Will future batteries be greener?

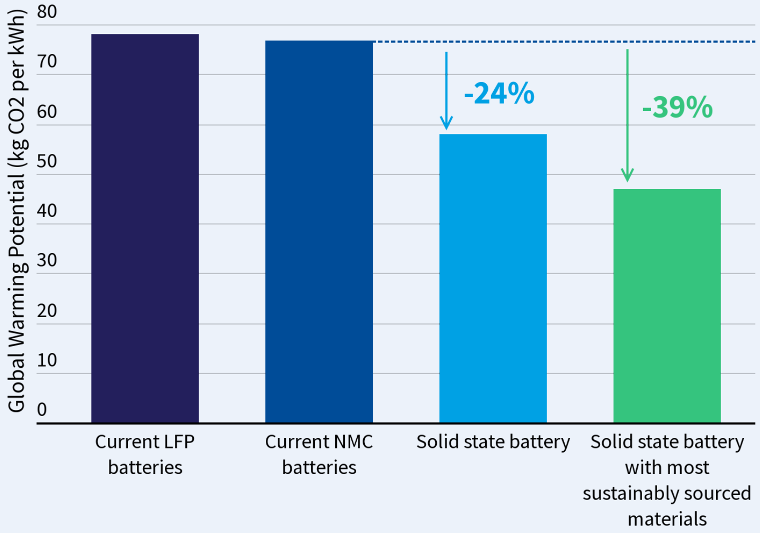
The lifecycle emissions of solid state batteries & future supply chains

July 2022

Summary

Batteries are the fastest growing storage technology and will ultimately be crucial in helping meet Europe's decarbonization goals, especially in the road transport sector. Car manufacturers globally are already thinking about what kind of batteries will power the vehicles of the future and, whilst the jury is still out, many regard solid-state batteries (SSBs) as the next generation of battery technology for electric vehicles (EVs).

Solid state batteries can reduce carbon footprint of EV batteries even further



Results for displayed solid state batteries are with an oxide solid electrolyte and a NMC cathode
Source: Minviro (2022), Comparative Life Cycle Assessment Study Of Solid State And Lithium-Ion Batteries For Electric Vehicle Application In Europe

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The expectations around the potential benefits of SSBs - which replace the liquid electrolytes with innovative solid materials - are high. This technology promises increased safety, longer driving range (due to higher energy density), faster charging times and, eventually, lower costs. However, little is known about their potential environmental impact compared to conventional lithium-ion batteries, and whether SSBs are an environmental, as well as industrial, opportunity.

Transport & Environment is one of the first to attempt to answer this question. We commissioned a study to Minviro, a company specialised in raw material life-cycle analysis, to look at the environmental performance of SSBs manufactured in Europe in

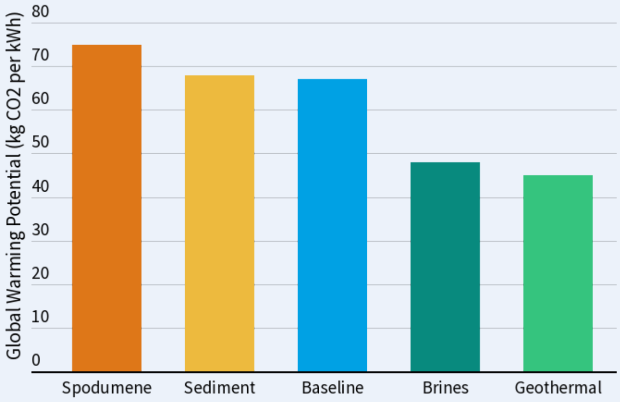
comparison to incumbent lithium-ion battery technologies. The study looks at global warming potential of solid-state batteries and compares them to the current and upcoming chemistries: nickel-manganese-cobalt-lithium (NMC-811), lithium-iron-phosphate (LFP) and its promising derivative lithium-iron-manganese-phosphate (LFMP).

Solid state batteries have a lower carbon footprint from the outset

The results show that most SSB battery configurations have lower global warming potential than today's chemistries. Notably, a likely example that uses an oxide electrolyte and an NMC-811 cathode has the lowest global warming potential, enabling a 24% reduction when compared to the latest lithium-ion technology. LFP batteries, which are fast entering the EV market, have low greenhouse gas impact per kg but, due to lower energy density, feature less well on the per kWh basis. Upcoming LFMP is more promising in this regard.

Despite potential for lower GHG impacts, the study also identified emission hotspots for different battery technologies, including future chemistries. In the case of SSBs, the hotspot is expected to be the lithium metal used in the anode, along with the cathode active material. This is because SSBs will require on average 35% more lithium than current lithium-ion chemistries.

Global Warming Potential depending on lithium carbonate source



Impact for a Sulfide SSB (LFP Cathode)
Source: Minviro (2022), Comparative Life Cycle Assessment Study Of Solid State And Lithium-Ion Batteries For Electric Vehicle Application In Europe

Sustainable sourcing of metals will remain key

The second part of the analysis done by Minviro looked at the different supply routes for key battery raw materials in order to better understand which sourcing and processing methods have the potential to significantly reduce, and in some instances even half, the carbon footprint of a battery.

In the case of lithium, the research found that spodumene and sedimentary clay-based lithium sources, which are mainly mined in Australia and refined in China, result in higher impacts compared to the other sources of lithium given the additional energy required to mine, prepare and refine to the final product. Brine-derived lithium and lithium directly extracted from geothermal wells on the contrary, have a significantly lower impact and potential to reduce emissions significantly.

Solid state batteries can therefore not only deliver on better performance, but can also bring significant environmental benefits. However, getting those environmental benefits will depend on the sustainability of the battery supply chains and processes used. In the case of nickel for instance, by using bioleaching the reduction of $kgCO_2/kWh$ is close to 50% compared to pig-iron sourcing, which is a carbon intensive way widely used today in China.

Given Europe's relatively competitive, low carbon electricity grid mix compared to other continents and strong technology know-how, SSBs are especially an opportunity for Europe to become a world leader in battery manufacturing. However, as Europe is reliant and will continue to rely on raw material imports for battery production, it is equally important that low-impact raw materials are selected and their use incentivised.

