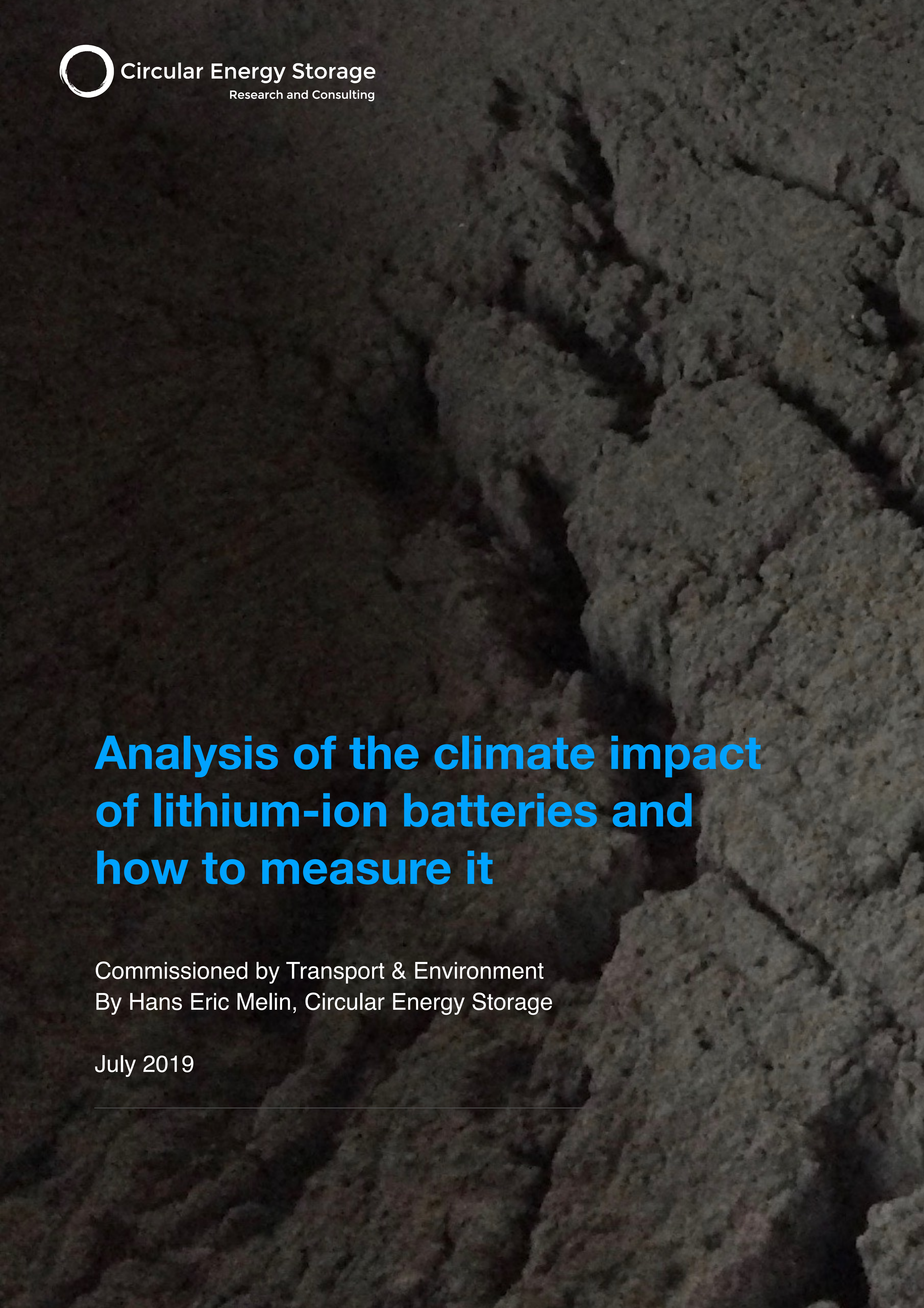

Circular Energy Storage
Research and Consulting

Analysis of the climate impact of lithium-ion batteries and how to measure it

Commissioned by Transport & Environment
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Introduction

Over the last ten years the lithium-ion battery has gone from an enabling technology for mobile electronics to play an important role in the world's decarbonisation and reduction of greenhouse gases (GHG). First of all as an enabler of electrification of today's vehicle fleets such as cars, buses, trucks and ferries but also of new disruptive applications such as electric bikes, scooters and autonomous robots. The lithium-ion battery has also rapidly become the technology of choice for different energy storage solutions which are becoming more and more important when fossil fuel-based energy sources are replaced with cleaner but less predictable renewable energy solutions such as wind and solar which themselves are prerequisites for the reduction of GHG.

Although electric vehicles basically are emission free, at least when they are powered by electricity from renewable sources, they still cause a climate impact which derives from the manufacturing of the car and not least the battery. Mining and refining of battery materials, and manufacturing of cells, modules and pack requires significant amounts of energy which could generate GHG emissions so high that the marginal climate benefit by using electric vehicles instead of ICE vehicles is reduced. This would mean emissions are only moved from one pipe to another which most probably would require new regulations .

