet i anoden. Det tidigare intervallet inkluderade också emissioner från återvinningen, som var cirka 15 kg CO_2-ekv / kWh, vilket inte det nya gör.

När det gäller standardisering av LCA har produktkategoriregler (PCR) publicerats för batteriernas produktmiljöavtryck som utvecklats av Europeiska kommissionen, Product Environmental Footprint Category Rules (PEFCR).

Det genomsnittliga nickelinnehållet förväntas öka och koboltinnehållet minska i nyare batterier, eftersom batterierna som produceras förväntas röra sig mot högre energitäthet och bort från kobolt, som är kritiskt ur ett försörjningsperspektiv. Försörjningen av nickel kan i framtiden också bli kritisk.

PEF-studien rapporterar att cirka tolv procent av de totala utsläppen av växthusgaser för batteriets livscykel uppstår vid återvinningen.

Det finns fortfarande ett behov av mer data, särskilt eftersom de olika produktionsstegen kan utföras på olika sätt med olika effektivitet. Dessutom måste data för elektronikproduktion fortfarande bli bättre. Ett standardiserat sätt för datainsamling rekommenderas, till exempel genom att använda produktkategorireglerna som tagits fram av Europeiska kommissionen (PEFCR). Dessutom behövs mer information om metallförsörjningskedjorna samt bättre spårbarhet, så att hållbar produktion kan uppnås och garanteras.

Abbreviation	Phrase and/or Definition
ANL	Argonne National Laboratory
BatPaC	Battery Performance and Cost – Argonne National Lab. A model that can quickly calculate an estimate of battery costs.
BEV	Battery Electric Vehicle
BOM	Bill of Materials
BMS	Battery Management System
CO_2-eq	Carbon dioxide equivalents
GHG	Greenhouse Gas
GREET	The Greenhouse gases, Regulated Emissions, and Energy use in Transportation Model – Argonne National Lab (ANL, 2018) https://greet.es.anl.gov/. Latest version is from October 2019.
GWP	Global Warming Potential
HEV	Hybrid Electric Vehicle
ICEV	Internal Combustion Engine Vehicle
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LFP	Lithium Iron Phosphate
LMO	Lithium Manganese Oxide
NCA	Lithium nickel cobalt aluminum oxide
NMC	Lithium manganese cobalt oxide
NMP	N-methylpyrrolidone
PCR	Project Product Category Rules
PHEV	Plug-in Hybrid Electric Vehicle

1 Introduction

This project was financed by the Swedish Energy Agency (Energimyndigheten) as an update to a previous IVL report from May of 2017. (Romare & Dahllöf, 2017) The report focuses on the energy consumption and Greenhouse Gas (GHG) emissions from the production of lithium-ion batteries for light-duty vehicles. Additionally, some of the scarce resources used in batteries will also be discussed.

The automotive trends for Sweden, and other EU countries, indicate an increase in the market for battery-powered cars both globally (IEA, 2018), for the Nordic countries, as well as Sweden separately (IEA/OECD, 2017). With this increased demand for battery electric vehicles (BEV) and plug-in hybrid electric vehicles (PHEV) there is a resulting increase in the demand for lithium-ion batteries. With battery developments in the past decades, lithium-ion batteries can provide enough power and energy in a single charge to make the driving experience in a BEV comparable to a car with a gasoline or diesel engine.

In the past decades, the increased awareness of climate change and the limited supply of fossil fuels has created a need for alternative energy sources for vehicle propulsion. A BEV produces zero tailpipe emissions during its normal use (Ellingsen & Hung, 2018). However, to make its total lifetime emissions comparable to a gasoline or diesel internal combustion engine vehicle (ICEV) an in-depth analysis of the battery emissions must also be considered. The battery materials and battery production are known to be major contributors to GHGs for several years (Ellingsen & Hung, 2018) (Yuan, et al., 2017). The emissions of the sourcing of materials, manufacture of the cells, compiling of the battery pack, are therefore of high interest for the proper comparison between BEVs and ICEVs, as well as the methodology of the life-cycle assessments (LCA) that are used for comparison.

The 2017 report estimated 150-200kg CO_2-eq/kWh as the likely value of GHG emissions measured as global warming (GWP) to produce lithium-ion batteries. The report was an LCA review, with an estimate of the GWP-value based on the perceived precision and transparency of the data from the other authors of scientific articles or reports. This new report uses scientific articles, reports and information on car manufacturers' websites to estimate the GWP.

Recycling has also become a relevant issue in recent years, especially regarding some of the metals that are found in the electrodes of the different lithium-ion battery chemistries. Some metals like lithium, cobalt, and nickel are crucial to produce the increasing amount of lithium ion batteries and may therefore be at supply risks. The metals used are often unevenly distributed around the world, meaning that battery manufacturers are extra sensitive to supply chain disruptions. Additionally, the mining of these metals is often the cause of both environmental and societal damage to varying degrees. Due to these supply issues, recycling has become something that most countries consider necessary for the continued adoption of lithium-ion batteries today and into the future.

2 Scope and Method

Several studies have reported that battery production is a major contributor to a BEV's energy use during its life cycle (Ellingsen & Hung, 2018) (Yuan, et al., 2017). Our goal was to investigate the causes for the high energy usage and attempt to find a reliable estimate based on recent studies.

A literature study and web search were done with the objective to update the production GWP for battery production. The focus was to find new data that provides further insight into the lifecycle energy consumption and GHG emissions of lithium-ion batteries today.

The likely energy mixes and energy requirements for the different production steps are considered. These are used as a basis for the calculations of energy consumption and GHG emissions.

In addition to the update of the battery production GHG emissions we also researched the lithium-ion battery materials that are at a supply risk.

Some additional points on the methodology are:

- The functional unit is kg CO_2-equivalents/kWh battery capacity. Less emphasis is placed on studies that used a different one because changing the functional unit means that the methodology is different and the studies incomparable in most regards.
- The system boundaries for the estimate of battery GWP is cradle-to-gate, thus the recycling energy or credits is not included in the battery emissions estimation.

We also studied how LCAs are made generally, and specifically we report on the new Product Environmental Standard developed by EU. One example is the product category rules (PCRs) developed specifically for lithium-ion batteries for vehicles.

Regarding news on recycling we summarized the current status with the information we got with another study IVL recently finished for the Nordic Council of Ministers (Dahllöf, et al., 2019).

2.1 Limitations

In this study there is no comparison between BEVs to ICEVs as the LCAs only pertain to a single component. A comparison between BEVs and ICEVs requires a comprehensive LCA including the car manufacturing and fuel or energy sourcing as well as considerations of the differences in usage due to differences in fueling or charging, maintenance (including part replacement). As such, the system boundaries and the functional unit are different in BEV LCAs than in battery LCAs. For these reasons, the authors would like to highlight that the estimates in this report are insufficient in themselves to draw any type of conclusions on comparison between BEVs and ICEVs regarding emissions.

The search was limited to current battery technologies, manufacturing techniques, and common energy mixes. The divisions of the different metal extraction and refining steps, and cell and battery pack manufacturing steps may be slightly different in this report than the original, but the energy use and GWP will be comparable as the system boundaries and functional units are the same.

The battery chemistries will be limited to the most common chemistries in BEVs and PHEVs today. Advances in battery technologies are happening at a rapid pace today, but only the lithium-ion battery chemistries will be discussed in this report.

GWP is used to measure the GHGs. In this report we do not include emissions that cause effects of air quality or toxicological effects that may be caused from the release of chemicals and gases in each of the production steps.

3 Literature Review

3.1 Car manufacturers' LCAs

A Google search for published data on LCA and GWP from car manufacturers was done to attempt to find useful data and to investigate the quality of information presented to the public with respect to lithium-ion traction batteries. Generally, car manufacturers do not disclose high detail on the production of batteries in their LCA reports or certificates.

There are a few LCA-results available from car manufacturers online. The sizes of the cars vary. The age span of the LCAs exceeded five years with the most recent one published in 2016. These reports show a varying amount of information disclosed on the specifics of the LCA, and generally the information is limited. Only one of the reports described the GWPs of the battery as separated from the rest of the BEV or PHEV. Only for the 2012 Volkswagen Golf blue-emotion did we manage to recalculate a GWP in the functional unit of kg CO_2-eq/kWh battery capacity, see Table 1.

Table 1. Data from tables and graphs in the respective reports for each car model. (1)

Car model	Powertrain	Cradle-to-grave car production GWP [ton CO_2-eq/lifetime]	Battery capacity [kWh]
2012 Volkswagen Golf blue-emotion concept car (2)	BEV	13	27
2013 Volkswagen e-up!	BEV		19
2016 Mercedes-Benz E-Class E 350 e Saloon	PHEV	10	6
2015 Mercedes-Benz C-Class C 350 e	PHEV	8	6
2014 Mercedes Benz B-Class Electric Drive	BEV	9	28
2012 Smart fourtwo electric drive	BEV	8	18
2013 BMW i3	BEV	57 percent of lifetime GWP, including End-of-Life	19
2014 BMW i8	PHEV	45 percent of lifetime, including End-of-Life	7

(1) (Volkswagen Group, 2012), (Volkswagen Group, 2013), (Daimler AG, 2016), (Daimler AG, 2015), (Daimler AG, 2014), (Daimler AG, 2012), (BMW AG, 2013), (BMW AG, 2014)

(2) 153kg CO_2-eq/kWh battery capacity was calculated from the data, using some assumptions about the car model.

Unfortunately, the low transparency of the data in these reports combined with the difficulty of separating the battery production emissions from the BEV and PHEV lifetime emissions, makes these car manufacturer's data incomparable to the data in the rest of this report.

3.2 Reports and Scientific Articles

The specific reports and articles studied in the survey are included because they:

- provide new data on process energies that they measured or bills of materials on batteries,
- provide new insights into battery manufacturing and the supply chain,
- model process energies with new data from pilot facilities, and
- provide information on the standardization of calculation methodologies.

Figure 1 shows a timeline of several sources included in the study. Most sources were scientific articles, but several reports have also been used. Further descriptions of the sources can be found in the Appendix.