Europe must use its regulatory powers to incentivise low carbon battery production and recycling of key metals, as well as ensure strong environmental and human rights due diligence across not only battery supply chains but for all extractive industries. These are some 'no regrets' policies that apply to both today's and future SSB chemistries:

- **Support an ambitious new Battery Regulation**. The final law should:
    - **Incentivise batteries with a lower carbon footprint via ambitious carbon footprint rules**.
    - **Support higher lithium recycling targets.** Given the higher need for Li in SSB, getting most out of lithium recycling is key. The lithium recovery targets put forward by the European Commission in the regulation should be increased to 70% in 2025 and 90% in 2030 as per the European Parliament position.
    - **Ensure strong due diligence rules for battery raw materials.** Due diligence is only as strong as the mechanisms that accompany it. The new law should include grievance and liability mechanisms, to ensure access to justice to those harmed and to remedy environmental damage.
- **Mandate human rights and environmental due diligence rules on all extractive industries.** The proposed Corporate Sustainability Due Diligence Directive presents an opportunity for Europe to once and for all regulate the extractive industries, setting mandatory obligations to trace, prevent and remedy any harm caused by companies globally for products entering the EU market.
- **Update European mining codes and waste legislation.** European mining laws (at national and EU level) must be reviewed and strengthened, so that when mining is done in Europe it follows the highest possible standards, e.g. on mining waste tailings. With the EU planning to propose a new Raw Materials Act, it is imperative that any proposal to streamline access to raw materials, such as lithium, on the EU territory - as well as funding - is attached to strict environmental and social conditions.

Beyond sustainability concerns, the increased demand for battery metals, notably lithium for SSB, raises the question if the current supply will be sufficient for the fast growing battery demand. With solid-state battery production expected to ramp up towards the end of the decade, this will coincide largely with new lithium capacity coming online. Carmakers today are already securing long-term supply agreements of battery metals (not only lithium) in line with their electric car pledges, which also gives them a say over the extraction conditions. A lot more metals towards the end of the decade will also come from recycling streams, which - alongside policies that need to shift to rightly sized EVs - should enable regions like Europe to secure enough supply for the Green Deal goals.

Further to this, in light of the war in Ukraine, and the effort to reduce the dependence on Russian oil and gas, it is evermore urgent that the EU utilises its diplomatic power to secure not fossil fuels but the metals needed for a green energy independence.

The future of road vehicles is electric. The future of batteries are lower carbon, higher performance chemistries. What we now need to ensure is that the metals that go into them are produced responsibly and sustainably, which is why the decisions taken on a number of regulations under consideration now are paramount.

1. Introduction

Batteries, already a fundamental part of our day to day lives, are set to become the key strategic technology of the 21st century. They are the fastest growing storage technology and will ultimately be crucial in ensuring the EU can meet its decarbonisation goals, especially in the transport sector.

Europe is shifting to mass-market production of electric vehicles (EVs), with plans for battery gigafactories to be built across the continent. To date, at least 38 gigafactories[1] are planned or announced, with a total estimated capacity of 460 GWh in 2025, enough to power around 8 million battery electric cars.

Automakers are already thinking about what kind of batteries will power the cars of the future and, whilst the jury is still out, many regard solid-state batteries (SSBs) as the next generation of battery technology for EVs.

Whilst there are big expectations for the potential benefits of SSBs regarding increased safety, longer driving range (due to higher energy density), faster charging and (eventually) lower costs, little is known about their potential environmental impact compared to conventional lithium-ion batteries (LIBs), and whether SSBs are an environmental, as well as industrial, opportunity.

This briefing seeks to shed some light on these questions, look at where the opportunities lie for development of SSBs, and what policy makers can do to take advantage of these. We will first look at what solid-state batteries are and how they are different to conventional lithium-ion batteries, why car companies are betting on them, and will summarise the findings of analysis conducted by Minviro (a company specialised in raw material life-cycle analysis), which looked at the environmental performance of manufacturing SSBs in Europe in comparison to incumbent lithium ion battery technologies.

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[1] https://www.transportenvironment.org/discover/weak-climate-rules-put-europes-battery-boom-at-risk/

Europe has the opportunity to become a world leader in battery manufacturing, given its relatively competitive, low impact electricity grid mix compared to other continents and strong technology infrastructure. However, Europe is reliant and will continue to rely on high amounts of raw material imports for production. It is imperative that whilst creating products to drive decarbonisation (prominently batteries for electric vehicles), low-impact raw materials are selected through the entire bill of materials to ensure that the environmental cost of the creation of these products aligns with their use phase purpose.

1.1. Solid state batteries explained

Commercialisation of electric vehicles today is largely thanks to the improvements achieved in lithium-ion battery chemistry over the past decade, from energy density improvements to overall cost reductions. Better performance, safety and cost is expected however from the next generation of batteries and that is why companies have their eyes on solid-state batteries.

In lithium ion batteries, a liquid electrolyte allows lithium ions to travel between electrodes moving from the cathode to the anode. The electrolyte effectively allows an electrical charge to pass between the two terminals, therefore converting stored energy into usable electrical energy. In solid-state batteries, the liquid electrolyte is replaced by a solid one which is coupled with a lithium metal anode. Replacing the graphite in the anode with a lithium metal is the most promising way to increase battery energy density. Nevertheless, conventional liquid electrolyte cannot be used with a lithium metal anode due to formation of lithium dendrites, a harmful phenomenon that can damage a battery causing short circuits and decrease in the battery capacity. Some solid state electrolytes have the potential to reduce the risk of lithium dendrite formation and expansion in automotive operating conditions[2].

These changes promise to increase the energy density of the battery by up to 60% compared to conventional lithium-ion batteries[3]. This would enable carmakers to either use lighter batteries with the same electric range, or to increase BEV range with batteries of similar weight.