With this as a background Transport & Environment has commissioned this study. The purpose is to frame the actual problem by a review of the research in the area and discuss potential ways of measuring, comparing and limit GHG emissions from batteries, as well as proposing tools to make this happen.

The CO2 footprint of the lithium-ion battery value chain

The lithium-ion battery value chain is complex. The production of a battery cell requires sourcing of as much as 20 different materials from around the world, which will pass through several refining stages, of which some are exclusively designed for making batteries and some are not. There after the materials are entering an advanced and energy-intensive manufacturing process with very different climate impact depending on which energy source is used. To accurately calculate the climate impact is therefore challenging.

It is not only the value chain that is difficult to study. The lithium-ion battery is not really one single battery type but basically the common denominator for several different chemistries used in the negative electrodes (cathodes) of the batteries which give the cells different characteristics and capabilities. Both the varying capabilities and the variance of materials cause different climate impact. Lastly, in the case for batteries in electric vehicles as for many other industrial applications the cells are assembled in modules and packs which, depending on what materials these are made of and how they are manufactured, also affect the battery's CO2 footprint and climate impact.

There are today over 100 research articles that cover the environmental impacts from lithium-ion batteries dating back to as early as 1999. The focus in the research varies, as do the methods. Of this reason the results are also widely different with a climate impact ranging from 39 kg CO2e/kWh to 196 kg CO2e/kWh[1]. If an electric vehicle is using a 40 kWh battery its embedded emissions from manufacturing would then be equivalent to the CO2 emissions caused by driving a diesel car with a fuel consumption of 5 litre per 100 km in between 11,800 km and 89,400 km before the electric car even has driven one meter. While the lower range might not be significant the latter would mean an electric car would have a positive climate impact first after seven years for the European average driver[2].

There are several reasons for the discrepancy in the results:

- **Origin of data inventory**
  Of all research done on lithium-ion battery's life cycle there are only a few studies that are using primary data. Even when this is done the primary data is rarely derived from real plants or production sites but are usually estimates and results from modelling. In a review of 36 LCA peer-reviewed articles on lithium-ion batteries dating from 1999 to 2016 Peters et al[3] identified eight articles with primary data. All other articles but one did not provide their own data inventories but based their assessment on the these eight studies which were all published between 2000 and 2012, three years before Tesla's announcement of the Gigafactory which was the first large scale plant for lithium-ion batteries outside of Japan, South Korea and China. Since then there has been only three studies that have used data from real plants and of these only two were at commercial scale[4].

  Moreover, there is only one study that address the actual energy consumption in the material extraction and refining step and even that study is based on modelling, although real cases are used for the calculation of the data[5]. All other studies are either referring to previous research or are using data from commercial or academic LCA material data bases which themselves usually are built on modelling. This means that in no study on the EV battery life cycle is there any primary data from real production on mining or refining of battery materials. It also means that depending on which database that has been used, the material values, and the actual availability of correct information of the different specialty chemical used in the lithium-ion battery, differ a lot between the different data sets, sometimes as much as much as 100 per cent[6].

- **Calculation approach**
  While some studies use a top-down approach where energy consumption for a typical plant is allocated to the different production steps and divided by the manufacturing output, other studies are using a bottom-up approach where the energy use for each process is calculated or estimated and distributed per battery. In general the top-down approach result in higher energy consumption. Most life cycle analysis's are made "cradle-to-gate" which means they are analysing the impact from material extraction to when the battery is ready for sale. In only a few cases has recycling been analysed and included in the life cycle analysis.

- **Different energy sources, battery types and refining methods**
  Depending on which energy mix, battery type and production methods that have been used the results are also very different. Some studies are not very transparent and it can sometimes be hard to get hold of comparable values such as energy input per battery capacity but instead articles are only showing how much GHG emissions per kg the production of the battery is causing.

That there are differences in energy sources, battery types and refining methods is natural and in fact where life cycle analysis can be helpful when trying to identify the optimal solution from a climate perspective. However, the combination with the other two factors undermines this benefit as it is still hard to isolate where the real differences are in the studies. It also raises the question whether it is at all meaningful to extract an average value from the studies as the different variables are so many and the reported values are so different. In some of the most referred reviews of previous literature the cumulative energy demand for battery productions are within ranges such as 500 MJ/kWh–2000 MJ/kWh (average 1030) [7], 316 MJ/kWh–2,318 MJ/kWh (most likely 960)[8], 349 MJ/kWh–651 MJ/kWh[9] and 2.4 MJ/kWh–1062 MJ/kWh[10]. Given that the reasons to these differences aren't always accessible and rely many times on old data in a rapidly changing market it seems more likely that studies with primary data, preferably from real operations give a better understanding than any of the previous studies.