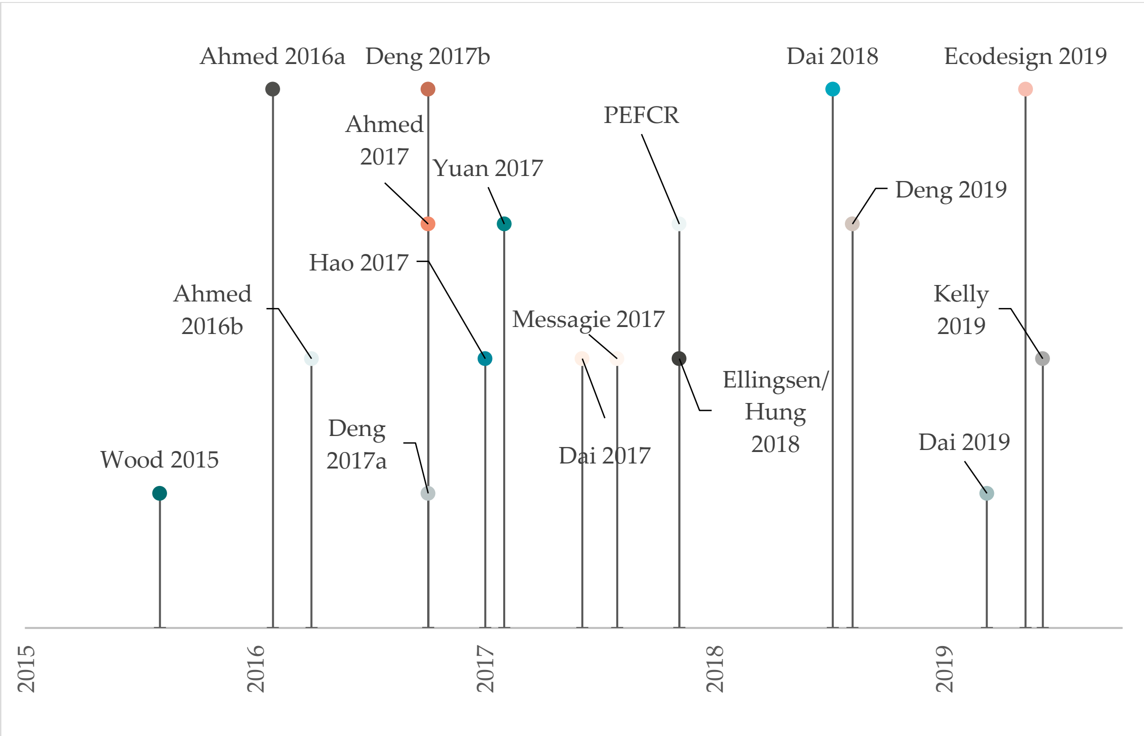

Figure 1. Timeline of several sources of information for this study, mainly scientific articles.

The research that became the base for the estimated CO_2-emissions from car battery production is found in the following sub-chapters.

3.2.1 Publications from Argonne National Laboratory

Several publications from Argonne National Laboratory (ANL) have been published recently(Dai, et al., 2017) (Dai, et al., 2018a) (Dai, et al., 2018b) (Dai, et al., 2019) (Kelly, et al., 2019). ANL is sponsored by the United States Department of Energy and is responsible for The Greenhouse gases, Regulated Emissions, and Energy use in Transportation Model (GREET) model (ANL, 2018) and the Battery Performance and Cost (BatPac) models.

The *Update of Life Cycle Analysis of Lithium-Ion Batteries in the GREET Model* (Dai, et al., 2017) focused on battery production and cathode materials production. It provided energy consumption comparisons to several other sources (such as Wood et al. (2014) and Ahmed et al. (2016a) (2016b), (2017)) with their own measurements from two manufacturers and one recycling facility in China (Dai, et al., 2017). They conclude that battery production (not including sourcing of materials) consumes 170MJ/kWh battery capacity with 30MJ from electricity and 140MJ from natural gas. They also found that the battery recycler they visited recovers nickel, manganese and cobalt from lithium-ion batteries.

Two other articles by Dai et al. updated the cobalt supply chain and the bill-of-materials (BOM) of several cathode materials (2018a) (2018b).

The article *Life Cycle Analysis of Lithium-Ion Batteries for Automotive Applications* compiles the data from the earlier work by ANL to provide their estimate of the GWP (in kg CO2-eq/kWh capacity) for NMC 111 BEV batteries (Dai, et al., 2019). The article *Globally regional life cycle analysis of automotive lithium-ion nickel manganese cobalt batteries* analyses how realistic variations in electricity mix in different parts of the supply chain affect the GWP (Kelly, et al., 2019).

See more detailed descriptions of these articles from ANL in the Appendix.

The newest article regards the update of the GREET model 2019 (Dai & Winjobi, 2019) and some information about the new data is found in chapter 4.1.

3.2.2 PEFCR

EU has developed Product Environmental Declaration methodology to make it possible to compare similar products from an environmental point of view. The system is currently in the transition phase which is before the adoption of policies implementing phase. (European Commission, 2019a) One of the pilot product types was "High Specific Energy Rechargeable Batteries for Mobile Applications" where lithium-ion batteries for vehicles were included. Therefore, there are product category rules (PCRs) for LCAs for them and also available data (RECHARGE, 2018) (European Commission, 2019). It will henceforth be denoted as Product Environmental Footprint Category Rules (PEFCR) in this report.

Through some calculations, a figure that could be used for comparison with other battery production GWPs was obtained. See the Appendix for the calculations. Note that some proxies had to be used in the calculations of the PEFCR benchmark figures due to lack of some data. They are found in Table 2. Proxies to be used according to the PEFCR . For this reason, the CO_2 emissions from battery manufacturing may be under- or overestimated to a larger extent than if no proxies were used.

Table 2. Proxies to be used according to the PEFCR (2018).

Data gap	Proxy to be used according to PEFCR
Stainless steel slab (X6CrNi17)	Recycling of steel into steel scrap: Steel billet (St)
Cobalt sulfate	Cobalt production (global)
Nickel hydroxide	Nickel production (global)
Lithium Hexafluorophosphate	Lithium hydroxide production (global)
Manganese sulfate	Manganese production (global)
Switch PCB (EPTA)	Populated Printed wiring board (PWB) (2-layers)
Plastic granulate secondary (low metal contamination	Not available, select data according to hierarchy mentioned in the PEFCR.

Nevertheless, a value of 77kg CO_2-eq/kWh was obtained in our study through a comparison with a modelled NMC 111 battery pack (NMC 111 is equivalent to NMC 333, which is a battery with roughly 30 percent nickel-, 30 percent manganese-, and 30 percent cobalt-content in the cathode). However, the GWP in the PEFCR was for the European benchmark which included manganese, nickel, cobalt and aluminum in the cathode (a mix of different typical battery cathode chemistries) and no iron phosphate. This estimate included a European energy mix for the cell production and pack assembly steps. This is a methodological uncertainty regarding battery chemistry but it can be accepted for an approximate result since NMC 333 is common and energy use in cell production is very much dependent on the energy use for the dry-rooms which is a common issue for all chemistries, see chapter 4.3.

The relation between the upstream materials acquisition versus the cell production and pack assembly GWPs reported from the PEFCR benchmark is shown in Figure 2.

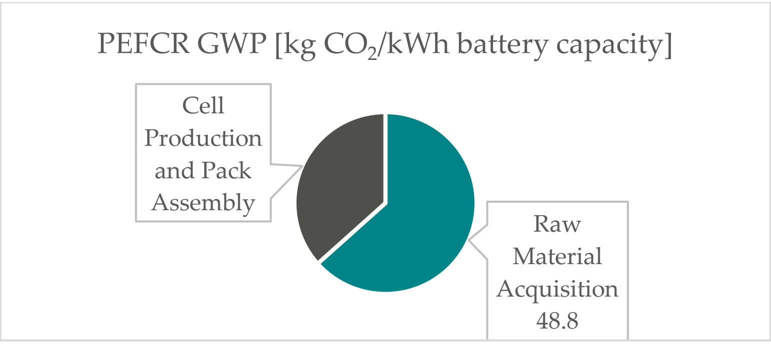

Figure 2. The total GWP of raw material sourcing, cell production and pack manufacture for NMC111 batteries, re-calculated from PEFCR (2018). This was recalculated from a different functional unit (energy per kWh of the total energy provided over the service life by the battery system), since the PEFCR measures the entire BEV battery lifetime. 26 percent of the total GWP was raw material sourcing.

3.2.3 Ecodesign 2019

A report for Ecodesign and Labelling also did a lifetime-battery emissions analysis (Lam, et al., 2019). The results are presented in Table 3. Unfortunately, the data is not as transparent, and the description of the process steps is not as descriptive as the publications from Argonne National Laboratory or the PEFCR. It is unclear what the battery chemistry is in the three cases in the report and what assumptions are made between the BEV and the PHEV. Some of the information presented in the report can be found in the Appendix.

Table 3. GWP for battery manufacturing in the Ecodesign report for the three base cases (Lam, et al., 2019). It is unclear if the Ecodesign report's energies include materials processing.

	GWP [kg CO_2-eq/kWh capacity]		
	BC1 (BEV)	**BC2 (BEV)**	**BC3 (PHEV)**
Raw materials	70.57	70.57	93.98
Manufacturing	36.96	36.96	51.93
Total Production	107.53	107.53	145.91

4 Energy and GWP in different steps of Battery Production

The impacts are divided in the following steps as shown in Figure 3. These steps are:

- Mining & Refining
- Battery Material Production
- Cell Production & Battery Pack Assembly

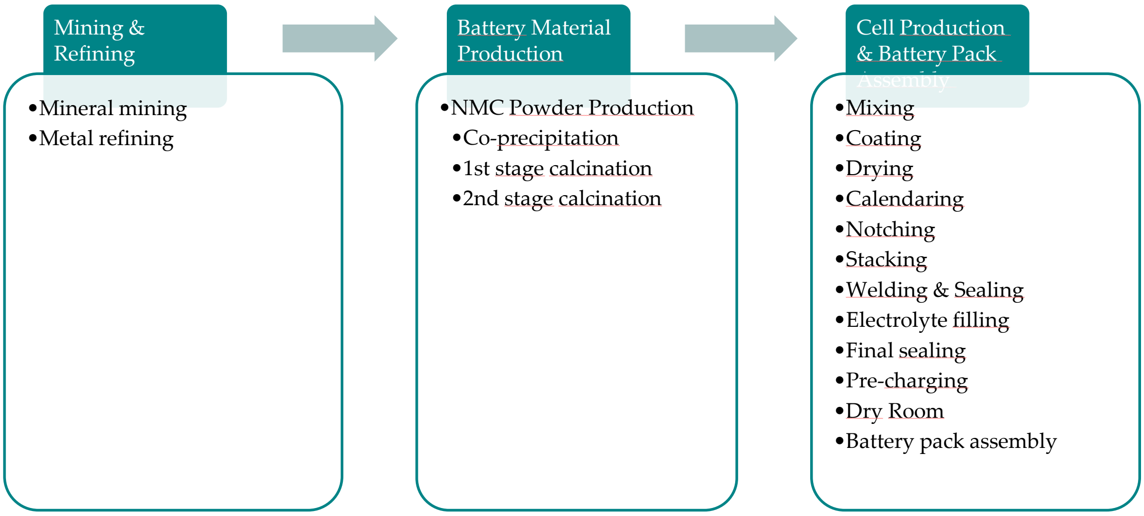

Figure 3. A very simplified outline of the steps in battery production. The main steps are on top and some of the more energy-demanding sub-steps in each step are included below. Based on EPA (2013), Dai et al. (2018b), and Yuan et al. (2017).

The steps may differ between two batteries produced in the same continent, country, or even factory. One reason for this is due to differences in material sourcing. There is also often more than one chemical process pathway to obtain the desired product. The transportation methods and routes can also be very different for different sources of the same type of material.

Mining and refining often occur in separate locations and the material refining for one material can be done in several smaller refining steps (Dai, et al., 2018a). Cell production occurs in a laboratory facility that needs strict controls on humidity, temperature, and cleanliness. Battery pack assembly can be done by the cell manufacturer or the battery pack components can be assembled by the automobile manufacturers (Ellingsen & Hung, 2018). Pack assembly doesn't have the same stringent requirements as cell production as the most sensitive parts have already been sealed in the cell production step (Ellingsen, et al., 2014) (Dai, et al., 2019).

Since different steps can occur in different locations, the choice of the local energy mixes for each processing step will affect the resulting GWP. Naturally, the choice of energy mix becomes more critical for the steps that require more energy, because the final GWP-value depends the most on their values.

