SIGNIFICANCY OF CAPITAL GOODS MANUFACTURING SITES RELATED EMISSIONS IN THE LIFE CYCLE OF CATHODE ACTIVE MATERIAL PRODUCTION

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ABSTRACT

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Significancy of capital goods manufacturing sites related emissions in the life cycle of cathode active material production

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Keywords: carbon footprint, cathode active material, industrial building

This study determined carbon footprint of planned Finnish cathode active material manufacturing and its production factories for 10-year period. The aim was to examine significancy of carbon footprint of building materials of two industrial buildings in relation to emissions caused by cathode active material production. The total emissions were examined as a process entity through a battery value chain from cradle to gate. Carbon footprint has been identified as a significant environmental impact category in battery as well as in construction industry.

For cathode active material, the emissions data was gained mainly from raw material producers, whereas material data for the plants was obtained from the factories' preliminary plans. The plans were used to calculate carbon footprint of the building materials with Oneclick LCA. Material flow quantities to be used in cathode active material production were based on Environmental impact assessment carried out for the ongoing plant projects.

The results indicated that nickel and cobalt sulfate and lithium hydroxide production cause clearly the largest emissions in the process. Emissions from the factories were found to be minor in the process. Finnish cathode active material was seen to be significantly less carbon intensive than Chinese, where most of the product is manufactured globally. Finnish cathode active material and electricity production achieves savings in carbon emissions during electric vehicle's life cycle compared to global production.

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Pääomahyödykkeiden tuotantolaitosten päästöjen merkitys katodiaktiivimateriaalin tuotannon elinkaaressa

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Tutkimuksessa määritettiin suunnitellun suomalaisen katodiaktiivimateriaalin valmistuksen ja sen tuotantotehtaiden hiilijalanjälki 10 vuoden ajanjaksolle. Tavoitteena oli selvittää kahden teollisuusrakennuksen rakennusmateriaalien elinkaaren vaiheiden hiilijalanjäljen merkittävyyttä katodiaktiivimateriaalin tuotannon aiheuttamiin hiilipäästöihin nähden. Kokonaispäästöjä tarkasteltiin prosessikokonaisuutena akkuarvoketjun kautta kehdosta portille. Hiilijalanjälki on tunnistettu merkittäväksi ympäristövaikutuskategoriaksi niin akku- kuin myös rakennusteollisuudessa.

Katodiaktiivimateriaalin osalta raaka-aineiden päästötiedot saatiin pääosin niiden tuottajilta, kun taas laitosten materiaalitiedot saatiin tehtaiden alustavista suunnitelmista. Rakennusmateriaalien hiilijalanjälki laskettiin Oneclick LCA -työkalulla perustuen suunnitelmien materiaalitietoihin. Katodiaktiivimateriaalin tuotantoon käytettävät materiaalivirrat perustuivat käynnissä olevien laitoshankkeiden ympäristövaikutusten arviointiin.

Tulokset osoittivat että nikkeli- ja kobolttisulfaatin sekä litiumhydroksidin tuotanto aiheuttaa selvästi suurimmat päästöt prosessissa. Tehtaiden päästöjen todettiin olevan vähäiset kokonaisuudessa. Suomalainen katodiaktiivimateriaali havaittiin huomattavasti vähemmän hiili-intensiiviseksi kuin kiinalainen, jossa suurin osa tuotteesta valmistetaan maailmanlaajuisesti. Suomalaisen katodiaktiivimateriaalin ja sähkön tuotannossa saavutetaan säästöjä sähköauton elinkaaren hiilipäästöissä globaaliin tuotantoon verrattuna.

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Abbreviations

GHG	Greenhouse gas
GWP	Global warming potential
LCA	Life cycle assessment
pCAM	Precursor cathode active material
CAM	Cathode active material
EV	Electric vehicle
EVB	Electric vehicle battery
LIB	Lithium-ion battery
PEFCR	Product environmental footprint category rules
HVAC	Heating, ventilation and air-conditioning