During 2018 and 2019 Argonne National Laboratories in the United States conducted several studies in which primary data from real operations was retrieved and used as new inventory for the life cycle database GREET. One study covered real cell manufacturing in two Chinese cell manufacturing plants[11], another covered the value chain for cobalt in which three mines in the Democratic Republic of Congo was studied[12] . Finally, a summary paper with a new cradle-to-gate LCA with the previous studies incorporated[13] was published. As these studies are the most comprehensive assessments with primary data from real operations that we have come across, these studies have be chosen as the main source of LCA data in this summary with additions of other studies when relevant. The summary paper from Argonne covers an LCA of an NCM111 (a third of nickel, a third of cobalt and third of manganese in the cathode) battery, a chemistry which is more and more replaced by more nickel-rich chemistries. The values can still be used for other chemistries to show the relationships at large between the different steps in the value chain.

Metrics for CO2 footprint from lithium-ion batteries

Although the research available today shows large differences in how to measure and evaluate the embedded climate impact of lithium-ion batteries there is an unanimous view of which main variables to use which primarily are two:

1. **Cumulative Energy Demand (CED)**
   With this metric we get an understanding of how much energy that has been used to produce the battery, no matter what the energy source is. Depending on the boundaries it may include all energy used to produce the battery, from raw material extraction to the final assembly of the battery or any range within. When measured per unit this is the metric a company in the value chain can alternate by changing its process or operation, regardless of what energy source it is using. In order to analyse the actual climate impact the metric is limited if not combined without information about the energy source but even as an independent number it can be used in comparison with for instance other power sources if used per unit.

2. **Amount of GHG or CO2 emissions (CO2e)**
   This is what really matters when analysing the climate effect of the batteries. However the metric is only marginally interesting if not combined with the CED. For example, in a market where the amount of non-fossil energy is limited a company which achieve close to zero amount of CO2 emissions by for instance buying green energy from the grid will only move the consumption of fossil fuel to somebody else on the grid, although the allocation of funds to renewable energy enable its long term growth. However in the short term it is important to use energy efficiently even if the energy source is clean.

For the variables to be useful and comparable they need to be combined with so called functional units. Which unit to choose depends on the actual comparison and purpose with the measurement. One common functional unit for both main variables is the battery's capacity: kWh as in MJ/kWh (CED to produce the battery's capacity) and kg CO2 equivalents/kWh (Amount of CO2 or other GHG emissions turned into CO2 equivalents, required to produce the battery's capacity). Other common functional units are the battery's total weight (kg CO2e/kg) or, if the battery is used in a car, the amount of CO2 emission from the battery per driven kilometre (g CO2e/km). In the overview of the value chain we will use the Cumulative Energy Demand for materials and activities as this is the more neutral functional unit which doesn't change even if the energy source is changing. This will however be complemented with comments about CO2 emissions as well as with a final analysis of CO2 footprint depending on energy source.

Equally important as functional units is the system boundary. This analysis has focused on the "cradle-to-gate" boundary which means it covers material production and the manufacturing of the battery but not the actual use, nor a second life or the effect of recycling. This means a battery's CO2 footprint will be regarded the same no matter if it will allow 500 charge and discharge cycles or 5,000.

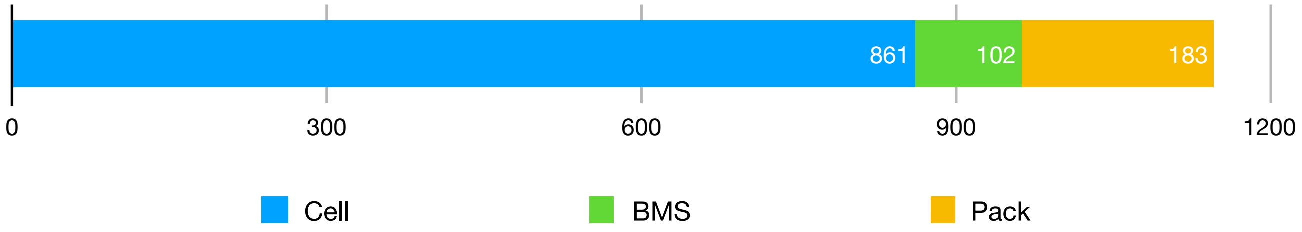
To be useful and fully comparable with other technologies this system boundary may need to change but everything will always start with cradle-to-gate analysis.

Energy consumption in the battery value chain

Basically, a lithium-ion battery can be divided into three main components: the cells, which contain the active materials, the battery management system, which controls the performance and safety of the battery, and the pack, which is the structure the cells are mounted in, usually with a cooling system, isolation material, electrical connections and enclosure.

All these components are part of a supply chain which starts with mining and material extraction to then continue with conversion and refining of the materials and ultimately the production of battery chemicals, cells and pack. As seen in figure 1 from an CED perspective the far biggest impact comes from the cells. It is also the value chain of the cells that is best covered in the research with primary data for several of the materials while almost all materials in the BMS and in the pack originates from different material databases with limited transparency. This does make sense as these materials, such as aluminium, steel and plastics, are usually well covered and are not exclusive or concentrated only to the lithium-ion battery value chain.