The previous report commented on the lack of information of the technology steps required for battery production (Romare & Dahllöf, 2017). Contributions from several authors, summarized in Figure 1 have increased the available information on battery production since then.

4.1 Mining & Refining

Several metals are required for the different battery chemistries. Essentially all BEVs for cars today use NMC or NCA chemistries, and both chemistries require the critical mineral cobalt, in addition to other metals such as lithium, nickel, copper, aluminum.

In 2018, Argonne released updates to the cobalt chemicals and cobalt metals (Dai, et al., 2018a). In the report it can be found that energy use in different mines can differ greatly depending of type of mine and ore. The only energy reported from one mine, the diesel use, was 163kWh/ton mined ore of 0.32% cobalt and the other mine reported electricity as the only energy use: 61.7kWh/ton mined ore of 0.51% cobalt, which is interesting information since the data in the GREET model does not report the variation. There are also new data for the production of lithium hydroxide and nickel sulphate, but the mining data are not new; it is the calculation that has changed (Dai & Winjobi, 2019).

4.2 Battery Material Production

Dai et al. have added some battery materials production in their BOM update for 2018 (2018b). The document describes the cathode materials and precursors materials and process energy requirements per kg of material produced for NMC, LCA, and LCO batteries. Their data is used in a report by Dai et al. from 2019 for NMC 111 batteries where they have calculated the energy requirements for both the materials and co-precipitation and calcination for the production of NMC 111 powder to be used in the cell production. The relative energy requirements for each are presented in Figure 4. The major energy users are the co-precipitation and calcination processes and $CoSO_4$. The production of the nickel-rich materials was identified as the most energy intensive by Dai et al. (2018a).

The co-precipitation and calcination are discussed in more detail in preceding publications (Ahmed, et al., 2017) (Dai, et al., 2017) (Dai, et al., 2018b). There are several other steps required to produce the battery materials, and presumably these are chosen because they are towards the end of cathode powder production and because they are very energy-intensive steps.

The co-precipitation step produces cathode precursor from metal sulfates (e.g. $CoSO_4$). Dai et al. calculated the steam consumption, which was at 200 degrees Celsius, for each type of precursor and translated it to energy consumption (2018b). The authors visited a plant which produced cathode powder from the cathode precursor (the calcination step), but the owner of the plant also owned a cathode precursor production plant (the co-precipitation step) and provided them with an environmental protection inspection and monitoring report (Dai, et al., 2018b).

The calcination step produces cathode powder from the cathode precursor produced from co-precipitation. The calcination step requires heating of a calcination kiln to temperatures over 1000 degrees Celsius for over 12 hours (Dai, et al., 2018b). In the plants visited by Dai et al., the kilns are run over night because they take too long to reach operating temperature from start-up (2018b). Two-stage calcination is needed for traction applications for NMC and NCA cathodes, and three-stage calcination is also possible for some cathode materials (Dai, et al., 2018b). The more steps that are required, more energy is consumed in this step of material processing. Also, NCA and NMC 811 cathode materials require slightly more electricity than NMC 111, while also requiring an input of LiOH instead of the Li_2CO_3 to produce the cathode powder (Dai, et al., 2018b).

There are also non-combustion process emissions in the GREET 2018 for calcination in cathode material production (Dai, et al., 2018b). The mining of metals can also produce non-combustion emissions (Dai, et al., 2018a) which are not accounted in our estimate because we are only considering the combustion process emissions.

The processing energy consumption of producing cathode active material was found to be very similar for NMC 333, NMC 622, NMC 532, NMC 811, and LMO and NCA. The maximum difference is about two percent according to modelling by Ahmed et al. (2017).

Figure 4 shows the percentage energy used for sourcing of precursors and process energies to produce NMC 111 powder and Figure 5 shows the energy use for the cathode powder production relative to cell production, NMC 111 powder and electronics. The other battery materials make up a large portion of the energy requirements for lithium-ion batteries.

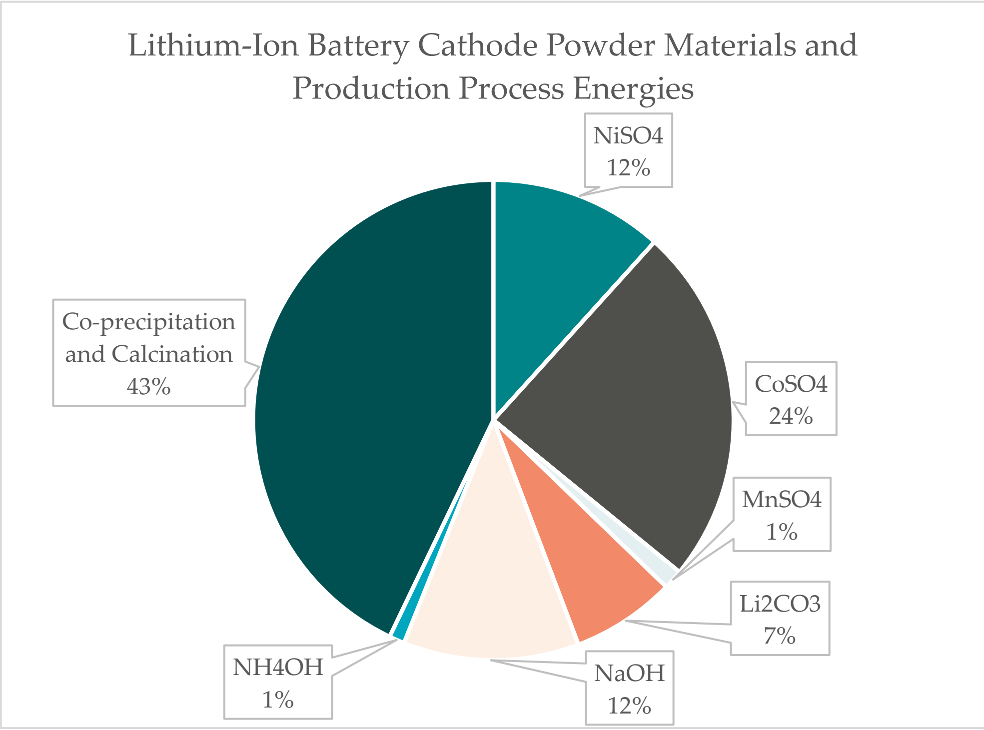

Figure 4. The percentage energy used for sourcing of precursors and process energies to produce NMC 111 powder which is later used in the cathode in cell manufacture. Data from Dai et al. (2019).

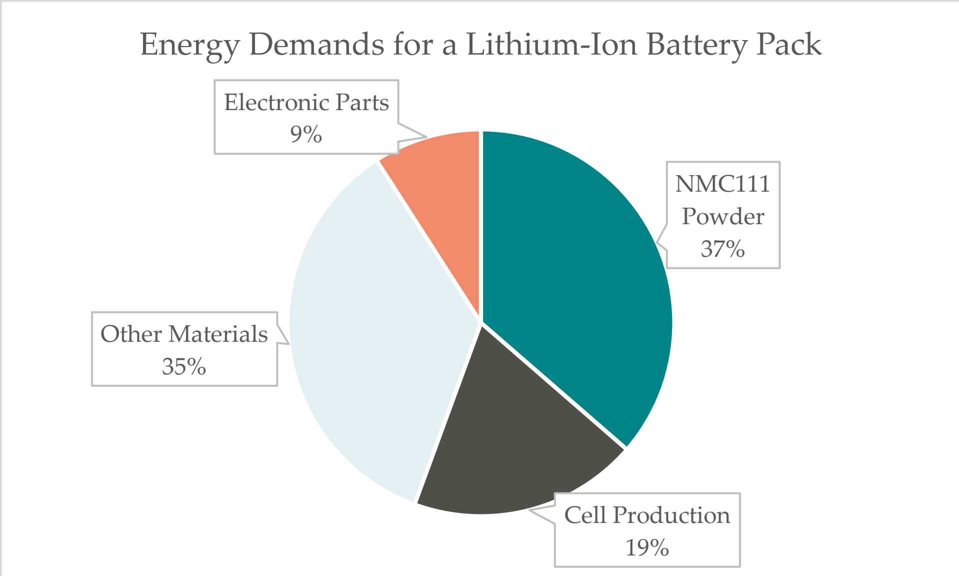

Figure 5. The percentage energy used for battery pack materials for NMC 111 lithium-ion batteries and cell production. Note that the energy for battery pack assembly is not included. Data from (Dai, et al., 2019). The materials in the 'Other Materials' are found in Table 4.

NMC111 powder material requires most of the energy for the battery pack, followed by 'Other Materials', cell production, and finally electronic parts. (Dunn, et al., 2015) wrote that for non-pioneer plants, the materials' production stage will likely be the driving impact for batteries. This is seen to some extent from the relatively low energy consumption reported from commercial production data by Dai et al. (2019) for cell production (19 percent) energy.

Table 4 details the materials and process energies required for cathode powder materials.

Table 4. Shares of energy consumption of materials, cell production and battery pack assembly per kg battery. Numbers from Dai et al. (2019).

	Material/process	Share of energy [%]
Cell components	NMC111 powder	45.0
	Graphite	9.74
	Carbon black	1.18
	Binder Polyvinylidene fluoride (PVDF)	0.60
	Copper	3.92
	Aluminum	5.57
	Electrolyte: Lithium hexafluorophosphate (LiPF6)	2.23
	Electrolyte: Ethylene carbonate (EC)	0.35
	Electrolyte: Dimethyl carbonate (DMC)	1.30
	Plastic: Polypropylene (PP)	0.67
	Plastic: Polyethylene (PE)	0.16
	Plastic: Polyethylene Terephthalate (PET)	0.12
Module components	Copper	0.09
	Aluminum	4.10
	Plastic: Polyethylene (PE)	0.07
	Insulation	0.01
	Electronic parts	2.09
Pack components	Copper	0.02
	Aluminum	12.7
	Steel	0.15
	Insulation	0.09
	Coolant	0.66
	Electric parts	9.16

4.3 Cell Manufacturing and Battery Pack Assembly

Cell manufacturing consists of several processing steps that eventually produce battery cells. Battery pack assembly is the assembly of the cells with other components, such as the cooling system, battery management system, and pack packaging (Yuan, et al., 2017).

The increased demand for batteries has increased awareness in battery manufacturing, and as a result more accurate data has been collected and more processes are included in the energy use. Assumptions were made by earlier LCAs that underestimated the energy required for the dry-room energy requirement, which decreased the calculated energy impact of battery production (Ellingsen, et al., 2017). Several newer sources note that the energy use in the dry room for cell production is substantial in comparison to other sources of energy use in lithium-ion battery production (Ahmed, et al., 2016b) (Dai, et al., 2017) (Yuan, et al., 2017). Yuan et al. conducted energy measurements of several process steps in the battery pack production in a pilot scale plant and they found the dry room and NMP-drying to be major contributors to process energy use in cell and pack manufacturing, see Figure 6.