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1. Introduction

Many governments are planning to ban combustion engine car selling from 2035 onwards. Electric vehicle (EV) markets have been growing faster than expected, which increases demand for energy transition materials. (Finnish Minerals Group, a, 2021). Various industrial companies have planned starting battery cell production in Europe, corresponding to a total annual production of roughly 790 gigawatt hours until the end of this decade (Benchmark Mineral Intelligence, 2022). Original equipment manufacturers in car industry are also committing to fully electrify their future products due to emission classes set by EU. This indicates that growing cell production capacity creates major need to improve activities of European battery value chain. (Finnish Minerals Group, a, 2021). Cathode active material (CAM) is a key part of large EV battery value chain and refined from precursor cathode active material (pCAM). CAM, anode material, electrolytes and separator membranes are the most essential components of a battery cell. Battery modules are produced in a stage after battery cell manufacturing and the final packs are installed for end uses. (Korkiakoski, et al., 2021). In global comparison Finnish battery material production has many competitive advantages as the know-how is extensive in several industries. There are solid knowledge and prominent businesses for example in mining and process industry, machinery, ICT and electrical engineering. In addition, Finland has traditionally been commercially stable operating environment where raw materials are sustainably produced and abundantly available. (Finnish Minerals group, b, 2022).

Current large and complex industrial ecosystem was built over the past 100+ years with the support of cheap and abundant energy source (oil), where mineral resources and financial credit were available in large amounts. Now the aim is to build yet more complex and expensive systems while the financial system is fragile and full of debt, minerals are scarce and human population is unprecedented. (Michaux, 2021). Transition to cleaner systems require a lot more metals than the conventional systems, as the demand only in an electric car is fourfold compared to combustion engine car, not to mention wind farms in comparison to fossil fuel plants. Nickel, cobalt, lithium and manganese are important raw materials for lithium-ion batteries (LIBs) and the current production capacity is not enough to meet the growing demand over the next ten years unless the production capacity and recycle rates are significantly increased. Replacing a metal in LIB with another would also mean a significant

reduction in either performance or the desired property, as cobalt, for example, enables a high efficiency and long operating range for the battery. (Jokilaakso, 2022).

As battery value chain products will be in large demand in the future where sustainable production plays a significant role, sustainable production requires, among other things, minimizing greenhouse gas emissions (GHG) throughout the life cycle of the value chain. (Finnish Minerals Group, a, 2021). Thus, carbon footprint studies are also increasingly needed to recognize the significant emission sources and further find solutions to minimize them. Large-scale production of CAM does not currently exist in Europe, and in order to implement sustainable production throughout the value chain, new information on GHG emissions at different stages of the value chain is needed. Considering industrial buildings, many LCA studies have been made for residential and office buildings, but industrial buildings are not surveyed as broadly. Studies that have investigated emissions from CAM production are also scarce. Furthermore, approximately a third of Finland's GHG emissions are produced by construction and buildings. The emissions need to be reduced in order for Finland to reach its climate targets, while not compromising social justice. Climate policy discussions consider how to speed up low-carbon construction and what would be the appropriate incentives for municipalities and organizations. (Ministry of the Environment, 2021).

This study focuses on determining carbon footprint of planned CAM production and industrial building plants. The aim is to define a carbon footprint of CAM production, which can be compared to building material emissions. From the results it is aimed to point out significant matters that have the highest impact on the carbon footprint. One of the plants produces cathode active material precursor (pCAM), from which the product is transported to another plant (or sold to other customers), where the final CAM product is produced.

Scope of the carbon footprint calculation is limited to the CAM production process, also including emissions from building materials of the two production plants. Considering the CAM production in battery value chain, the study's scope includes all the phases from raw material stage to the CAM production phase, excluding cell and pack manufacturing and downstream applications. Building materials comprise the site infrastructure including building materials of the complexes, coating of external areas, and site elements, but excluding process equipment and building service elements (HVAC). CAM production emissions were examined using life cycle assessment (LCA) from gradle-to-gate according

to ISO 14040 standards, whereas building material emissions were calculated for each life cycle stage. The total carbon footprint consists of CAM production process, life cycle material-bound emissions, building material transportation and energy consumption of the plants. Data on emissions from commercial raw materials production for CAM manufacturing were gathered according to the values reported by raw material producers. Some values were also obtained from the literature. Building material data was gained from plans made for the factory projects. Carbon footprint of the factories was calculated using One Click LCA tool, which is a software made for calculating building environmental impacts.