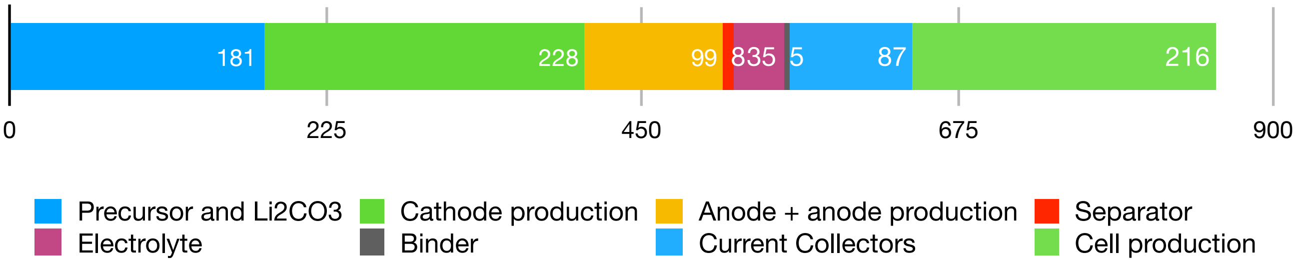
Figure 1 – MJ/kWh for a NCM111 battery pack (modified from Dai et al 2019



Energy consumption from cells
As much as 75 per cent of energy consumption from a battery comes from the cells. However this is distributed over several different steps.

The first significant step is found in the mining, conversion and refining step of the active materials where nickel, manganese and cobalt are processed into sulphates, and lithium either into lithium hydroxide or lithium carbonate. This process consumes 20 per cent of the total energy used for the cell or nearly 16 per cent of the whole battery. This number is depending on the battery cathode chemistry. In the analysis from

Figure 2 – MJ/kWh for a NCM111 battery cell without casing (mod. from Dai et al 2019



Argonne cobalt sulphate is consuming twice as much energy as nickel sulphate and almost nine times as much as Manganese sulphate which would indicate that for instance a lithium manganese oxide battery would consume considerably less energy. It is however only the CED from cobalt sulphate that derives from real site data. A similar approach to the values of nickel sulphate and manganese sulphate might change the values. From the same study it can be learned that of the 56MJ of energy required to produce cobalt for 1 kg cobalt sulphate about half (26.29MJ) comes from direct energy consumption while the rest derives from the embedded CED in the reagents used to produce the chemical. If this would be applied to all chemical products in the precursor it would mean that as much as 8 per cent of a battery's CED comes from auxiliary products from the virgin mining, conversion and refining process.

The largest climate impact of the cell does however come from the synthesising of the precursor and lithium compound, either lithium carbonate or lithium hydroxide, into cathode powder. In Argonne's latest update of the GREET database this represent as much as 27 per cent of the cell's CED and 20 per cent of the entire battery. It's both the co-precipitation and calcination processes that consumes considerable amount of energy, both in the actual processes but also from eg waste water treatment that consumes a lot of heat. The energy is supplied both in electric and natural gas for heating. In total the cathode production generate 47 per cent of the cell's CED and 35 per cent of the CED of the battery.

Other components, the anode, binder, current collectors, separator and electrolyte collectively account for 27 per cent of which the anode and the current collectors are the most important. This data is however primarily generated through modelling and include no real site visits or data from real plants. There are examples of other results such as an Chinese study[14] which used energy and environmental data from filed sustainability reports from Chinese battery material manufacturing companies. In this the authors identified the materials used in the membranes in the battery's separator as very energy consuming as well as use of the solvent NMP which is used in the binder. This is discussed but not included in Argonne's study.

Finally the actual cell production is the second most energy demanding activity with 216 MJ per kWh, representing 25 per cent of the cell's CED. This number is highly depending on the plant's capacity as many of the energy intensive activities in cell production relates to drying and heating which is taking place in large rooms where the energy used remains the same no matter if one of several thousands of cells are in production. According to the authors of the paper from Argonne this might also be the reason why those few other studies that are using primary data from real plants arrive to significantly higher number. For instance is a 2 GWh plant in South Korea reported to consume 990 MJ/kWh of which 340 MJ/kWh is electricity and 640 MJ/kWh is heat[15] but the capacity at the point in time might have been heavily under-utilised.

Also, in previous studies the impact from cell production is considered as more important compared to the other steps in the value chain. Unfortunately few studies shows the actual energy consumptions but only report the GHG emissions which in a review by Romare and Dahlöf[16] is reported as a range between the 70 and 110kg CO2e/kWh for cell production while material production, including mining, conversion and refining, is only between 60kg and 70kg. Most of these studies are however made top-down and without any real primary data, why we still believe the latest information from Argonne is much closer to the truth.