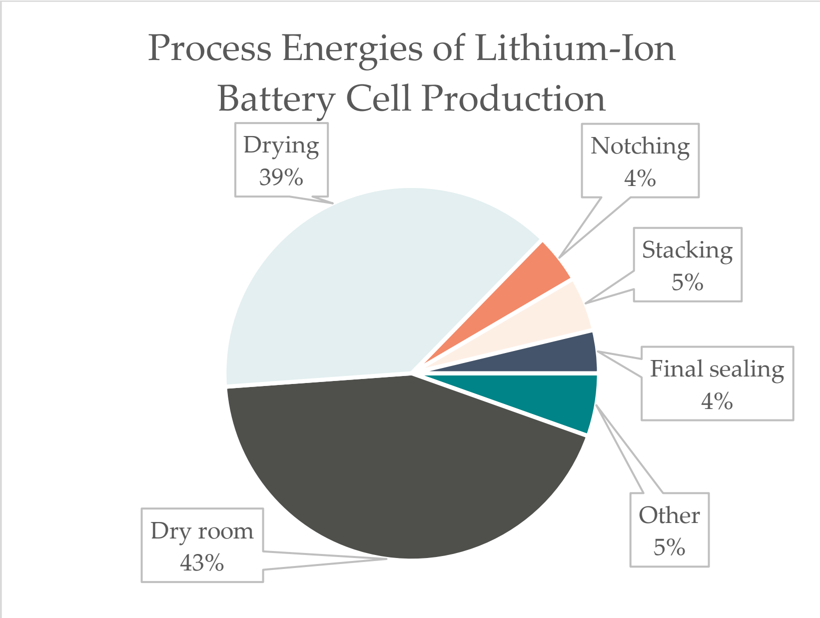

Figure 6. Circle diagram with different sources' energy contributions to the total cell production and battery pack assembly energy. Data from Yuan et al. (2017). The processes included in 'other' are: mixing, coating, calendaring, welding & sealing, $LiPF_6$ (electrolyte) filling, and pre-charging. It is clear here that running dry room equipment and NMP-drying are significantly larger contributors to process energy use than the sources.

In their study, Ahmed et al. found that the amount of air needed has the greatest effect on the differences in energy uses in dry rooms (Ahmed, et al., 2016b), meaning that more voluminous dry-rooms require more energy. Also, the moisture content of the outside air has a direct correlation with the amount of energy required to keep the air dry in the dry room. The authors write that the air entering from the outside can vary significantly and cause significant changes to the energy use of operations. Ellingsen & Hung noted that some regions in China have annual periods of intense rainfall and warm climate, resulting in humid air that requires more energy to remove the water content (Ellingsen & Hung, 2018). Heat pumps and condensers need to do more work in warm and/or humid areas than cold and/or dry areas to keep the air entering the dry-room at acceptable humidity and temperature. Since the dry-room is so energy-intensive, it can be expected that the cell factory location has a noticeable impact on the total cell-manufacturing energy use.

For batter pack assembly, Dai et al. found that it was done manually in the factory they visited in China and they also noted that any energy used in the assembly step would be trivial compared to the energy used for the cell manufacturing (Dai, et al., 2017). If the assembly is automated or semi-automated, then the electricity required will not be very high.

Pack manufacture and assembly was found to be between 0.5-1.2 percent of the battery energy-requirement in the previous IVL report (Romare & Dahllöf, 2017).

4.3.1 Drying NMP in anode is more energy intensive than water

The solvent for both the anode and cathode can be either NMP or water, and it needs to be evaporated from the cell before the sealing. NMP is flammable and therefore its drying process requires a large amount of heated air-flow to evaporate the gas and simultaneously keep it from being an explosive hazard (Wood III, et al., 2014). This makes it a considerable contributor to the energy required in cell manufacturing.

It is common practice to use NMP in the cathode and water in the anode (Dai, et al., 2019). Previously, Wood III et al. wrote that Japan and South Korea almost exclusively use water in anodes (Wood III, et al., 2014). However Dai et al. (2019) note that Ellingsen et al.'s (2014) LCA estimation of the energy required for drying is likely an overestimation due to their assumption of NMP being used in the anode instead of water .

In theory, either NMP or water can be used as a solvent for both the cathode and the anode. However, today NMP is most commonly used in the cathode slurry instead of water because of the difficulty of dispersing the electrode materials properly. Wood et al. and other authors write that switching to water in the cathode will save large amounts of energy in the cell manufacturing stage (2014) (Dai, et al., 2017). However, we have not found any indications that this is done in plants today.

It is common practice to recover and reuse NMP due to high costs and safety and environmental concerns (Dai, et al., 2019). Less NMP consumed also means that it contributes less to GHG emissions. An estimated of 98 percent of NMP solvent is used in Deng et al.'s calculations, albeit this number is provided for lithium-sulfur batteries (2018). We expect a similar fraction is recycled for lithium-ion batteries.

4.3.2 Cell Formation Cycling Losses

Formation cycling is a production step that requires electricity for the charging and discharging before the batteries can be used in cars. It is not the same as charging the battery in the use-phase, and the energy losses from this step are separate from the energy losses during charging and using the battery. It is required for the battery to function.

Dai et al. estimated a ten percent charge/discharge loss for a 1.2kWh/kWh battery capacity (2017). Deng et al. estimated a four percent charge/discharge loss (Deng, et al., 2017a). Energy is lost for each cycle and the level of charging/discharging also affects the energy lost.

One concern is that formation cycling energy may not be reused in practice. If that is the case, there is potential for a significant increase in the energy used for this step of cell production

4.3.3 Cell Factory Equipment Energy Consumption

Some processing equipment cannot be practically switched off without affecting the production. An example is the calcination kilns which run 24/7 in the plants visited by (Dai, et al., 2018b).

Some equipment consumes about the same amount of energy regardless of the amount of materials going in or out, such as the over-dimensioned calcination kilns in the battery production plant visits by (Dai, et al., 2019) and the likely the dry-room (Dunn, et al., 2015).

Wastewater treatment, as pointed out by Dai et al. (2019), may be mandatory in factories. We interpreted that they include wastewater treatment in the co-precipitation step from the 2018 GREET BOM-update (Dai, et al., 2018b), which they state can be a large energy consumer at 45 percent of the heat demand for co-precipitation.

4.3.4 Heat Consumption

Heat energy needed for cell production has been reported to come from either natural gas, steam, or electricity (Dai, et al., 2017). Dai et al. chose natural gas as the source of heating for their GREET model inputs, based on their observations of commercial battery factories (Dai, et al., 2019). The emissions from a heat source will depend both on the emissions per energy unit and the effeciency at which the heat can reach the source.

The amount of factory heat recovery also affects the emissions. All other things kept equal, less energy is consumed from factories with good heat recovery.

4.4 Energy Consumption and GHG Emissions from Lithium-Ion Battery Production

The energies for the materials and processes of cell and pack production from Dai et al. (2019) are used to calculate GWPs for different energy mixes. The authors assumedly extrapolated the energies from a factory at 75 percent capacity and then calculated the resulting emissions. Only 30MJ out of 170MJ come from electricity in Dai et al. (2019), and the rest was estimated as heat produced with natural gas.

We did not find information about the electricity mix used by Dai et al., but they likely calculated the emissions from the heating and electricity separately. Their resulting GWP to produce NMC 111 batteries was 72.9kg CO_2-eq/kWh capacity. The results from only the upstream materials sourcing was 59kg CO_2-eq/kWh capacity (Dai, et al., 2019).

The energy for NMP recovery was included in the GREET 2017 battery update for battery production (Dai, et al., 2017). Therefore, we presume that NMP recovery is also included in the 72.9kg CO_2-eq/kWh capacity result. (Dai, et al., 2019).

Note that we combine the energy from heating and electricity in the approximations of the emissions. Different heating configurations in the cell manufacture and battery pack assembly steps are possible. Table 5 presents the GWPs from Dai, et al. (2019).

Table 5. Energy for materials and cell manufacture processes and GWP from the same study. A row for NMP has been added to show that no extra energy is consumed since it is normally recycled. The energy for battery pack assembly is assumed to be insignificant compared to the rest of the energies (Dai, et al., 2019).

Materials and Processes		Energy [MJ/kWh capacity battery]
Cell components	NMC111 powder	409.9
	Graphite	88.6
	Carbon black	10.7
	Binder (PVDF)	5.5
	Copper	35.7
	Aluminum	50.7
	Electrolyte: LiPF6	20.3
	Electrolyte: EC	3.2
	Electrolyte: DMC	11.8
	Plastic: PP	6.1
	Plastic: PE	1.4
	Plastic: PET	1.1
Module components	Copper	0.8
	Aluminum	37.4
	Plastic: PE	0.6
	Insulation	0.1
	Electronic parts	19.0
Pack components	Copper	0.2
	Aluminum	116
	Steel	1.3
	Insulation	0.8
	Coolant	6.0
	Electric parts	83.4
Solvent	NMP (recycled)	0.0
Cell Production and Battery Pack Assembly		216.2
Total		1 127

In Table 6, the entire energy demand from the cell production and battery pack assembly are added to the 59kg CO_2-eq/kWh capacity from upstream materials (Dai, et al., 2019) to give a range of 59 to 119kg CO_2-eq/kWh capacity for a clean and a fossil-fuel rich electricity mix, respectively. Table 7 presents how adjusting the energy mix in cell production can affect the emissions.

Table 6. Energies and emissions of upstream materials and cell production and battery pack assembly. The emissions range for cell production and battery pack assembly are calculated with a renewable electricity mix, estimated at 0kg CO_2-eq/kWh consumed, and a fossil-fuel rich mix, estimated at 1kg CO_2-eq/kWh consumed. For reference, (Dai, et al., 2019) reported 13.85kg CO_2-eq/kWh battery capacity for cell production and 0kg CO_2-eq/kWh consumed for battery pack assembly.

Parts or process	MJ/kWh capacity		kgCO_2-eq/kWh capacity	
	Value	**Source**	**Value**	**Source**
Battery materials upstream	910.6	(Dai, et al., 2019)	59	(Dai, et al., 2019)
Cell production and battery pack assembly	216.2	(Dai, et al., 2019)	0-60	Range: Renewable – fossil-fuel rich electricity mix
Sum of material upstream and cell production and pack assembly.	1 127	Sum	59-119	Sum

The 216.2MJ/kWh capacity for cell production (battery pack assembly being negligible) in Table 6 can be compared to the 350-650MJ/kWh estimated in the 2017 report, which used earlier LCAs as basis for the estimation.

The range of emission values is wide, and we believe that the upper range is an overestimate because electricity is unlikely used for heating in processes that could be heated with more energy-efficient alternatives, such as natural gas or other fuels. However, some exceptions could be if renewables are purposely being used to lower emissions, or if the electricity happens to be cheaper than fuels such as natural gas.

Adjusting only the electricity mix for cell production and battery pack assembly reflects how cell production facilities may influence the emissions. Because only a small portion (30MJ out of 170MJ) of energy use comes from electricity in Dai et al. (2019), varying only the electricity mix will not have a significant effect on the resulting GWP. Since heating can also be from electricity, it is also interesting how the GWP is affected if the heating sources (i.e. emissions from the rest of the 170MJ) were varied. Additional results are presented in Table 7 where the heating comes from natural gas or electricity and the electricity mix is varied from a renewable energy mix to a fossil-rich mix. The fossil-rich mix GWP is similar to the China-mix. See the Appendix for further discussions on the carbon-intensity of some electricity mixes in different countries. Table 8 presents the total battery emissions for these calculations, in which the total range became 61-106kg CO_2-eq/kWh capacity.

Table 7. Scenarios varying only the heat source of cell and pack manufacture. The electricity used is 30MJ/kWh capacity and the heat is 140MJ/kWh capacity from Dai et al. (2019). A kWh is equivalent to 3.6MJ.