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[2] https://www.quantumscape.com/resources/blog/can-lithium-metal-anodes-work-with-liquid-or-polymer-electrolytes/

[3] SSB are expected to reach a 400 Wh/kg energy density whereas LIB would achieve 250 Wh/kg (NMC-811 cathode)

INFO BOX: Solid electrolytes

The electrolyte is the part of the battery that allows current to flow between the anode and the cathode (plus pole) and the anode (minus pole). In a conventional lithium ion battery, the current flow is actually a flow of lithium ions in a liquid electrolyte made of lithium salt, organic solvent, and additives. In a SSB, this liquid electrolyte is replaced by various solid materials, such as ceramic or polymer materials for instance.

The most common forms of solid electrolytes studied in the literature can be classified in three families: oxide, sulfide and polymer. While sulfide and oxide manufacturing processes are sufficiently documented in available literature, polymer electrolyte appears to still be an emerging technology and was not included in the Minviro analysis. The race between the different types of electrolyte is still unclear as they all have different pros and cons. Oxides benefit from an excellent chemical stability and safety but their manufacturing process is more energy intensive due to higher temperature required and the material has a lower mechanical strength. Sulfides benefit from a higher conductivity and can be manufactured at lower temperature, but the material emits hazardous gas when it is in contact with moisture and it has a lower chemical stability.

Beyond improved energy density, solid-state battery chemistry also boasts greater chemical stability and safety. Although extremely rare these days, any safety concerns associated with EVs are often linked to the battery overheating and thereby creating a risk of fire. Solid-state batteries promise to solve this issue as they significantly decrease these risks thanks to the use of non-flammable solid-state electrolytes. Further to this, improved chemical stability of SSBs means that fewer safety systems are needed, thereby increasing the energy density at the cell pack level.

Car companies are attracted by solid-state batteries also because they promise to greatly reduce one of the biggest barriers to consumer adoption of EVs: charging times. QuantumScape, a Californian startup that has a joint-venture with VW, claims that its solid-state batteries are able to charge to 80% of capacity in 15 minutes[4], which almost halves what lithium-ion batteries can achieve today on a fast charge.

Car OEMs and battery companies are therefore increasingly looking to shift to solid-state batteries either through in-house developments, forming industry consortiums or investing in promising start-ups. For example, in Europe a research cluster called “FastBatt” was founded in Germany with car manufacturers VW, BMW and Daimler as well as European companies Umicore, BASF and Solvay involved.

Solid-state batteries are moving from the R&D production phase to the pilot production phase, with some Chinese OEMs claiming commercialisation is only three to four years away. Similarly, Toyota and Volkswagen have publicly announced that vehicles with SSBs could be expected on the road already in

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[4] https://ir.quantumscape.com/resources/press-releases/news-details/2022/QuantumScape-Data-Shows-Industry-First-15-minute-Fast-Charging-for-Hundreds-of-Consecutive-Cycles/default.aspx

2025. The large majority of players in this space however, including battery manufacturers LG Chem and Samsung SDI, have been more conservative in their forecasts and are promising the technology to be used in EVs for the second half of the decade.

Research by BNEF[5] expects the cost of solid-state battery per kWh to be eventually lower than its lithium-ion counterparts once supply chains are established. This is due to the fact that when using solid-state electrolytes with higher energy density, the material cost is reduced as less raw material is required per kWh. Moreover, some manufacturing steps and components can be eliminated thereby saving on equipment and production costs. Further to this, this new chemistry will benefit from the downward trajectory of overall battery manufacturing costs as some of the components of today's batteries will remain the same.

Regardless of when SSBs will be commercially available, one thing is certain: the technology will drive up the demand for lithium while at the same time lowering the demand for other materials. In solid-state technology, lithium is used both in the cathode and in the anode, and its intensity in the solid electrolyte is around 14 times higher than for liquid electrolyte. According to BNEF, an average increase of 35% of lithium is expected when compared to traditional battery cells.

But while SSBs are expected to deliver numerous commercial and consumer benefits, how good will this technology actually be from an environmental perspective? Transport & Environment (T&E) is the first to attempt to answer this question.

2. Environmental impact of SSB production

T&E commissioned Minviro, a company specialised in life cycle assessment (LCA)'s for raw materials, to carry out a LCA on the production of solid-state batteries in Europe. This section summarises the findings of the study[6], which looks at the global warming potential (GWP) for SSB production and compares it to two incumbent commercial lithium-ion battery chemistries. The chosen chemistries, which are NMC-811 (lithium-ion battery with a nickel-manganese-cobalt cathode) and LFP (lithium-ion battery with a lithium-iron-phosphate cathode), are the latest best in class chemistries. Furthermore, Minviro also investigated a third chemistry which is currently less developed compared to the other two (LFMP, an LFP battery with the addition of manganese).

Beyond assessing the GWP of these chemistries, T&E also asked Minviro to explore different supply routes for sourcing key battery raw materials to identify potential supply routes and manufacturing processes where significant improvements on carbon footprint could be made.

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[5] BNEF. (2021) A route for solid-state battery adoption: Europe and U.S.

[6] This study has been conducted according to the requirements of the ISO-14040:2006 and ISO-14044:2006. All results are for the specific set of assumptions detailed in the Minviro report and are based on the best available academic and industrial data for the solid-state battery manufacturing process. In the absence of measured impact values or an industrial third-party review, the results from this predictive study are indicative and for educational purposes.

2.1 Global Warming Potential

The key impact category selected for the LCA Minviro conducted is the global warming potential. Developed by the UN Intergovernmental Panel on Climate Change (IPPC), the GWP metric was developed to allow comparisons of the global warming impacts of different gases, with the reference unit being kg CO_2 eq. It was specifically chosen for this project because it enabled Minviro to assess battery supply chains at a high-level and it is not based on a specific project development.

Minviro analysed the environmental impact of solid-state batteries with a solid sulfide and oxide electrolyte with two different cathode chemistries and a lithium metal anode. These were compared to incumbent lithium-iron-phosphate (LFP) and nickel-manganese-cobalt-lithium (NMC-811) chemistries as well as with the less-developed but promising lithium-iron-manganese-phosphate (LFMP) chemistry[7].