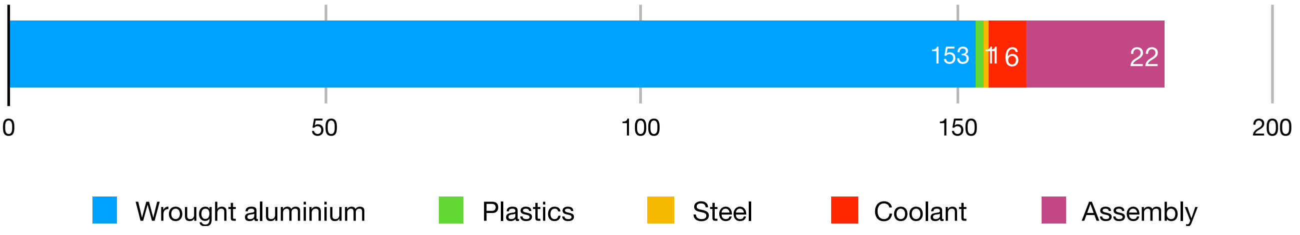
Energy consumption from pack production

As shown in figure 2 the dominant energy consumption from the pack comes from the aluminium used in the pack. Aluminium is a very energy intensive material and is important in the pack not least for its light weight. All other materials have a relatively smaller impact. It's however important to mention that battery packs can have very different specific energy as in kWh per kg which derives both from cell to pack ratio but also what materials and components that are used in the pack.

The only study done on real pack production is the previous mentioned study by Kim et al where a pack manufacturing plant in the United States has been studied. The authors don't share the energy consumption for pack manufacturing but do only report a breakout of the CO2 emissions. The total CO2 emissions are 140 kg CO2e/kWh while the cumulative energy consumed is 990 MJ/kWh. If the same percentages for energy consumption as for climate impact would apply for the pack manufacturing it would correspond to 327 MJ/kWh. Of this 31 per cent is related to the material used such as battery management system, electrical system, enclosure and thermal management. The actual production is less than 20 MJ/kWh.

A very similar number can be traced in Dunn et al[17] where the assembly and testing of the battery, which include charging and discharging, amounts to 22.23 MJ/kWh. Most probably this number can vary a lot, but it's clear that the assembly of the pack has relatively low impact on the CED of the battery as a whole.

Figure 3 – MJ/kWh for a NCM111 battery pack without cells and BMS (mod. from Dai et al 2019

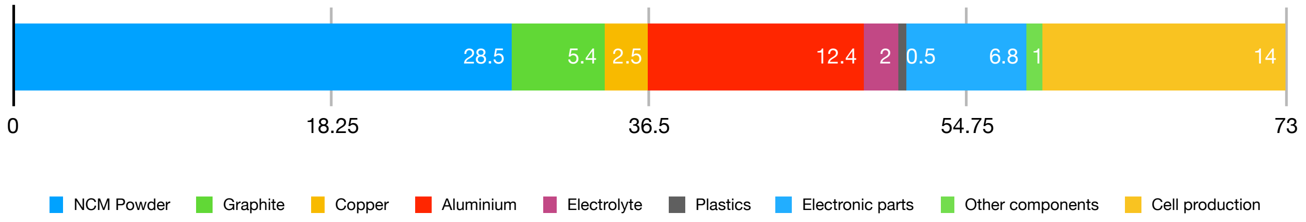


The climate impact of the battery supply chain

While the cumulative energy demand for a product is one side of the climate impact equation the source of energy is the other. As of today the battery value chain is truly global, often including all production on populated continents. The source of energy is therefore very different in the various steps of the value chain depending on where the materials are being produced.

There are also differences on a local level. Companies can for instance have different strategies for what energy sources they are using for heat which can either be supplied indirectly through electricity or directly by using fuel such as natural gas. Companies can also choose to actively source energy from specific

Figure 4 – kg CO2e/kWh for a NCM111 battery pack (mod. from Dai et al 2019)



generation modes through agreements with their energy supplier, such as “green power”, and they can also generate energy themselves by building microgrids with solar or wind power .

Whether heat is supplied from electricity or fuel can have a significant impact already. In Argonne’s study almost 60 per cent of the energy was supplied by fuels which means only 40 per cent of the production is affected by the energy mix in electricity. This shows how important it is to track the production to individual production sites.

The same is true for the energy mix for electricity. In Argonne’s latest update of GREET the assumption is that both NCM111 precursors and the rest of the battery is produced in the United States with electricity from the national grid mix, although the site data is taken from Chinese plants. Also the aluminium, which has a high relative impact, is assumed to be sourced from the US while most of the raw materials for the cathode and anode are sourced from where the production is concentrated such as Chile, DRC, Finland, China and Australia. The result is a total of GHG emissions from a NCM 111 battery of 73 kg CO2e/kWh.