Scenarios (different energy source for heat)	Energy sources of cell and pack manufacture	kg CO_2-eq/kWh consumed (1)	GWP, 30 MJ electricity consumed/kWh capacity	GWP 140 MJ heat consumed/kWh capacity	Sum GWP from cell and pack manufacture [kg CO_2-eq/kWh
Scenario 1	Electricity: Renewable mix – fossil-fuel rich mix	0.05–1	0.4–8.3		2–47
	Heat: Electricity, Renewable mix – fossil-fuel rich mix	0.05–1		2.0–38.8	
Scenario 2	Electricity: Renewable mix – fossil-fuel rich mix	0.05–1	0.4–8.3		11–18
	Heat: Natural gas with boiler efficiency 80%. Calculated from (EIA, 2016) (2).	0.26		10.1	

(1) Please note that kWh consumption is the energy consumed during battery production while kWh capacity is the specific energy of the battery.

(2) Calculations: $\frac{53.07\ kg\ CO_2}{million\ Btu} * \frac{1\ million\ Btu}{293{,}07\ kWh} * \frac{100\%\ boiler\ efficiency}{80\%\ boiler\ efficiency} = 0.23 \frac{kg\ CO_2}{kWh\ consumption}$

Table 8. The sum of the results of the two scenarios for cell production and pack assembly from Table 7 and the upstream material GWP from Dai et al. (2019) which was 59kg CO_2-eq/kWh consumed.

Scenario	Energy sources of cell and pack manufacture	Sum GWP from cell and pack manufacture [kg CO_2-eq/kWh	Total GWP [kg CO_2-eq /kWh capacity]
Scenario 1	Electricity: Renewable mix – fossil-fuel rich mix Heat: Electricity, Renewable mix – fossil-fuel rich mix	2–47	61-106
Scenario 2	Electricity: Renewable mix – fossil-fuel rich mix Heat: Natural gas with boiler efficiency 80%.	11-18	70-77

With some design considerations the emissions from heating could potentially be smaller. For instance, waste heat from exothermic processes can be used to save energy in other processes that either require low-temperature heating or that can benefit from pre-heating before using fuel or electricity for higher temperatures. The heat can also be moved outside of the system boundaries of an LCA, for instance as district heating if the factory is connected. Both forms of energy-saving designs require extra pumps and heat-exchangers, which increase the initial costs of purchase and installation, but can break even after some time in energy-savings. The energy savings would have the benefit of lowering the required emissions.

The energy required for the production per kWh battery capacity ranges from 61-106 when varying the electricity mix from a clean (0kg CO_2-eq/kWh) to a fossil-fuel rich (1kg CO_2-eq/kWh) electricity mix for a 100 percent electricity powered cell manufacture and battery pack assembly factory using material sourcing emissions from Dari et al. (2019). With varying the electricity only when natural gas is used for heating, the emissions range from 70-77kg CO_2-eq/kWh battery capacity.

For the top range of 106kg CO_2-eq/kWh battery capacity we consider that on the one hand it is unlikely for electricity to be used for heating if energy savings can be achieved with heating with fuels. On the other hand, we remember that battery assembly may be automated rather than done by hand as the numbers show in (Dai, et al., 2019). This means that there may be some additional electricity required. Taking these two factors into account, a higher range of GWP is kept at 106kg CO_2-eq/kWh battery.

The lower estimate is kept at 61kg CO_2-eq/kWh battery capacity, partly because other sources of heating can be renewable fuels (e.g. biogas), electricity from local and nonlocal sources. All or parts of the required heating energy can come from excess heat from local factories or from other local sources, which would lower the battery production emissions to the lower side of the estimate. Understanding the system boundaries in such a situation would be very important, as it could potentially produce a very low estimate.

For these reasons we estimate a 61-106kg CO_2-eq/kWh battery capacity for lithium-ion battery production from virgin materials.

Using the figures from Dai et al. (2019) for energy consumption of an NMC 111 lithium-ion battery pack and the BOMs from GREET 2018 (Dai, et al., 2018b) and respective specific energies for cathode chemistries for NMC 622 and NMC 811, an estimate was calculated of the difference in total energy consumption and GWP for batteries with NMC 622 and NMC 811 cathodes chemistries. The results show that a decrease a 7 percent decrease in energy consumption and 14 percent decrease in GWP of NMC 811 battery production compared to for NMC 111. Note that although there are notably some differences between the chemistries, these estimates do not account for differences in battery design or process distinctions. See the last section in the Appendix for details on the calculations.

4.5 Comparison with Data in the Previous IVL Report

4.5.1 Battery Grade Materials Production

In Romare and Dahllöf (2017) some data for battery grade materials (including electronics, BMS) were reported. The data from sources had been collected and in table 19 in the report the range was 48-121 kg CO_2-eq/kg battery grade material with 216 as an extreme value. Taking transparency into the judgement, the range became 60-70kg CO_2-eq/kg battery grade material as most likely. Dai et al. (2019) reported 59kg CO_2-eq/kg battery materials upstream (including electronics data). Our calculated value from PEFCR is lower, 48.8kg CO_2-eq/kg raw material.

The previous report also included GHG data for production of different metals and their compounds. In table Table 9 new and older data are reported.

Table 9 Comparison between data reported in Romare and Dahllöf (2017) and data for GREET, 2019 (Dai & Winjobi, 2019)

	From GREET, 2019			From Romare and Dahllöf, 2017	
CO_2-eq /kg product	**Economic allocation**	**Mass allocation**	**Reference**	**GREET 2016**	**Ecoinvent version 3.1**
Refined cobalt oxides	28.51	21.45	Dai et al. 2018		
Cobalt in cobalt salts	24.21	17.15	Dai et al. 2018		
Cobalt chloride (CoCl2)	10.99	7.78	Dai et al. 2018		
Cobalt oxide (Co3O4)	20.93	15.75	Dai et al. 2018		
Cobalt oxide (CoO)	22.42	16.87	Dai et al. 2018		
Cobalt sulfate (CoSO4)	9.2	6.52	Dai et al. 2018		
Cobalt				1.45 (including recycled metal with proxy data)	
Cobalt					9-10 (global)
Li hydroxide (LiOH) from brine	7.84 (no allocation)		Dai and Winjobi, 2019		
Lithium carbonate from brine				4	2 (global)
Ni hydroxide (NiOH)	3.15 (no allocation)		Dai and Winjobi, 2019		
Nickel				5.25 (44% recycled)	10 (global)

4.5.2 Difference in the GHG emissions Range

The apparent decrease in total GWP from the 2017 report (150-200kg CO_2-eq/kWh battery capacity) to 61-106kg CO_2-eq/kWh battery capacity is partly due to that this report includes battery production with nearly fossil free electricity use which is the main reason for the decrease in the lowest value. The lowering of the high value is mainly due to improved efficiency in cell production. Another reason for a decrease is that the emissions from recycling are not included in the new range. They were about 15kg CO_2-eq/kWh battery capacity in the 2017 report.

The newer data regarded mainly the process energies from, for example, the dry-room and electrode drying, which are energy intensive processes that have received attention as high energy consumers in battery production. The main difference now is that the commercial facilities that Argonne has studied operated close to maximum design capacity and their processes were better optimized for efficiency than earlier data (Dai, et al., 2019).

Another reason for the differences in emissions is the use of water instead of NMP in the anode in cell production solvent drying for the LCA modelling. NMP was used in the calculations of the anode solvent evaporation in (Ellingsen, et al., 2014) which was used in the input data from the previous IVL report (Romare & Dahllöf, 2017). Water requires much less energy to evaporate because it doesn't have the same explosive hazard as NMP, and therefore the new estimate for anode solvent evaporation is much lower. Also, NMP is not consumed in the new estimate because it is assumed to be reused.

5 Battery Metals with Supply Risks

In addition to energy and GHGs during production, the resource risks of lithium-ion battery metals that are at supply risk will also be discussed.

The supplies of certain metals are generally more at supply risk when their supply is distributed unevenly around the world and/or when governance instabilities exist in the countries with the supply. For example, if there is an embargo for one of these metals in a country that holds most of the world supply, the available world supply will suddenly drop. The world supply distribution of certain metals can thus affect the whole battery supply chain, especially when they are difficult or impossible to substitute with other materials. Recycling batteries is one method to increase the supply of battery metals that doesn't involve sourcing virgin metals.

The extractions of some of these metals have more steps than others, which adds up to even greater supply risks, albeit as temporary deficits. For instance, cobalt is a byproduct of copper, nickel, and silver (Dai, et al., 2018a), making it more difficult to control the supply flows, especially in the short term.

In 2015, 17 percent of the copper-cobalt mining in the Democratic Republic of the Congo (DRC) was artisanal (Dai, et al., 2018a), meaning that the workers are not officially employed by a company or the state.

The cobalt content of battery materials is less in battery chemistries that are planned for future cars than current batteries (Dai, et al., 2018b). Figure 7 shows the energy density for a selection of batteries. NMC 811 is a cathode material that battery producers are looking at for next-generation batteries as the trend is moving towards more energy dense batteries, see Figure 7.

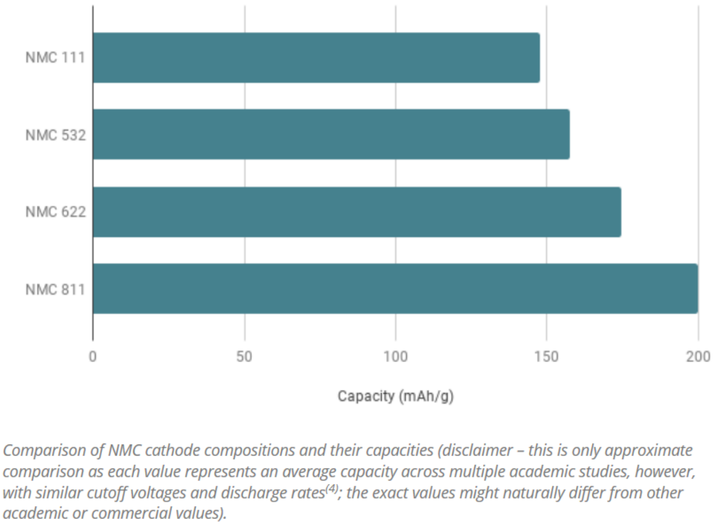

Figure 7. Pack specific energies for different cathode chemistries in lithium ion batteries (RESEARCHINTERFACES, 2018).

Figure 8 shows how NMC 811 also has the lowest cobalt content and the highest nickel content of the presented cathode chemistries, per kWh battery capacity. NCA is also used as a cathode material in many cars, and since both NMC 811 and NCA have high nickel content, the demand for it in batteries is expected to increase while cobalt will decrease (Ellingsen & Hung, 2018).