The results of the analysis, which are summarised in the graph below, show that, among all considered options, a SSB battery configuration that uses an oxide electrolyte and an NMC-811 cathode has the lowest global warming potential (58 kgCO_2/kWh). The type of solid electrolyte used appears to have a relatively low influence on the results as the sulfide option has only a 3% higher impact (60 kgCO_2/kWh). Compared to the latest NMC-811 technology with liquid electrolyte (77 kgCO_2/kWh), the use of a solid state configuration enables a 24% reduction of the global warming potential. This reduction is primarily explained by the improvement of the battery pack energy density that goes from 250 Wh/kg for LIB to 400 Wh/kg for SSB[8].

In terms of impact by kg of material, LFP technology is the solution with the lowest global warming potential among the investigated technologies. Indeed, an LFP cathode avoids the use of more impactful materials (nickel and cobalt) compared to NMC. But the impact per kg of battery is not the most important functional unit as the impact needs to be compared per kWh of battery. It is mostly the energy contained in the battery that matters for an electric vehicle range, so the global warming potential has to be compared per kWh of batteries. The analysis highlights that the lower energy density of the LFP battery packs (174 Wh/kg in the case of LFP LIB[9] and 250 Wh/kg for LFP SSB configurations) implies a larger impact compared to battery configuration using NMC cathode: with 64 kgCO_2/kWh, an oxide SSB with a LFP cathode has a 11% higher impact than an oxide SSB with an NMC cathode, whereas conventional LFP LIB (78 kgCO_2/kWh) have a 2% higher impact than NMC LIB. As new LFP LIB with higher energy density (more than 180 Wh/kg) are expected in the market, the LFP technology's global warming potential could soon become similar or lower than the NMC technology. Nevertheless, the new LFMP technology that combines manganese in the LFP cathode active material appears to be a promising

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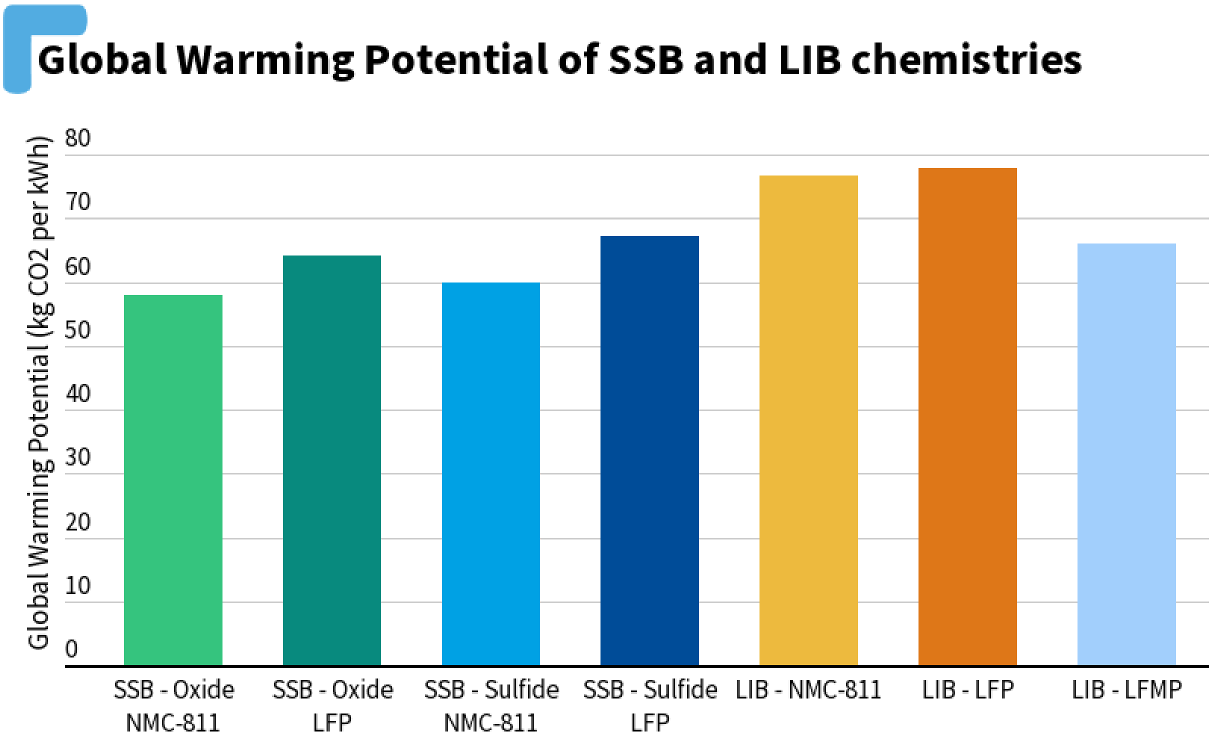
[7] In the 2022 EV outlook, BloombergNEF forecast LFMP chemistry to amount to 6% of the chemistry used in 2023 and 12% from 2025.

[8] Energy densities reported by Minviro and defined by best-estimate academic studies.

[9] Minviro used the latest best-in-class technology at the time of the study but the latest report from Gotion High-Tech suggests that its technology planned to be produced at the end of 2022 could reach an energy density higher than 180 Wh/kg at pack level (230 Wh/kg at cell level).
https://www.electrive.com/2022/04/01/gotion-high-tech-begins-serial-production-of-210-wh-kg-lfp-batteries/

solution. Indeed, it has the potential to increase the energy density by 25%, hence reducing the global warming potential to 66 $kgCO_2/kWh$,a 15% reduction compared to LFP LIB.


Global Warming Potential of SSB and LIB chemistries

Source: Minviro (2022), Comparative Life Cycle Assessment Study Of Solid State And Lithium-Ion Batteries For Electric Vehicle Application In Europe

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Beyond assessing the overall global warming potential impact of the different chemistries, the study identified for each given battery chemistry specific emission hotspots.