The pCAM plant will be built in the city of Hamina and the CAM plant in the city of Kotka. Both cities are located in Kymenlaakso region, Finland. Thus, the study focuses on determining emissions from Finnish production. According to Korkiakoski, et al. (2021) the locations were seen best in national location comparison and therefore chosen as construction sites. The plant in Hamina will produce pCAM from 2025 onwards, whereof the material is transported to Kotka plant for further processing or sold elsewhere for other customers. The plant complexes include main factory buildings together with other process buildings. The building infrastructure related emissions provide perspective on how significant the infrastructure environmental impacts are in relation to CAM production emissions. The study also raises general awareness of both, the plant constructors and public about emission formation of industrial construction and CAM production.

2. Cathode Active Material Manufacturing

This section provides a literature-based background for the research. At first, relevant processes of CAM manufacturing are reviewed and processes causing environmental impacts are discussed. The second chapter provides an overview of lithium-ion battery and cathode materials. The third chapter includes relevant aspects related to determination of carbon footprint of building and battery materials.

2.1. Raw materials production

EV adoption growth drives the demand of LIB and its input materials. LIB cathode structure consists of variety of non-renewable metals. Raw material resources are limited meaning that LIB manufacturing can be restricted in the future. The material resources are neither evenly distributed across the world and some of them are located in unsteady regions. Furthermore, some of them are obtained as by-products instead of being produced as primary materials. The bigger concern of high-performance battery technology is therefore more in raw material supply than in its inherent properties. (Greenwood, et al., 2021).

The technology in general is versatile, as there are a variety of material combinations that can be applied to cathodes (Weimer, et al., 2019). Today the key metals of LIB chemistries are nickel, cobalt, manganese and lithium. Lithium is obtained from brine and hard-rock reserves. Different kind of ores, such as sulfidic and lateritic ores and many refined raw materials, such as nickel sulfide hold nickel and cobalt, from which the metals are refined. After required pyrometallurgical (thermal treatment) refining phases, the hydrometallurgical (aqueous solvent treatment) phases typically include material treatment, leaching, liquid purification, and battery metal/chemical production. As high purity is vital for further materials processing, the starting material purity level determines how many downstream steps are needed after leaching to meet the required purity levels used in CAM manufacturing. Pregnant leach solution (PLS), which is formed as a result of metal containing raw material leaching, is typically in need of purification. The purification methods include typically precipitation, solvent extraction and ion transfer. The purification

results in a purified and concentrated metal sulfate solution, which is next evaporated and crystallized to create metal sulfate crystals that are used as raw material in pCAM manufacturing process. If the metal sulfate solution composition is optimal, it may also be possible to manufacture pCAM without metal sulfate crystallization phase. (Metso:Outotec, 2022).

A single company is often responsible for the synthesis of raw material processes, which are usually carried out at one location in the value chain. Weimer, et al. (2019) have divided the material related value chain phases into four stages that include Raw Material, Intermediate Material and Product Material Stages, as well as a final ‘’Tier-n-Stage’’ (Figure 1). There are different steps within these stages that vary depending on desired material requirements. At least one step from each stage will take place regardless of the initial material and final product in concern.