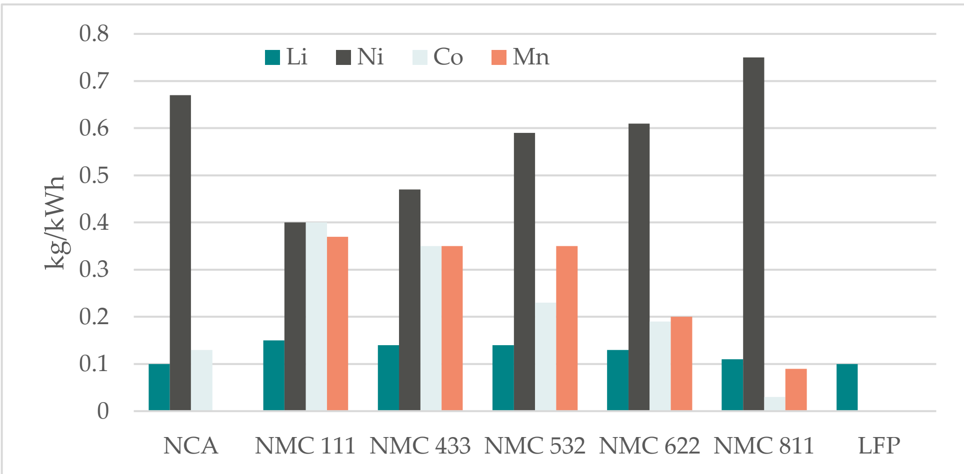

Figure 8. Material energy intensities for lithium-ion batteries with varying cathode chemistries. Moving from the left to the right on the NMC battery chemistries the amounts of cobalt and manganese required decrease while the amount of nickel increase. The source is (IEA, 2018) while the data came originally from ANL's BatPac.

There is a concern that nickel will become critical when its content increases in the batteries. Also, lithium may become a bottle neck metal for certain periods. Since these questions are very important, several investigations are done, for example by IEA (International Energy Agency, 2019).

6 Recycling

Recycling consists of three major steps in which there may be several smaller steps. The major steps are pretreatment, metal extraction and product preparation. The optimal recycling process is not yet in place and it is difficult to find new data for GHG emissions. Pyrometallurgy followed with hydrometallurgy, or hydrometallurgy only are the most common techniques (Dahllöf, et al., 2019).

The mechanical recycling route, which is not in large scale yet, would be most energy efficient while the hydrometallurgical and pyrometallurgical routes are less energy efficient (Lv, et al., 2018).

Dai and Winjobi (2019) reported new data on recycling for GREET (2019) based on Argonne's own research. According to this report pyrometallurgy has highest energy use, 4.54mmBtu/ton cells recycled, followed by 2.86 from direct recycling, 2.78 from hydrometallurgical with inorganic acid leaching and 2.20 from hydrometallurgical with organic acid leaching. There are however more chemicals needed for leaching and the energy use for their production was not included in the values. Regarding CO_2 emissions, pyrometallurgy causes clearly the highest CO_2 emissions from non-fuel combustion.

The PEFCR battery study reports that twelve percent of the GHG emissions of a lithium-ion battery's lifetime occurs in the end of life stage (European Commission, 2019b).

7 Discussion

The data for the GWPs are presented in Table 10.

Table 10. Total GWPs comparison between value range obtained from calculations in this report with data from Dai et al. (see Section 4.4) and other sources.

Source of data	This report, see Section 4.4	Argonne National Laboratory (Dai, et al., 2019)	Argonne National Laboratory (Kelly, et al., 2019)	PEFCR (recalculated) (RECHARGE, 2018)
Total production and materials GWP [kg CO_2-eq/kWh battery capacity]	61-106	73	65 (European supply chain), 100 (Chinese supply chain)	77

The range for all the sources in this report is 61-146kg CO_2-eq/kWh battery capacity.

In our calculations we only varied the electricity mix for cell production and pack assembly, but also included heat in the variation calculations. In the report from Kelly et al. (2019) the authors varied the mix for the entire supply chain. We believe that both analyses are reasonable and realistic, as well as more transparent than other sources. Therefore, these data should carry more weight.

Based on the newer and transparent data found in the literature presented in this report, the new estimated GWP range is lowered to 61-106kg CO_2-eq/kWh battery capacity from the 2017 report. This range is primarily for NMC 111 lithium-ion batteries for light-duty vehicles.

In comparison to our value of 61-106kg CO_2/kWh battery capacity, the PEFCR calculated emissions were within our estimated range at 77kg CO_2/kWh battery capacity. It also includes wastewater treatment as we believe Dai et al. (2019) did.

As stated earlier, the information on the Ecodesign and Energy Labelling report is not as transparent as the GREET articles and PERCR report. For this reason, it is not included in Table 10. In the report, the PHEV battery GWP (146kg CO_2-eq/kWh battery capacity) is higher than the BEV battery GWP (108kg CO_2-eq/kWh battery capacity), but the reason is unclear. Although it does include data from more reliable sources, the lack of transparency makes it less comparable to the data from ANL and the PEFCR than is necessary for a comparison, by our judgement.

The car manufacturer LCAs were unfortunately not comparable as they either

1. had functional units that included the whole car lifetime, or
2. provided insufficient data (153kg CO_2-eq/kWh battery capacity was obtained for the only car with the same functional unit as in this report).

Variation of the electricity mix of only cell production (with pack manufacture assumed to be negligible) gave a considerable range of the total battery GWP (61-106kg CO_2-eq/kWh battery capacity). This wide range shows the impact that the choice of electricity mix of cell production has on the total battery emissions. The higher end of this range could potentially be even higher if the different energy mixes used for material sourcing are especially carbon-intensive, although a thorough analysis of material sourcing was not part of the scope of this report.

The range of electricity mix carbon intensities should be used with care when calculating GWP. The minimum and maximum carbon-intensities used to calculate the 61-106kg CO_2-eq/kWh battery capacity range only represent snapshots of what the national energy mixes could be. The actual average emissions produced also requires information about how the carbon-intensity varies throughout the year. See the Appendix for further discussion on energy mixes. Additionally, apart from the electricity mix used, the humidity and temperature of the geographical location can have a large impact on total emissions as the dry-room is responsible for the most energy intensive parts of cell production.

An additional level of complexity was also added in this report as the energy use in cell production was divided into heating and electricity requirements according to Dai et al. (2017) (2019). The data present large-scale industrial production from several commercial battery factories, and thus we expect the data to be more accurate than that from earlier studies. Since the newer data was based on commercial-scale cell production factories, we believe that the values are more in line with how battery plants operate today. However, more information on the sources of heating from other factories is required to narrow the estimate of the emissions. We suspect that the design in newer factories could utilize heating from local sources and renewable electricity, but that is only speculation. Additionally, strategic use of energy mixes in energy-intensive processes (such as peak shaving or night-time production), as well as heat recycling can offset the energy consumption burden of battery production in surrounding regions even more.

To keep in mind is that transport industry is becoming more involved with the production of batteries than before. Greater volumes of batteries are being bought and the emissions of battery factories has been put into scrutiny since they are potentially the main source of a car's lifetime GWP. It is therefore highly likely that many newer factories will be more optimized for energy efficiency. A better energy efficiency for battery production means a lower GWP potential, regardless of electricity mix, all other things kept equal. The estimated lower energy consumption (7 percent) and lower GWP (14 percent) of the more modern NMC 811 to the current NMC 111 batteries indicate that it may be possible that future batteries may also benefit from decreased energy requirements and emissions due to design differences.

Materials sourcing and electronic components emissions have large shares of energy consumption for battery production compared to cell production (assumedly including wastewater treatment and NMP recovery) (19 percent energy consumption) with the recent estimates from Dai et el. (2019). Uncertainties and variations in these parts of battery production can therefore have relatively large effects on the total energy use and emissions. Specifically, the effect of cathode powder materials represents 37 percent of the total batter energy consumption, meaning that the metals proportions in the cathode can have a more noticeable impact on the total energy consumption than in earlier studies that estimated higher cell-production and pack assembly figures. Additionally, the energy consumptions of other materials (35 percent) and electronic components (9 percent) are now also more pronounced in the total.

Cathode materials have evolved towards using less cobalt, more nickel and higher specific energy. Different battery chemistries will require different ratios of metals, and the question of these resources, including the recycling of battery metals, will be an important aspect to keep track of in the future as battery production ramps up in the coming years.

8 Conclusions

Based on the new data, filtered by the reporting transparency, an estimate of 61-106kg CO_2-eq/kWh battery capacity was calculated for NMC batteries in light-duty vehicles. The interval mainly depends on the electricity mix and the energy source of heating required in cell production. If data with less transparency are included the maximum value is 146kg CO_2-eq/kWh for smaller PHEV batteries.

The new GWP range is substantially lower than the earlier reported 150-200kg CO_2-eq/kWh battery. One important reason is that this report includes battery manufacturing with nearly 100 percent fossil free electricity in the range, which is not common yet, but may be more common in the future. The decrease in the higher end of the range is mainly due to new and more accurate production data for cell production, including dry-room process energies. The new data is also for commercial-scale factories instead of pilot-scale factories, which lowered the emissions per unit produced due to higher production efficiencies. Also, the use of water instead of NMP in the anode slurry evaporation step in the LCA modelling lowered the calculated GWP. Lastly, the former range also included emissions from battery recycling which was about 15 CO_2-eq/kWh battery capacity.

Regarding standardization of LCA, Product Category Rules (PCRs) are published for their Product Environmental Footprint developed by the European Commission. It standardizes the method of calculating energy use and emissions, which may be different from the methods used by other authors. The calculated emissions were within our estimated range at 77kg CO_2/kWh battery capacity. Both the PEFCR and our new estimate were calculated for the NMC 111-graphite chemistry. However, our calculations also show that there is potentially a 7 percent lower energy consumption and 14% lower GWP for NMC 811 batteries per kWh battery capacity compared to NMC 111.

Average nickel content is expected to increase and cobalt content to decrease in newer batteries as the batteries that are produced are expected to move towards higher energy density and away from cobalt, which is at supply risk, but nickel may therefore become at risk too.

Regarding GHG emissions in the recycling step the PEF benchmark reports that 12 percent of the total is in the end of life stage in Europe.

It is motivating to see that the estimated GHG values for battery production have decreased, but it is also important to continue research and development into resource-risks and handling of battery materials. Recycling will become more important in the future as the batteries produced today will all eventually reach their end-of-life. When they do, it will become a higher priority to take responsibility from their resource flows.

There is still a need for more accurate and detailed data, especially since the different production steps can be performed in different ways with different efficiencies. Also, data for electronics production still needs to become better. More information on the supply risks of different metals is also needed, as well as traceability of the metals, so that sustainable production can eventually be achieved and guaranteed.

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Appendix

Literature Review – Scientific Articles and Reports

Prospects for reducing the processing cost of lithium-ion batteries (Wood III, et al., 2014)

An article that wasn't included in the previous IVL report states that there is high interest in switching to water instead of NMP as a cathode solvent, as well as some of the problems of doing so. These problems are: difficulty of dispersing the substances in water, agglomeration of particles, and inferior wetting of the cathode dispersion onto the aluminum collector.

Energy impact of cathode drying and solvent recovery during lithium-ion battery manufacturing (Ahmed, et al., 2016a)

Studied the effect of the evaporating of NMP and drying. The drying and recovery is found to require almost 45 times the energy to vaporize NMP. This is partially because the NMP vapor concentration needs to stay below the flammability limit, which is very low. Therefore, the drying is a slow process that requires consistent heating.

Study of a dry room in a battery manufacturing plant using a process model (Ahmed, et al., 2016b)

A model was done to measure the energy requirements of a dry-room. The size of the room is found to have a big impact on the energy use in the dry-room. The room size is proportional to the amount of air that needs to be dehumidified and heated or cooled.

Cost and energy demand of producing nickel manganese cobalt cathode material for lithium-ion batteries (Ahmed, et al., 2017)

The energy data for a model using process equipment to produce an NMC cathode material using co-precipitation was presented in this article. The energy demands of different chemical process pathways of producing NMC 333 were not remarkably different.