What the analysis found is that the main driver of the GWP impact in SSBs is the lithium metal used in the anode, along with the cathode active material and the electricity consumption during certain manufacturing processes. With SSB having an increase of lithium of up to 35% in some cases compared to LIB (as mentioned in Section 1), policies aimed at recycling and recovering high percentages and yields of lithium from current spent batteries will be crucial to secure as much secondary raw material as possible for a sustainable shift to SSB adoption. Further to this, a fast penetration of renewable energy coupled with policies aimed at lowering the intensity of the energy used to produce batteries will enable greater benefits of shifting to this technology.

In lithium-ion batteries, the study found that for NMC-811 chemistry the main drivers of GWP are the nickel sulfate production used in the cathode, the graphite production used in the anode and energy for drying processes. For LFP chemistry, the picture is similar with graphite production used in the anode and energy for drying processes being the biggest drivers along with the lithium carbonate production used in cathode active material manufacturing. Finally, for LFMP, the addition of manganese oxide to the LFP bill of materials results in a higher impact per kilogram.

Overall, what the first part of Minviro's detailed analysis shows is that future battery chemistries in the SSB family will not only have better performance, but also have potential to reduce lifecycle emissions (or carbon footprint) of batteries, therefore further improving the environmental performance of EVs. In general, there are significant opportunities to address and reduce a battery's carbon footprint.

2.2. Supply chain scenarios analysis

The different components that make up batteries can have high impacts on their final carbon footprint, which is dependent on their production process, region of origin, energy and resources used in manufacturing. The second part of Minviro's study therefore looked at the following raw materials and the impact of using different sourcing and refining options: (1) lithium chemicals, (2) nickel sulfate, (3) manganese sulfate, (4) graphite and (5) iron oxide.

For the purpose of this report, a summary of the findings for lithium, nickel and graphite are presented below. Manganese and iron have not been included in this briefing as the results of each of the scenarios modelled do not present remarkable differences. In the case of manganese, this is due to the lack of data linked to the raw material's supply chains, therefore making it difficult to have a clear insight into the difference in impact of primary and secondary sourcing. In the case of iron, the material is responsible for a minor part of LFP battery global warming potential meaning that changes in the supply chain have little impact on the overall carbon footprint.

2.2.1 Lithium chemicals

In SSBs and lithium-ion batteries, two types of lithium chemicals are used: lithium carbonate and lithium hydroxide. Whilst both can be sourced from the same lithium deposit, they require different approaches to create the final chemical, ultimately determining (together with the original source of the mineral) the overall material and energy requirements. In general, both types of lithium can be manufactured directly from spodumene (a lithium ore), but lithium from brines must be converted into carbonate before being converted into hydroxide.

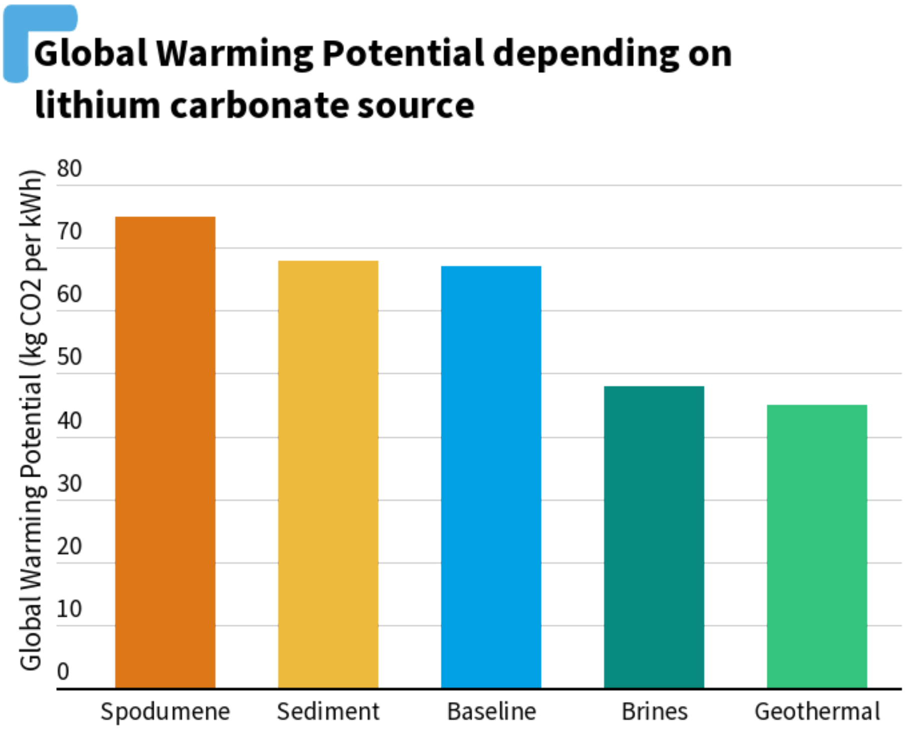
Lithium carbonate can be formed in two ways. Either by conversion directly from spodumene concentrate via a sulfate chemical process or by treating brines via a thermal treatment and evaporation process before combining with sodium carbonate. It can be used in cathode manufacturing, for example for creating the lithium iron phosphate active material in LFP cathodes by combining with other materials.

Lithium hydroxide can also be formed in two ways. The first one is the conversion, like for lithium carbonate, via a sulfate chemical process. The second one is the conversion from brine-derived lithium carbonate products, entailing a slightly higher energy requirement due to the extra steps beyond those in the carbonate route and therefore, higher project costs. However, lithium hydroxide's performance

exceeds that of lithium carbonate, which degrades quicker. This type of lithium is used in NMC-811 battery cathodes alongside base metal sulfates, as the chemistry benefits from the higher performance provided.
In solid-state technology, more lithium will be required compared to LIB technology as the raw material is used both in the cathode and in the anode. The content of graphite however, will significantly drop.

Lithium carbonate

The below graph presents the total GWP impact of different lithium carbonate supply chains specific to sulfide SSB (LFP cathode).