If the same battery would have been produced in Europe the CO2 impact would likely have been smaller. As shown in figure 5[18] the average energy mix in Europe is less carbon intensive primarily thanks to a higher share of hydro and nuclear power. If the battery would have been produced in China it would have higher CO2 impact due to a higher share of coal. However, the difference between the US and China is not huge. Still, for an analysis to be really useful the energy mix must be applied on a lower aggregate level as the regional differences can be significant as shown in figure 6. If for example a battery is produced in South China where many of the battery companies are based, the carbon intensity is much smaller than in Poland

Figure 5 – Average energy mix

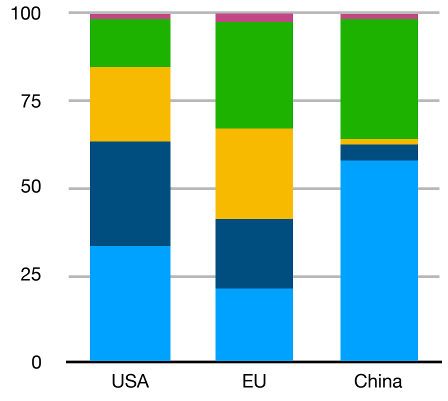
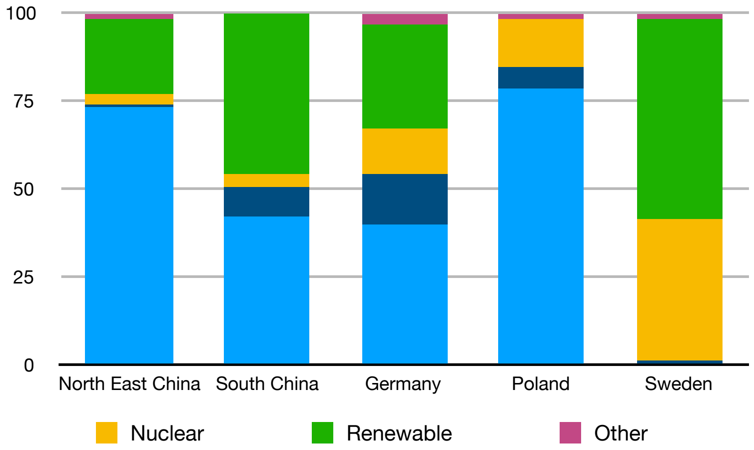


Figure 6 – Average energy mix per country/region



Sources in end note 18

and basically on par with Germany, both two countries where battery production capacity is on the rise. On the other hand, in comparison with Sweden where also battery capacity is being built the carbon intensity is much smaller than on any other market.

Another contributing factor is emissions from transportation. This is obviously highly depending on where the different productions sites are located and where the final destination for the battery is, as well as which mode of transportation is used and what kind of energy the vehicle/vessel is using. In the study by Kim et al cells are transported from South Korea to Michigan in the United States causing additional GHG emissions of 4.1 kg CO2e/kWh. Here it becomes clear that the battery's or cell's specific energy becomes very important as this determines how many kWh that can be shipped per kg CO2e/tonne-kilometer.

The case for recycling and second life

Recycling has a potential to decrease the CO2 impact by making already extracted material available for production of new batteries and thus avoiding the processing of new raw materials. Dunn et al shows that the use of recycled materials can decrease the energy demand in material production with 48 per cent. This requires of course that the recycling process doesn't consume more energy than the process for the virgin materials it is to replace. Several studies show that the choice of recycling process is very important. The best options is what is called a direct recycling in which the cathodes and anodes retain its composition followed by different types of hydro metallurgic processing. Pyrometallurgy, primarily smelting, is regarded as a method which generates more GHG emissions than it saves[19] [20] [21].

As recycling is happening a long time after the battery has been placed on the market recycling is usually not accounted for in the end of the life cycle but rather in the beginning. Credits are given based on recycled content in either the conversion or material production phase where recycled content can contribute to lower GHG emissions for the material.

Second life is the use of batteries after they have been deemed not fit for their original purpose. Thus it takes place after the first use and before recycling. Despite that second life can contribute to a longer life and hence a higher user rate of the battery, second life has rarely been included in most LCA's. Instead there have been a few dedicated studies that explicitly have investigated the effects of second life. These studies have many times looked at the second life battery from the perspective of use in the new application such as energy storage where second life batteries can save between 15 and 70 per cent of the cumulative energy demand and GHG emissions can be saved[22] compared to other solutions such as lead-acid batteries or natural gas.

Like in recycling this means that second life batteries have been included in the beginning of a new value chain with its own system boundaries instead of in the end of their original value chain. Basically all studies that have been found verify the environmental benefits with a longer use although the approaches to the problem differ[23] [24] [25] [26] [27] [28]. No matter how its calculated it is however clear that batteries that can last in many lifecycles are very beneficial with the potential to basically cut the embedded emissions in half if it's possible to run as many cycles in the second life application as in the original application.

Measuring the CO2 footprint from batteries

The challenge of measuring the CO2 footprint of a battery is that is can't be physically measured in the usage phase. While the emissions from combustion of fuels can be measured by analysing the emissions and an electric motor through how much energy it consumes, the only way to track the embedded emissions from a battery is to measure the direct and indirect energy consumption for the different steps in the production chain.