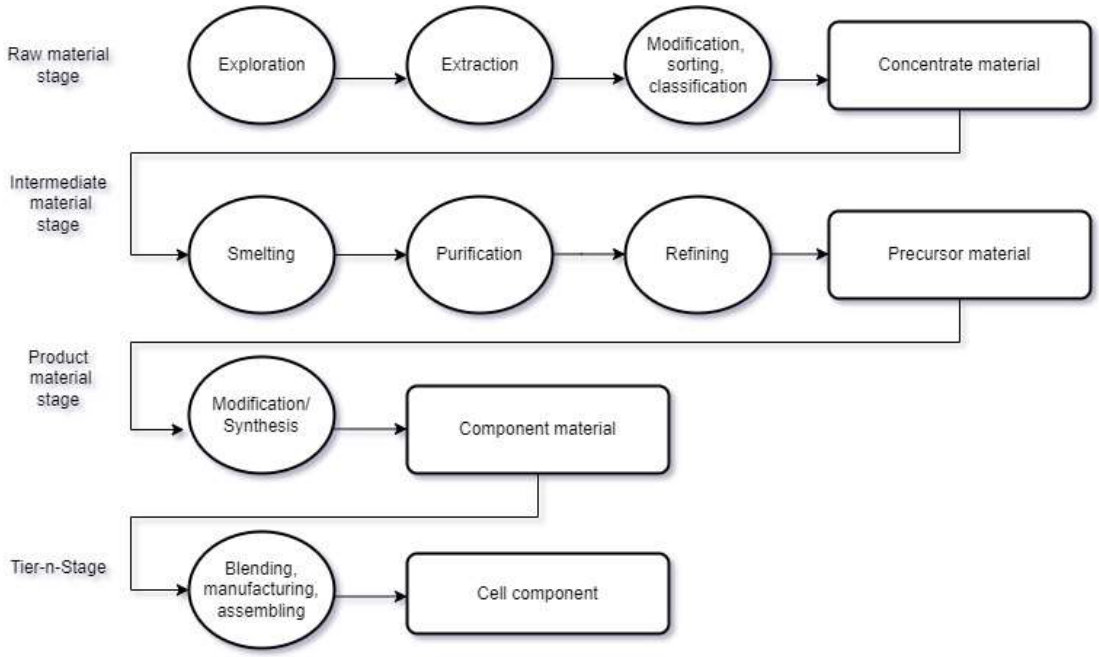

Figure 1. Material stages of battery production (Weimer, et al., 2019).

Raw material can be defined as being any material, such as mineral, wood or salt in its original shape before it is used for industrial processes (Cambridge Dictionary, 2022). The term therefore refers to natural deposit materials and thus the Raw Material Stage comprises all mining related activities including exploration, extraction and beneficiation. Besides initial investments, proactive exploration and availability planning are important when assessing the value chain of mineral raw materials. Extraction is also a key step as it is related

to all forms of reserves utilization including surface, underground and solution mining. Overall, the factors that distinguishes the raw material stage from others is that the chemical properties do not change during the stage processes. (Weimer, et al., 2019).

In Intermediate Material Stage, the material is transferred to further processing but is still quite independent from final application. Thus, the term ‘’intermediate’’ is suitable to describe the stage in the middle of the three material stages. The Intermediate material stage uses concentrate from the Raw Material Stage as its feedstock and can include smelting, purification, or refining depending on concentrate material characteristics. In smelting a metal is chemically reduced from its ore. Therefore, in contrast to Raw Material Stage, this stage always includes material chemical modification. The aim of the phase is to deliver pCAM with adequate quality or chemical properties so that the product is suitable for the third stage. Raw Material and Intermediate Material Stage processes can be taken care of a single or multiple companies, as the processes in these stages are not necessarily product specific. (Weimer, et al., 2019).

In the Product Material Stage, a specific component material (CAM) is produced which is needed for proposed application. In this phase most often the material is modified in a way that its form fulfils required chemical and physical attributes. (Weimer, et al., 2019). In opposite to Raw Material Stage, mixing and combining various precursor materials in this stage is possible (Dunn, et al., 2015). The final Tier-n-Stage can include a variety of stages and therefore specified more accurately by the operators. As final cell components (anode, cathode, electrolyte, separator) are produced in this stage (Weimer, et al., 2019), it is not part of this study’s CAM manufacturing scope, which is discussed in fifth chapter.

Considering the key metals for LIBs, Finnish mining company Terrafame is one example producer of nickel and cobalt. The company uses large-scale open-pit mining, in addition to which the production process includes material treatment, bio heap leaching and metal recovery. After drilling and blasting, ore is loaded to trucks, and transported to crushing. In ore treatment the ore is crushed and screened into granules of almost the same size so that it will be suitable for bio heap leaching. A primary pile is first created for bio heap leaching, which is an exothermic and continuous dynamic process, where the primary pile is leached for 13-18 months after which the primary pile is started to unload and gradually piled up again to secondary pile for further leaching. The leaching is continued for three to four years in secondary pile to recover metals that were poorly dissolved in the primary pile. Solvent

used in leaching contains mainly water, microbes, dissolved metals and sulfuric acid. When metal content is sufficient in the circulation solution, a flow is directed to metals recovery. In the metal recovery the solution is directed to reactors where metal sulfides are extracted from the solution using chemicals. When the metal sulfides are extracted, the solution is directed to purification and neutralization and then returned to production process to irrigate the piles again. (Terrafame, a, 2022).