Global Warming Potential depending on lithium carbonate source

Impact for a Sulfide SSB (LFP Cathode)
Source: Minviro (2022), Comparative Life Cycle Assessment Study Of Solid State And Lithium-Ion Batteries For Electric Vehicle Application In Europe

What is shown is that spodumene and sedimentary clay-based lithium sources, which are mainly mined in Australia and refined in China, result in higher impacts compared to the other sources of lithium given the additional processing required to mine, prepare and refine to the final carbonate product.

Brine-derived lithium and lithium extracted via geothermal processing on the contrary, have a significantly lower GWP impact. Brines however, which today are mainly encountered in the Atacama Desert region in South America, are linked to other environmental concerns such as water depletion.

It is crucial, therefore, that innovative, low impact methods of extracting lithium are explored. In the case of lithium derived from brines for instance (or even geothermal), Direct Lithium Extraction (DLE) is gaining prominence given the potential it has to greatly reduce water consumption compared to traditional evaporation techniques used in most brine projects. DLE, as the name suggests, extracts lithium directly from underground brines using a process that involves a highly selective absorbent. The extracted solution is then polished of impurities to yield high-grade lithium carbonate and lithium hydroxide. Crucially, DLE enables the brine to be returned to its original place of extraction once the lithium has been recovered, thereby significantly reducing water consumption. Other advantages of this technology include the rapidity by which lithium can be extracted versus traditional brine evaporation methods and the fact that it can recover a much higher percentage of lithium (close to 90%) compared to conventional extraction processes (closer to 40%).

Uniquely, DLE technology can be coupled with geothermal energy giving origin to so-called geothermal lithium. Geothermal lithium combines the benefits of DLE with those of renewable energy thereby having a zero-carbon footprint. With geothermal lithium deposits also present across the European region, companies are launching pilot projects such as Eramet in France[10], Cornish Lithium in the UK[11] and Vulcan Energy Resources in Germany[12] and France.

Some barriers to this technology however include that it is not yet tested at large scale over a longer period of time, with the economics of it still to be determined. However, regulation can play a key role in incentivising this promising new technology (*see recommendations below*).

Lithium hydroxide

For lithium hydroxide, similarly to lithium carbonate, spodumene and sedimentary clay are the highest impact routes. Whilst brine-derived and geothermal lithium are once again lower impact, they do have a higher impact compared to lithium carbonate. This is because, as outlined above, to obtain lithium hydroxide extra steps are required resulting in a higher energy requirement.

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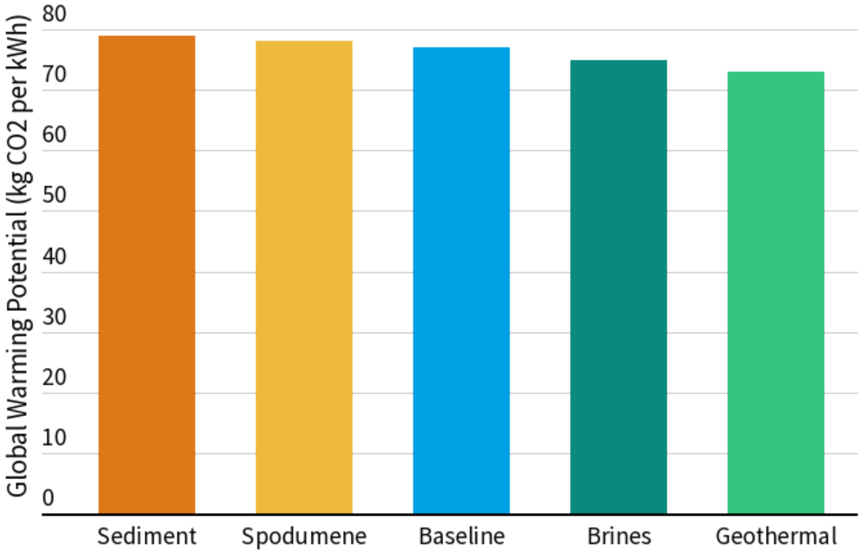
[10] https://www.eramet.com/en/eramet-and-electricite-de-strasbourg-announce-success-first-pilot-test-extract-lithium-geothermal

[11] https://cornishlithium.com/projects/lithium-in-geothermal-waters/direct-lithium-extraction/

[12] https://www.reuters.com/business/lithium-miner-vulcan-gets-five-more-exploration-licences-germany-2022-01-04/

Global Warming Potential depending on lithium hydroxide source

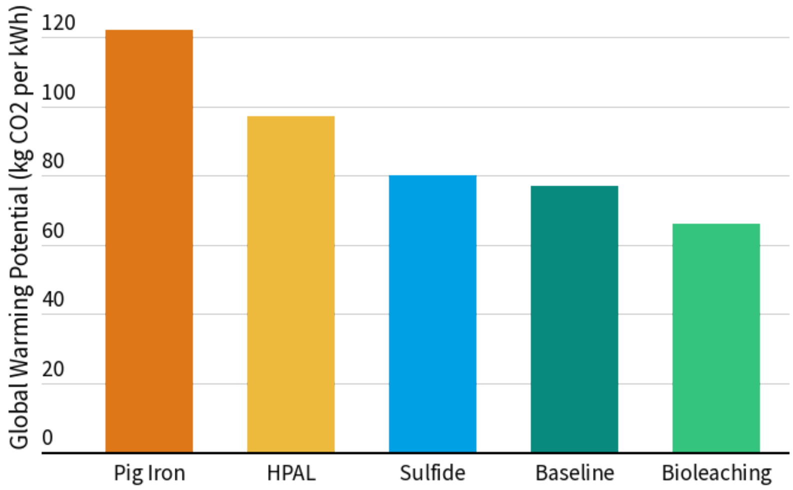


Impact for a LIB (NMC-811 Cathode)
Source: Minviro (2022), Comparative Life Cycle Assessment Study Of Solid State And Lithium-Ion Batteries For Electric Vehicle Application In Europe

2.2. Nickel sulfate

For nickel, the highest impact source is by far nickel pig iron which is a cheap source of the material which is created by mixing low-grade nickel ore with coking coal. This practice, which is widely used in China and Indonesia, has a large environmental impact due to the consumption of fossil fuels in its production process.