The situation in the research field shows clearly that this is not done easily. Several research papers point at the difficulty of acquiring correct data as the reason why their life cycle analysis's lack data from real production. Difficulties range from access to corporate data to challenges of accurately distributing the energy consumption in a plant on the measured batteries or battery components.

As mentioned above there are two different ways of measuring GHG emissions when doing a life cycle analysis – top-down or bottom-up. Arguable a bottom-up approach is more accurate as it measures the energy consumption as close as possible to the component, for instance the energy consumption of a furnace or a heating equipment for a dry room, divided by the actual output. The reason why this is the least used method by researchers is that it is more time consuming and above all, requires direct access to the production line. With legislation in place which would require companies to make these measurements this problem would be considerably easier to solve.

Essentially three variables are needed for correct measurement of GHG emissions:

- Total energy used for each activity in the value chain over a specific period of time (MJ/kWh)
- The source of energy for each activity during the specific period of time (CO2e/MJ)
- The actual throughput during the specific period of time (units or kg or kWh/MJ)

As shown in the discussion around energy consumption the throughput is a very important number especially in cell production where in some processes the same amount of energy will be used for only a few cells as for the full capacity.

Another challenge in measuring the GHG emissions of the production sites is the fact that a battery in a specific car model can contain components from various production sites and even various suppliers. This is especially happening on the material side but it can basically happen in any step of the supply chain. Therefore an accurate measurement of every component requires the ability to connect it to a specific production site at a particular time.

To be able to verify this data each part in the value chain needs to be able to present evidence of each of the three parameters and to assign it to specific cells. This can be done by presenting utility bills, internal production data and by marking the date on all components and batches of materials.

Tools for measuring and regulating the CO2 footprint from batteries

The first question one could ask about regulation is if it really is needed. As shown in the review of life cycle analysis's it is likely that the climate impact from EV batteries is not as big as many studies have indicated. The main reason for this is the scale new battery factories have. While the largest real plant studied in a publicly available life cycle analysis is 3.2 GWh it's clear that batteries in the future will be produced in significantly larger production units. The average capacity of the 70 largest current and planned battery factories in 2028 will be more than 20 GWh of which some factories will have production capacities exceeding 60 GWh[29]. This means the most energy intensive processes in the production most probably will be significantly more efficient and cause smaller CO2 footprint per cell.

On the other hand will the total CO2 footprint from battery production increase in unprecedented pace and to an enormous scale. If the value from GREET 2018 is used (73kg CO2e/kWh) the industry will go from 12 million tonnes CO2 equivalents to 106 million tonnes which is equal to almost two thirds of GHG emissions from aviation in Europe[30]. Even if this contributes to a decrease of direct fossil fuel emissions, through the replacement of ICEVs to EVs, it will be a large source of CO2 emissions.

In order to regulate the GHG emissions from lithium-ion batteries, or even to have a discussion around it there must be one or several studies commissioned which generate primary data from an European perspective and create a baseline not only for the lithium-ion batteries but also all other batteries and energy storage devices that can be affected by the same regulations. The quality and the depth of the available research in Europe is not accurate enough to be used as a foundation for setting thresholds or target values.

Tools that can be developed are:

- **Method for calculating CED and GHG emissions**
  The procedure for retrieving lifecycle inventory must be crystal clear and rely on a solid platform making batteries and other energy storage technologies fully comparable. There must be instructions for how primary data should be collected, documented, updated and how they should be assigned to the batteries produced.

- **Moving target value**
  Based on commissioned studies there should be a target value which can be tied to incentives or sanctions. A target value should be as close to best practice as possible, in order to push the entire industry to improve. The target should be a moving value as it can be expected that the GHG emissions will continue to improve due to higher scale and increased volume of renewable energy sources around the world. It should also not only take GHG emissions into account but also Cumulated Energy Demand as low energy use is important in itself when the energy sources available are not 100 per cent free from CO2 emissions.

- **Standard values for activities in the value chain**
  Similar to the target value there should be standard or general values available for each activity, adapted for variations such as chemistry and origin. Essentially it could be a database similar to GREET. This would enable companies that are unable to fully trace the GHG emissions in the value chain to apply these value where are blanc spots. With such values there is no reason for companies to be exempted for not having the traceability infrastructure in place. It can also be necessary for parts of the value chain as for instance electronic components or reagents in the conversion and refining process, which especially for smaller OEMs can very difficult to retrieve.

- **Traceability system**
  In order to accurately measure the GHG emission on each battery a system for tracking and monitoring the flows of batteries is required. A similar system is since August 2018 in place in China where the manufacturers of batteries need to track the batteries on module and pack level not only throughout the

> forward supply chain but also when the battery is reaching end-of-life, is disassembled and used in second life applications and ultimately when it is recycled[31]. Batteries are being assigned individual codes which then are checked when the battery is placed in a vehicle, is removed from a vehicle and wether it is reused or recycled. Although the original purpose of the tracking system is not to measure energy consumption or GHG emissions it could serve as tool to trace this on a component level. A similar system in Europe would enable not only the connection of the GHG emissions to individual battery packs but also, just like in China, increase the transparency and facilitate the end-of-life management of the batteries.