Life Cycle Assessment of Lithium-Sulfur Battery for Electric Vehicles (Deng, et al., 2017a)

This article has new process data that was measured in a pilot scale prototyping facility that produces NMC-graphite cells. The data was used to extrapolate for LCA of lithium-sulfur batteries. However, there is new process energy data in the supplementary material of this report that can be used for the purpose of finding the life cycle emissions of lithium-ion batteries.

The dry-room energy usage was measured over 21 days and set at 20 degrees C and 100ppm moisture content. Although the facilities were pilot-scales, the authors drew an estimation for the lithium-sulfur batteries in large production scale compared to pilot scale. This estimate is almost about 15 percent less energy per battery. Although it isn't stated in the report, a similar reduction in energy requirement per kWh capacity could likely be made for lithium-ion batteries for data comparison between pilot scale and large industrial scale.

At full production capacity, the factory produced 100,000 packs annually with 96 10-Ah cells in each pack. The pack capacity was 61.3kWh. The authors present the energy consumption for each process step per cell and calculate the dry room energy consumption per cell. This cell production data is compared to other data in section. Some of the cell production data are similar to what is found in Yuan et al.'s article on manufacturing energies (Yuan, et al., 2017). The data in this paper was for NMC, but Yuan et al. was for LFP. We believe that the numbers being similar is an indication that the authors believe that the processing energies are at least comparable.

Life cycle assessment of high capacity molybdenum disulfide lithium-ion battery for electric vehicles (Deng, et al., 2017b)

In this article, an NMC cathode is combined with a potential future chemistry, molybdenum disulfide anode. We are not looking at future lithium-ion battery chemistries, but since this article measured the energy of the same processes used in lithium-ion battery production, it is still of interest.

The LCA performed in Deng et al.'s project is a cradle to grave, split up into: raw materials extraction, battery components production, battery pack production, battery use, and End of life, EoL, (hydrometallurgical metal recycling). The functional unit is defined as "per km driving of a mid-sized BEV under U.S. average conditions with an overall 200,000 kilometers driving distance, representing approximately 10-years of service life." They did a bottom-up approach and assumed the same energy consumption of battery pack assembly as NMC-graphite batteries.

Life Cycle Analysis of the Climate Impact of Electric Vehicles (Messagie, 2017)

This paper is a review of electric cars, rather than electric car batteries. It summarizes several papers and reviews on LCAs for all stages of the battery and electric cars.

The report highlights that toxicity levels of batteries are also relevant, stating that LFP-cathode batteries should score better than other chemistries due to the absence of nickel and cobalt (both NMC and NCA contain both nickel and cobalt).

The report also highlights that a problem with providing decision makers with a single-digit value for impacts is that it can lead to different results and interpretations. An example (albeit for electric cars) is that it can show the same GWP for different cars, one with high fuel consumption but low weight, and one with low fuel consumption and high weight. The value, on its own, fails to give the whole picture. According to the paper, it is essential to consider the parameters on the LCA results.

The author writes that the use of renewable energy (electricity as well as heat) is important for reduction of electric car lifetime emissions. He also writes that recycling has a positive impact because it saves materials and lowers the emissions from producing batteries from primary material. He gives the recommendation to increase the recycling efficiency by coupling the vehicle and battery end-of-life directives.

GHG Emissions from the Production of Lithium-Ion Batteries for Electric Vehicles in China (Hao, et al., 2017)

This study was a cradle-to-gate GWP analysis of LFP, NMC, and NCA battery chemistries (and calculated 109.9, 104.1, and 96.6kg CO2-eq/kWh battery capacities, respectively. The emission data for exploitation, transportation, and production of anode materials for LMO and LFP chemistries came from a dissertation from 2012. Unfortunately, the data is likely outdated and, additionally, we couldn't find the dissertation. Consequently, the report did not have enough transparency for comparison with other values.

Manufacturing energy analysis of lithium-ion battery pack for electric vehicles (Yuan, et al., 2017)

The authors studied an LMO-graphite 24kWh battery with 192 cells. They obtained a 3.7GJ/kWh battery capacity as the manufacturing energy. The data they collected were from real industrial processes in a pilot scale site.

The authors note that the differences in direct industrial data is the cause for the big differences in energy estimates for lithium-ion battery production. The numbers range from 0.4-22kWh/kg battery in the seven studies the authors referenced.

Update of Life Cycle Analysis of Lithium-ion Batteries in the GREET Model (Dai, et al., 2017)

This update was for the 2017 GREET version. The LCI for cell manufacturing, pack assembly, and material data for the NMC chemistry was updated with primary data from visits to two battery manufacturers and one recycling facility in China. Data that was modelled by Ahmed et al. was also used.

The largest energy consumers were identified to be the dry room operation and electrode drying for the cell production. The plants use steam for the electrode drying and the dehumidifying processes, and they use electricity for the rest. However, since the heating for the electrode drying and dehumidifying can come from other sources, such as electricity, the authors calculated the energy requirement with a boiler efficiency of 80 percent.

The specific energy consumption of the cell formation, charging, and pack assembly wasn't available on their visits. For formation cycling, the authors were told by the workers that the electricity was reused and that the manufacturers did either 1.5 or 2.5 cycles of charging/discharging. Using this information and assuming 90 percent efficiency, the authors could estimate the losses from this step. They also saw that the battery pack production was done manually and therefore assume no energy loss for this step. They also stated that even if it is done by robotics using electricity in other facilities, that the energy use would be minor compared to the other processes.

The authors concluded in this update that the energy requirement for battery production (not including sourcing of materials) to be 170MJ/kWh battery capacity with 30MJ from electricity and 140MJ from natural gas. These numbers were an estimation from their own battery visit and the literature review they did.

They also calculated energy use for the recycling of materials and found that the battery recycler they visited recovers nickel, manganese and cobalt.

Research for TRAN Committee – Battery-powered electric vehicles: market development and lifecycle emissions (Part 2) (Ellingsen & Hung, 2018)

Various articles have pointed out the flaws in cell production values for some articles. Ellingsen & Hung have stated that the data from studies that modelled the battery cell production facilities, rather than getting data directly from the manufacturer, show significantly lower numbers for the energy use. Additionally, they highlight that cell manufacturing is one of the most energy intensive steps in battery production.

The article/report does a good job of describing and outlining important aspects of battery production, mineral use and their supply risks and recycling, as well as estimating lifetime BEV GWP from a literature review. It is a good starting point for someone new to battery production and still has a good amount of detail.

Cobalt Life Cycle Analysis Update for the GREET Model (Dai, et al., 2018a)

This is another update to the GREET model. The authors collected primary data from three mines in the Democratic Republic of Congo, DRC, and modelled the cradle-to-gate LCI of different cobalt products. There are several cobalt products in the update, but for battery production $CoSO_4$ and Co_3O_4 are of interest.

The transportation of consumables and intermediary products was included, as well as the use of diesel fuel to operate the mining equipment. The type of energy for the average consumption was split into electricity, natural gas, and diesel. However, depending on the mining location, the energy source used can vary.

The mining activities do release their fair share of particulate matter and SO_2, and although this report focuses on the GWP, other environmentally damaging effects of emissions may also be worth noting.

Update of Bill-of-Materials and Cathode Materials Production for Lithium-Ion Batteries in the GREET Model (Dai, et al., 2018b)

For this update on the 2018 GREET version, the bill of materials of lithium-ion batteries in HEVs, PHEVs, and BEVs were updated as well as LCIs for cathode materials with more primary data based on their visit to a leading cathode material producer and a literature review (some references in Chinese). The authors write that this update is a better representation of industry standards at the time of publishing.

In their visit to the cathode material producer they measure the energy required to the calcination kiln to be, by far, the most electricity-intensive processes lasting up to twelve hours at temperatures over 1 000 degrees C. All cathode materials used in batteries for traction motors require at least two-stage calcination. Li_2CO_3 is used to produce LCO, NMC 111, and NMC 622. LiOH is used for NMC 811 and NCA. The calcination kilns usually run continuously in the plant, even at night, as they take a long time to reach the operating temperatures from start-up.

Both the energy and the material inputs were updated. The material efficiency is higher in the 2018 version of GREET.

Steam (likely at 200 degrees C) is used at 13.37 tons per ton of precursor produced and is predicted to be the only energy source for precursor production. The authors converted the energy required to natural gas with a boiler efficiency of 80 percent This efficiency is likely different for an electrically heated precursor production. They also include an equivalent to wastewater treatment in their energy consumption calculation.

Life Cycle Assessment of Silicon-Nanotube-Based Lithium Ion Battery for Electric Vehicles (Deng, et al., 2018)

The authors modelled a more advanced type of battery than is focused on this report. The researchers did an LCA on a 63kWh NMC-SiNT battery meant for a mid-size BEV. The inventory of the SiNT anode came from their own lab experiments and the inventory of the battery from their industrial partners' pilot scale production facilities, but the inventory analyses came from literature reviews and software.

They did their calculations with NMP solvent recovery and reuse at 98 percent.

It is unclear if there is any new data used in the calculation for the GWP of the batteries. There is a diagram showing that the LCI is a combination of literature consultation and factory investigation, but the authors weren't so transparent on what of data they measured or received in the factory investigation. They do state that they used anode data from a dissertation from South China university from 2012.

They used the BatPac model and Argonne 2015 to obtain material data for each of the battery chemistries. They found that the production of cathode materials and aluminum were the main contributors to GWP.

The authors write that there is a slight difference between the U.S. and Chinese battery models, i.e. a battery of the same capacity should have slightly different materials compositions in each of the two regions. There are some interesting graphs on the summed totals of the GWP and comparisons with other studies, but it would have been both interesting and useful if the authors had been more transparent with the acquisition of their data.

Life Cycle Analysis of Lithium-Ion Batteries for Automotive Applications (Dai, et al., 2019)

In this new article from some of the contributors to the recent updates to the primary data in the GREET model, a cradle-to-gate analysis of NMC batteries was done. The authors use the updated

GREET model to do a cradle-to-gate analysis of an NMC 111-graphite battery. The article updates the energy use in battery production to reflect current day practice.

In addition to the calculations of energy use and GHG emissions, there is also a relevant discussion on the present state of LCAs, including suggestions for where future efforts would do be of the most benefit to increase our understanding of the environmental impacts of lithium-ion batteries. A discussion on the differences in impact by varying the energy sources and materials sourcing is also included.

They did the study using the battery pack from the GREET Bill of Material (BOM) update of 23.5kWh, 165kg, containing 140 46-Ah prismatic cells. They warn against the direct use of this number because of varying characteristics with other batteries and they therefore included the results for 1 kg of battery materials.

Similarly, to their update they assumed that the battery pack assembly is manual and requires no energy. They also note that NMP use for only the cathode (water for the anode) is common practice, as is recovering NMP.

They find that the upstream processes require more energy than the cell production and pack assembly. They also find that the NMC111 powder, aluminum, cell production, and electronic parts are the highest contributors to energy use and GHG.

Globally regional life cycle analysis of automotive lithium-ion nickel manganese cobalt batteries (Kelly, et al., 2019)

A new article that examines the emissions from NMC lithium-ion batteries when varying the energy sources at different production stages. The results were that, for 27kWh NMC 111 lithium-ion batteries, a European-dominant supply chain generates 65kg CO_2-eq/kWh capacity while a Chinese-dominant supply chain generates 100kg CO_2-eq/kWh capacity. The authors conclude that supply chains powered by renewable electricity provide the greatest emission reduction potential.