Global Warming Potential depending on nickel sulfate source



Impact for a LIB (NMC-811 Cathode)
Source: Minviro (2022), Comparative Life Cycle Assessment Study Of Solid State And Lithium-Ion Batteries For Electric Vehicle Application In Europe

The second-highest impact source, high pressure acid leach (HPAL), is also widely conducted in Indonesia, where the electricity grid mix is dominated by fossil-sources. Further, the HPAL process is also chemically-intensive and the embodied impacts of creating such reagents can result in a high total impact for nickel sulfate derived from these sources.

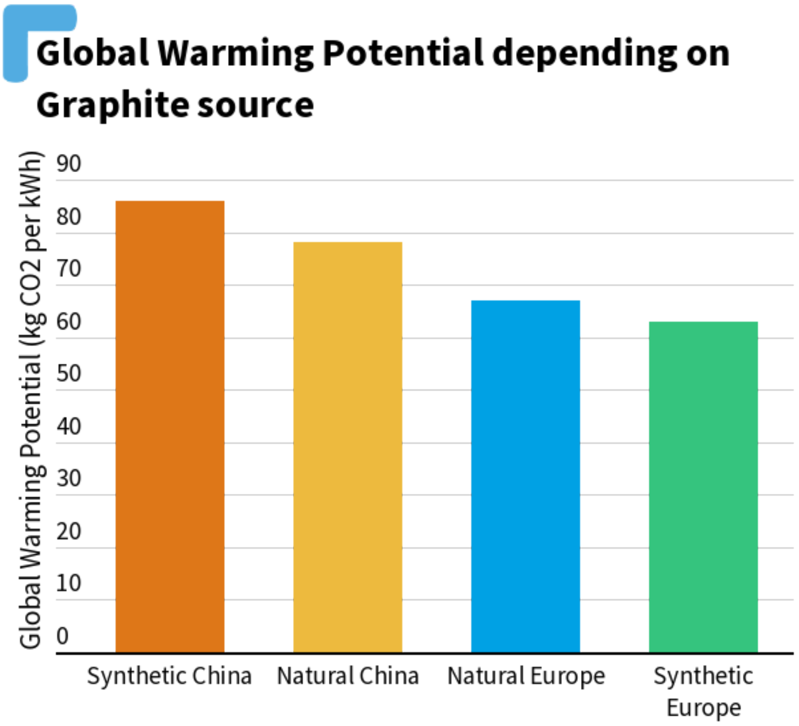
With the potential of reducing the $kgCO_2/kWh$ by close to 50%, the lowest impact source is bioleaching. This method is a process in mining and biohydrometallurgy (natural processes of interactions between microbes and minerals) that consists in extracting valuable metals from low-grade ores with the help of microorganisms such as bacteria therefore removing the need for intense chemical processing and ultimately significantly reducing the embedded emissions.

Bioleaching is a promising technology from an environmental perspective as it can be used also to treat and recover materials from tailing sites (mining waste) to extract residual metals. It also has potential as it avoids completely the use of sulphur dioxide emissions, which in contrast are used in traditional nickel extraction methods. Due to the lack of regulatory incentives at present that favour low-carbon technologies however, pig-iron is often chosen as the primary source of nickel despite its poor environmental credentials. Therefore, the proposed Battery Regulation, which will include emission thresholds, can support the deployment of bioleaching through incentivising less impactful technologies.

2.3. Graphite

In the case of graphite, as it is mainly sourced and produced in China to date, its GWP reflects the energy input of the fossil fuel dominated grid mix in the country.

Synthetic graphite has an even higher GWP than natural graphite as it is created via chemical processing of coke, on top of all the steps necessary to process natural graphite.



Impact for a LIB (LFP Cathode)
Source: Minviro (2022), Comparative Life Cycle Assessment Study Of Solid State And Lithium-Ion Batteries For Electric Vehicle Application In Europe

The study finds that producing graphite in Europe has a significantly lower impact compared to China, thanks to a greater share of renewable energy in its grid mix. While short-term innovation in the battery chemistry space will include silicon into graphite anodes, future SSB chemistries are expected to move away from graphite in the future in favour of lithium-metal anodes.

Low-carbon graphite in Europe is a reality today. Talga, an Australian battery anode and graphene additives company, is in fact scaling up its operations in northern Sweden creating a vertically integrated supply chain able to deliver high-quality graphite with a low CO_2 footprint[13] for batteries made in Europe. Opportunities such as this one in Europe can be further incentivised by the upcoming carbon footprint rules in the proposed Battery Regulation.

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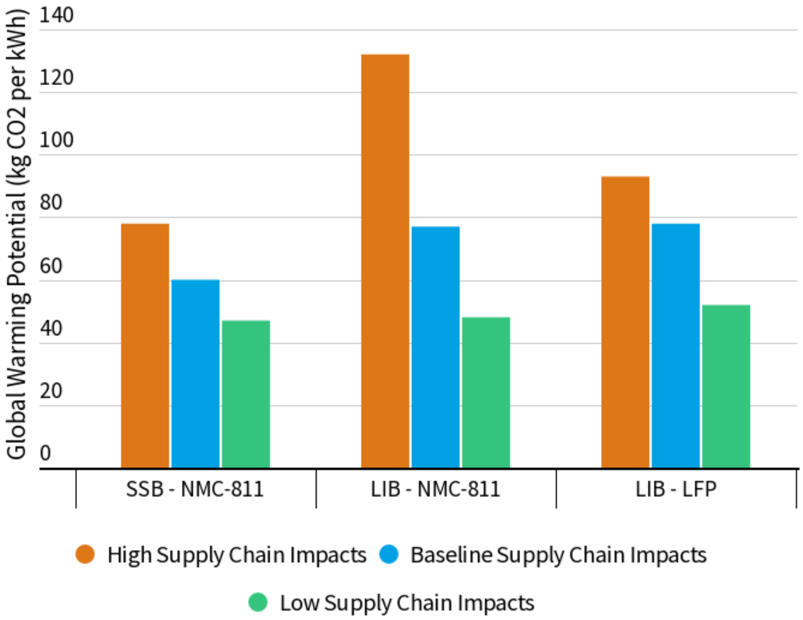
[13] https://www.talgagroup.com/irm/PDF/c8a38dfc-39cd-42c2-be94-4355dc2a3289/IndustryLeadingGreenBatteryAnodeLCAResults

3. Conclusions

With electric vehicles penetrating market share across Europe, European policymakers must have a clear vision and help create a competitive, future proof battery market with ambitious sustainability objectives.