What's important to emphasise is that by using the cradle-to-gate boundary capacity (kWh) as functional unit there is nothing that says anything about the battery's life time. One way to address this is to extend the system boundary to cradle-to-grave and change the functional unit to "total energy supplied" when developing target and standard values. This would incentivise manufacturers not only to produce batteries in an energy efficient way but also to build batteries that last longer. Long lifetime is the most obvious way to pave the way for second life which also is important for recycling as second life applications often means consolidation of many batteries in one place which automatically improves the recycling economics due to less transportation.

For recycling it is important that the standard procedure for calculating GHG emissions include a credit system for recycled material which will contribute to make recycled material attractive and valuable which in itself increase the prerequisites for efficient recycling and collection.

Level of accountability and traceability

All tools listed above can be used in everything from voluntary reporting to regulated product compliance. However if the regulation path is taken there will be high requirements of a secure and transparent system. While the methods for measuring both GHG emissions and CED must be designed with a minimum need for interpretation and the best practice level, as a basis for a moving target value, must be adequately balanced, the largest challenge is that of traceability.

The complexity of the value chain, with a global footprint, constant change in relative power among participants and highly different level of national governance, does not only bring high barriers to the establishment of traceability infrastructure but does also make it difficult to secure and verify the quality of the data. However this is a challenge OEMs already are facing for other than purely environmental reasons. Quality, safety and logistics are all parameters which can be improved and optimised when components and even materials can be traced throughout the value chain. Thus legislation, which creates a common playing field, can benefit many players in the value chain.

There are several issues that have be addressed for full traceability in the battery value chain. First of all there must be a unified system in place which is adopted by all participants. Secondly, there has to be a way to efficiently collect and assign the data, which should be included in battery's footprint, to each component or gram material, and lastly the accuracy of that information has to be verifiable.

There are today initiatives for instance by the Global Battery Alliance to use blockchain as a platform for tracing material and components in the battery value chain[32]. Blockchain technology assigns a distributed ledger to the components in the value chain which is immutable. The technology has been used in the diamond industry enabling full transparency from mining to final product[33]. However, as pointed out in

Cohan, 2018, minerals like cobalt and lithium are very different to diamonds with many more processing steps and difficulties to identify materials on an individual basis, at least in the mining and refining stages. A better comparison would therefore be the food industry. In a research paper about use of blockchain in the food value chain for authentication the authors point out the big potential by using a distributed ledger but also point out the difficulties both in verifying that correct information about the raw materials is entered in the system and also in creating a secure sensor-based tracking system[34].

The battery value chain share the same issues where the identification of materials rely on tagged and packaged batches all the way until it is first turned into a cell. And while authentication potentially could be done by for instance by analysing the actual material it is significantly more complicated to assign energy data to the material. That does however not mean that is impossible. The real benefits come with the ability to follow all components in a pack, even when cells or cell components have been produced at different sites or even by different companies. It could even be possible to use special formulas in real time for instance for calculation of utilisation rate and energy source which would give packs very accurate GHG values.

From a CO2 footprint perspective the traceability down to cell level, and preferably even down to mining site, is essential as that is where the biggest climate impact is found. This requires possibilities to tag each package of material and later each cell to be able to follow the entire chain. Tagging could be based on active or passive RFID or even bar codes. However with active tags it is even possible to log external variables such as temperature which from a quality perspective can be very beneficial and, together with the use of an intelligent battery management system (BMS), can give full understand of the conditions that have affected the battery. Multiple benefits of the system would facilitate its implementation and help to compensate for the costs associated with equipment and additional labour.

Other sustainability issues

Besides the issue of embedded GHG emissions lithium-ion batteries are frequently connected to local problems associated with material extraction, both environmental and human. Especially artisanal mining in the Democratic Republic of Congo (DRC) with verified forced and child labour involved[35] has been in focus as well as environmental problems in there areas in South America where lithium is extracted[36].

Although these problems seem to be similar to the embedded GHG emissions, as in that they are not wanted, they do have another dimension. First of there is no current legislation on EU level that regulate the use of forced or child labour in products sold in Europe. Neither is there legislation regulating environmental harm outside of EU. Given that GHG emissions are global in its nature and that there is legislation regulating how much CO2 vehicles can emit, it is therefore hard to make fully accurate comparison. To make the matter more complicated many of these activities are often legal in the countries where they are taking place.

There are many industrial activities that can be connected to child and forced labour and local environmental problems[37], including mining of other materials than only battery metals[38]. If regulations should be designed to prevent this they should address the larger problem and not tie it exclusively to lithium-ion batteries.

With a traceability system in place this could however be used by OEMs to voluntarily trace the origin of the materials in the batteries and how they have been produced. As this aligns with the interests of mining companies in Europe, where both child and forced labour as well as local environmental impact is regulated, a traceability or tracking system could be used by OEMs to show their batteries are produced in best possible ethical and environmental way.

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