2.2. Greenhouse gas emissions of raw material manufacturing

According to Aichberger & Jungmeier (2020), CAM production contributes the most to the GHG emissions formation of LIB manufacturing process alongside cell manufacturing. Considering the CAM production, important aspect mentioned often in the literature is primary energy demand, as the metal raw material production is an energy intensive process. The most critical phases of CAM production for GHGs are metal refining processes, in which China is globally a major player (Schmidt, et al., 2016). Since China's energy production is widely relied on conventional sources (70 % of electricity generation was coal-based in 2019) (Zhang, et al., 2021)), its electrical grid also has higher GHG intensity than other raw material producing regions like Japan, South Korea, Europe and USA (Kelly, et al., 2019). It has been also reported that in nickel and cobalt sulfide production process, refining and primary extraction have greater GWP than mining process (Cobalt Institute, 2020).

Gaseous emissions such as particles, nitrogen and VOC compounds are formed in nickel and cobalt sulfate ($CoSO_4$) production. Some small concentrations of sulfur dioxide and hydrogen sulfide may also be generated. (Ramboll, 2018). Airborne emissions from pCAM plant are mostly generated in drying and ammonia recovery. The gases at pCAM plant are treated in either a dry or a wet scrubber before releasing to the environment. At CAM plant the airborne emissions are generated during raw material treatment and product drying and packaging. The gases are also treated in a dry scrubber before releasing to the environment. (Korkiakoski, et al., 2021).

Nickel

Nickel allows the battery to gain higher storage capacity and energy density with lower price (Nickel Institute, 2022). From the land-based resources, 60 % of the worldwide nickel reserves are incorporated in laterite nickel deposits, while the rest are constituted in sulfidic nickel reserves. (McRae, 2018). Compared for example to lithium production, nickel is produced broadly in a variety of countries with Canada, Russia, New Caledonia, Indonesia and Philippines being the major producers. At the moment, European Union do not see nickel as critical raw material (CRM) (European Commission, 2020). CRMs are seen as scarce, as well as strategically and economically important for the economy of Europe (Ferro & Bonollo, 2019). However, this might not be the case in the future, as value of all kinds of metals will increase due to electrification and EV market growth (Michaux, 2021). Open-pit mining and blasting are used as methods to extract nickel ores (Weimer, et al., 2019). Laterite ores include typically from 0,9 % to 3 % of nickel (Bide, et al., 2008).

Energy consumption of nickel production has a major role in GHG emissions formation (Mudd, 2010). Ore grade and mineralogy have the highest influence on energy consumption in metallurgical processes (Mistry, et al., 2015). Traditionally nickel sulfides have been less energy intensive to process than laterites (Mudd, 2010). Worldwide many projects vary in their energy performance, as (Mudd, 2010) reported that companies in Canada and Australia have announced that energy consumption of their sulfide projects have been below 100 GJ/t metal, while the corresponding value for laterite have been 252-572 GJ/t metal. In these projects sulfide GHG emissions have reported being less than 10 t CO_2 eq./t metal, whereas laterite emissions have reported to vary from 25 t to 45 t CO_2 eq./t metal. Nickel Institute (2020) has provided recent data on nickel GHG emissions. The Institute reported that nickel product industry average is 5.4 t CO_2 eq./t Nickel sulfate ($NiSO_4$). Terrafame's corresponding reported value is 1.75 t CO_2 eq./t $NiSO_4$, which is ''the lowest in the industry''. Terrafame's low carbon footprint is mainly explained with the aforementioned energy efficient bioleaching process. (Terrafame, b, 2020).

Cobalt

Cobalt is needed in cathodes for better energy density and to prolong battery life (Patel, 2020). The metal is found in different land-based reserves including primary magmatic sulfides, layered sediments and oxides, and secondary laterites (Slack, et al., 2017). Vast

majority of the world's cobalt is produced as a by-product of nickel and copper (National Emergency Supply Agency). The main cobalt mining country is The Democratic Republic of the Congo, whereas China is the biggest refiner. Finland has large cobalt reserves by European standards, and it is one of the few countries in EU that produces cobalt from ore in its own mines. (National Emergency Supply Agency). Main cobalt consumers in 2011 were China, Japan and the United States. Total worldwide terrestrial cobalt reserves have been estimated to be 25.5 million tons, but additional resources are known to locate deep in the seabed. Exploitation of these resources have posed technological, legal and economic issues, but the production is likely to become economically viable as the production technologies develop. (Slack, et al., 2017). Some producers also desire to eliminate cobalt from the compounds completely, as it has been reported that cobalt mining in Congo is conducted at the expense of human rights and the environment. Thus, new cobalt-free cathode materials are being tested. (Patel, 2020).