What the analysis done by Minviro shows is that future battery chemistries coupled with better material sourcing and processing practices have the potential to significantly reduce, and in some instances even half for selected raw materials, the carbon footprint of a battery.

Global Warming Potential under different supply chain scenarios



Source: Minviro (2022), Comparative Life Cycle Assessment Study Of Solid State And Lithium-Ion Batteries For Electric Vehicle Application In Europe

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Solid state batteries can therefore not only deliver on the promises that are so attractive for automakers such as improved range and reduced charging time, but can - compared to lithium ion batteries - bring even further environmental benefits. As summarised in the above graph, solid state batteries are already better from the off-set thanks to having a lower carbon footprint. Key emission hotspots however will remain, linked to specific stages of the manufacturing process or to certain raw materials such as lithium.

In order to address these issues, Europe must incentivise better production practices. With European regulators now discussing the details of the proposed Battery Regulation, including provisions on carbon footprint, recycling and due diligence rules, T&E calls on policymakers to support “no regret” options in the proposed regulation, namely:

- **Incentivise batteries with a lower carbon footprint.** What the Minviro report shows is that how battery materials are produced and sourced can have a significant impact on the overall carbon footprint of the battery. With batteries produced in Europe already having a much lower carbon footprint, policymakers should incentivise low carbon solutions such as lithium produced by geothermal in central Europe or natural graphite extracted in northern Sweden. Ultimately, Europe has the opportunity to become a world leader in battery manufacturing, thanks to its relatively competitive, low impact electricity grid mix compared to other continents and strong technology infrastructure. Manufacturing of low carbon batteries benefits European industry and the environment.
- **Support higher lithium recycling targets.** Solid state batteries will require a 35% increase of lithium content compared to lithium-ion chemistries. For this reason, it is key that the lithium recovery targets put forward by the European Commission in the regulation are increased to 70% in 2025 and 90% in 2030 - targets which are already today within the current commercial range for recycling[14].
- **Strong due diligence rules for battery raw materials.** Binding due diligence rules on environmental and social protection can only encourage sustainable mineral extraction, regardless of a battery's end chemistry. With European companies already having a strong track record of supply chain due diligence policies, binding rules can help promote less impactful extraction methods such as geothermal lithium extraction.

Human rights and environmental protection however should not only apply to the raw materials identified in the Battery Regulation, but to the entire extractive industry. This is why **the new Corporate Sustainability Due Diligence Directive presents an opportunity for Europe to once and for all regulate the extractive industry**, by setting mandatory obligations to trace, prevent and remedy any harm caused by companies globally for products entering the EU market. Likewise, **European mining codes and waste legislation should be updated and strengthened**. National mining laws in many countries are outdated[15], allowing companies to implement poor practices around mining waste tailings for example. Europe should therefore review mining laws ensuring that when mining is done in Europe it follows the highest possible standards.

Given the results outlined above and the investments already happening today, solid-state batteries will be a key technology in the coming years. Europe should therefore not only adopt policies, like the Battery Regulation, that have the potential to improve the environmental credentials of batteries but should also aim at increasing the push for electromobility at large. **The current revision of EU car and van CO_2 standards is an opportunity to create a growing EV market and ecosystem** in which breakthrough innovations such as solid state batteries and other next generation battery chemistries are more likely to develop. Although the targets proposed by the European Commission for 2025 and 2030 - and since confirmed by the Parliament and Council - fall far short of what would be needed to accelerate the transition to emobility this decade, the decision to end the sale of new combustion engine cars by 2035

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[14] BNEF, Lithium-Ion Battery Recycling Market Outlook, 2021

[15] https://www.europarl.europa.eu/cmsdata/243324/Hearing%2002.12.2021%20testimony%20Emerman.pdf

makes the full shift to battery electric vehicles in Europe now inevitable.. To ensure the market for EVs, and EV batteries, does not stagnate during the 2020s due to weak CO2 targets, other policy measures will be needed. For example, a new EU fleets regulation - included as part of the Commission's recent REpowerEU strategy - should include a requirement for **all corporate fleets above a certain size to be 100% zero emission by 2030**.

The increased lithium demand in solid-state batteries however naturally raises the question if the current supply will be sufficient, or if indeed there will be shortages of the raw material. With solid-state battery production only expected to ramp up towards the end of the decade, this will coincide at large with new lithium capacity coming online. Carmakers today are already securing long-term supply agreements of battery metals (not only lithium) in line with their electric car pledges. Ultimately, smart procurement strategies that prioritise long term contracts over reacting to volatile spot markets will enable security of supply for car manufacturers. Furthermore, sourcing raw materials directly also gives the car industry leverage and oversight over the environmental and human rights conditions under which they are extracted.

The EU also has a role to play in this. Europe should use its diplomatic muscle to secure metals for the green transition, by prioritising trade relations with resource-rich countries. These trade deals however should come with strings attached, from environmental protection safeguards and guarantees of human rights protection. Beyond this, the EU should also consider creating a centralised authority to coordinate the security of supply in critical metals, either under the aegis of the European Battery Alliance or directly within the Commission.

The future of road vehicles is electric. The future of batteries are lower carbon, higher performance chemistries. What we now need to ensure is that the metals that go into them are produced responsibly and sustainably, which is why the decisions taken on a number of regulations under consideration now are paramount.

Further information

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