PEFCR (RECHARGE, 2018)

We calculated the battery production GWP by taking the entire lifetime GWP for a BEV and removing the use-phase and end-of-life phase. The results for the production included wastewater treatment, and some consumption of NMP in the process. One assumption was that the GWP-value (kg CO_2-eq/kWh) was constant regardless of the total capacity of the battery.

The PEFCR benchmark battery was calculated to be 36.8kWh. This number was calculated for the NMC 333 lithium-ion battery. The battery was 225kg. To estimate the battery capacity, a different battery that was modelled for a car using the Battery Performance and Cost (BatPac) model by Argonne National Laboratory, was used as a comparison. The battery for comparison was also an NMC 333 lithium ion battery which was modelled to weigh 520kg and had a capacity of 85.1kWh. (Lewrén , 2019)

$$\frac{225kg}{\frac{520kg}{85.1kWh}} = 36.8kWh$$

The reported emissions for the entire lifetime found in PEF, including the battery End-of-Life were 4298kg CO_2-eq. The GWPs for the battery Use-stage and End-of-Life were removed from the total calculated emissions. The remaining emissions for battery pack production were 77kg CO_2-eq/kWh. This estimate included a European energy mix for the cell production and pack assembly steps.

PEFCR also includes the battery charging losses in the use-phase for the total environmental footprint of the battery, which is interesting because it is not self-evident to include this into the life cycle of the battery.

Ecodesign 2019 (Lam, et al., 2019)

In an Ecodesign report from the European Commission, another calculation and estimate of the GWP was produced with the functional unit of "1 kWh of the total output energy delivered over the service life by the battery system (measured in kWh)". Inventories from the GREET2 Model and the PEFCR on rechargeable batteries have been used as complementary battery information in the EcoReport tool.

Seven base cases are presented, but only the first three are relevant to light-duty vehicles. Base case 1 (BC1) and BC2 are batteries for BEVs that are different sizes. BC3 is a battery for a PHEV, so it is smaller than both BC1 and BC2. The weights and battery capacities are presented in Table 11.

Table 11. Weights, capacities, and number of replacements for three cases in the EcoDesign report.

	BC1 (BEV)	BC2 (BEV)	BC3 (PHEV)
Weight [kg]	609	304	126
Capacity [kWh]	80	40	12

As in PEFCR, the battery lifetime emissions results are presented, but with several assumptions pertaining to driving behavior and battery replacements which are outside the scope of our study. The difference in scope between this report and ours unfortunately means that only small portions of the report can be used for comparison of battery production emissions.

Some auxiliary materials included in the Ecodesign report are presented in Table 12 after some simple arithmetic to produce comparable results to (Dai, et al., 2019). The consumption of NMP requires an additional 6-8kg CO_2/kWh.

Table 12. Comparison between the auxiliary materials during the manufacturing of batteries between Dai et al. (Dai, et al., 2018b) and the Ecodesign report.

Auxiliary materials during manufacturing		(Dai, et al., 2019)	BC1 (BEV)	BC2 (BEV)	BC3 (PHEV)
NMP	kg/kWh capacity	0	1.1	1.1	1.5
	MJ/kWh capacity, using NMP energy impacts from (Dai, et al., 2019)	0	110	110	150
	kg CO_2-eq/kWh capacity, using NMP GWP impacts from (Dai, et al., 2019)	0	6	6	8
Hydrochloric acid [kg/kWh capacity]		0	2.8	2.8	3.9

Although several battery chemistries are presented, there is no indication of any differences in production energies and emissions between them. There is a table with the NMP and hydrochloric acid (HCl) use during manufacturing, which we take as indication that these substances are consumed during the manufacturing. There is also no indication that any NMP recovery is considered in the calculations, so the energy required for this process is likely not included. We note that the hydrochloric acid is included in the manufacturing category, see Table 12. In contrast, Dai et al. (2019) don't include hydrochloric acid in cell production.

Table 13 shows the energy-using processes in cell production and battery manufacture.

Table 13. Three main energy-using processes and the total energy use for cell production and battery assembly. Values from Dai et al. 2019 are compared to the three base cases in the Ecodesign report.

Process energy, electricity and heat combined [MJ/kWh]	(Dai, et al., 2019)	BC1 (BEV)	BC2 (BEV)	BC3 (PHEV)
Electrode drying and dry-room	216	305	304	420
Cell forming (charging)	4	9.1	9.1	12.6
Battery assembly	0	0.01	0.01	0.01
Total manufacture energy	220	314	313	433

There is no information in the report about which electrodes the used water and/or NMP. This detail is of importance to the energy use and GWP (Dai, et al., 2019) (Wood III, et al., 2014).

The total manufacture energy for the Ecodesign cases are 30-50 percent higher than the values in Dai et al. (2019). We are unclear on the reason for the discrepancy and are left to wonder due to the difficulty of decoupling the production results with the rest of the energy use in the battery lifetime.

The calculated emissions for the Ecodesign report are presented in Table 3 in the main text. Similar to the energy use, the GWP is around 32-50 percent higher for the Ecodesign cases than Dai et al. (2019).

Putting Electricity Mix into Perspective

Several large manufacturing factories for lithium-ion batteries are built or are planned to be built in China, Japan, Germany, India, Sweden, and Hungary (IEA, 2018). The electricity mix varies between these countries, and thus the emissions from production will also vary, granted that the factories use electricity from the local grids. There are also examples of factories that use their own electricity to varying degrees, such as at Tesla (2018).

The time and season when the production facilities are producing batteries influences the emissions, as well as the location. Generally, it is more economical to produce energy from energy sources such as coal, but it is more carbon-intensive. A country like Sweden may have a relatively clean energy mix when the demand for electricity is low, but during peak hours the mix may become more carbon-intensive due to import of coal-based electricity.

In addition to time, the mix can vary between locations. It varies between countries and sometimes between regions in the same country. One country can sell energy to another country at different rates of energy at different times of the day.

If it is possible, manufacturing facilities can maximize their energy consumption during the hours of higher renewable energy production to minimize their carbon footprint. For instance, the Tesla Fremont and Lathrop factories use solar power for peak-shaving (Tesla, 2018), which lowers the burden on the grid during hours of high demand. There can also be an economical incentive for factories to consume energy in this manner. Messagie et al. (2017) also highlighted Nordelöf et al.'s findings from investigating several LCA's from earlier reports. Although the report focuses on electric vehicle LCA rather than electric vehicle battery LCA, the finding that the differences in reported results being due to the differences in allocated average or marginal electricity mix is also true for battery production. I.e. the emissions from electricity-use can vary significantly merely from how it is calculated.

Different parts of the supply chain will use energy from different sources. Not only electricity is used for energy since the options of energy used will depend heavily on the type of process it is used for.

Figure 9 shows some examples of the range of carbon-intensities of national electricity mixes from several sources. The actual range is likely wider if more sources are used. As stated in the Discussion, these ranges are not sufficient in themselves to make accurate predictions of the average.

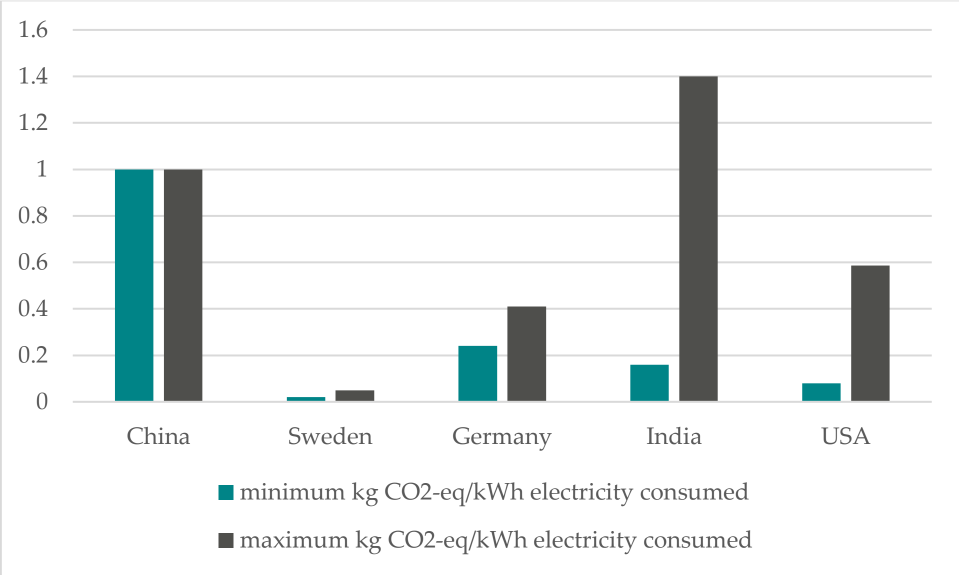

Figure 9. Greenhouse gas emissions from different electricity mixes. The minimum and maximum values differ because the values come from different locations and time of day and different sources. The minimum and maximum values are the furthest extremes of the three sources: (Romare & Dahllöf, 2017) (Messagie, 2017) (Tomorrow, 2019) The range may be wider than shown as only samples are shown. For instance, Sweden can have a much greater maximum when it imports coal-based electricity.

The wide differences in values for some countries in Figure 9 shows that the values of the electricity mix carbon-intensities are an important part of the GWP-estimates in LCAs. As an example, the deviation between the smallest and the largest value for Sweden is 60% if the largest GWP is chosen for modelling and the smaller value is the real GWP. If the modelled and real GWP switch places it means that the deviation rises to 150%. For Germany, these respective deviations are 41% and 70%. There are undoubtedly some errors for the China mix also, if more data-points from additional sources are added.

Thus, there are large variations of emission-values that can be obtained from variations of the region of different parts of production, as well as the interpretations of the carbon-intensity of the electricity in each region for the different parts of battery production. For any modelling to be trustworthy there needs to be transparency in all steps included (and/or a clear presentation of assumptions where data is unavailable or unnecessary for the analysis). Essentially this means that emissions values on their own without information about the electricity mix used to calculate them hold no, or very little, significance. Alternatively, referencing the reliable source(s) used and/or stating all assumptions regarding the electricity mix can be presented in its place.

Calculations Estimating Cathode Chemistry Effect on Total Energy Consumption and Total GWP for Battery Production

The ratio of the specific energy of NMC 622 and NMC 811 to the existing data for NMC 111 was applied to all materials, but not co-precipitation, calcination and cell production. The relative amounts of NiSO4, CoSO4, and MnSO4 were compared between the NMC 622 and NMC 811 batteries to the existing data for NMC 111 batteries found in Dai et al. (2019).

The results are shown as percentages of the total energy and GWP for the battery production in Table 14.

Table 14: Energy consumption and GWP differences between NMC 111 lithium-ion batteries with NMC 622 and NMC 811 batteries. Note that the negative values signify a decrease in the difference, e.g. NMC 811 have an estimated 6% less energy consumption than NMC 111.

Energy Consumption difference in respect to NMC 111			GWP difference in respect to NMC 111		
NMC 111	NMC 622	NMC 811	NMC 111	NMC 622	NMC 811
0%	-4%	-7%	0%	-11%	-14%

IVL Swedish Environmental Research Institute Ltd.
P.O. Box 210 60 // S-100 31 Stockholm // Sweden
Phone +46-(0)10-7886500 // www.ivl.se