Cobalt refining process consumes the most electricity in cobalt production, and it is an important factor to optimize for lower GHGs and other environmental impacts especially in Chinese cobalt refining, where coal is the predominant source of electricity. Although China has notable renewable energy reserves due to its versatile climate and terrain, the reserves are not adequately exploited. The environmental impacts of cobalt sulfate production have been studied through LCA in China, and research showed that production of one ton of cobalt sulfate causes 35,6 t CO2 eq. (Zhang, et al., 2021). However, Zhang, et al. (2021) studied how much the value could be reduced and compared the emissions of electricity generation in 2017 to 2050 level, where the share of renewables is much higher than currently. They found that the result could be reduced by 24 % through the energy optimization.

Furthermore, the source of mined cobalt affects the environmental impact of refined cobalt. Cu-Co and Ni-Co mines are the main production sources of cobalt. As an example, Congo's mines can produce ores containing ten times more cobalt than ores produced in China. Thus, to extract the same amount of cobalt requires more resources in China. Therefore, a big share of cobalt raw materials is imported in China to meet the refined cobalt market demand. (Zhang, et al., 2021). One solution to reduce environmental burden of cobalt mining is urban mining (Huisman, et al., 2016), which refers to extracting the useful materials from a final product in its end-of-life phase (Krook & Baas, 2013). Urban mining has potential, as roughly 98 % of cobalt in LIBs can be regenerated through mechanochemical process (Dunn,

et al., 2015; Wang & Ge, 2020). However, the exploitable volume is still not yet very high, but attempts for larger cobalt waste recycling rate have been made (Sun, et al., 2019).

Manganese

Manganese is an important cathode material as it stabilizes the cathode structure and has an impact on the battery cell safety (Umicore, 2022). Geologically there is no global deficiency of observed manganese reserves, which are estimated to meet the demand for several upcoming decades. Quantified terrestrial number of the global deposits is approximately 17 billion tons but the seabed reserves are even larger, the extent of which are not fully known. The terrestrial deposits are unevenly spread as in 2013 around 65 % of observed resources were located in South Africa, Ukraine and Brazil. The main manganese ore producers are China, South Africa and Australia. Due to vast marine reserves, the most dominant processes in manganese production occur in the oceans. Manganese concentration in the ores vary, as many common rocks contain small percentages (0,1-0,2 %) of manganese, while high-grade ores can contain up to 45 % of manganese. (Cannon, et al., 2017).

GHGs are considered one of the main sources of environmental burden of manganese production. Globally, electricity generation, manganese oxide and concentrate production have noted as being the most impactful processes for the environment due to coal-based power generation and mineral intensive industries. Ore grades also affect energy consumption and waste generation in the production. Therefore, effective raw material usage and utilization of renewable energy sources are emphasized in emissions reduction. (Zhang, et al., 2020). In order to be used as a raw material for LIB, manganese must be highly pure. Types of high-purity manganese (HPM) used in LIBs are high purity manganese sulphate monohydrate (HPMSM) and high purity electrolytic manganese metal (HPEMM). The vast majority of HPM utilized for example in Europe and North America is imported. The share of HPEMM in manganese sulphate ($MnSO_4$) production is increasing although its production cost is growing. $MnSO_4$ is one of the key raw materials for NMC and LMO battery cathodes. (Euro Manganese Inc., 2022). Today there are only few countries (China and South Africa) that produce HPEMM, as concerns towards environment and rising costs have grown. Environmental concerns are related to HPEMM's production technology, as HPEMM can be produced using high-grade ores with sulfur dioxide technology that does not use selenium. The technology uses less water and manganese ores and generates less normal and hazardous waste than conventional method, in which chromium and selenium

are used that end up as hazardous waste. Long-term use of these materials generates residues that can have significant impacts on both the environment and human health. (Zhang, et al., 2020).

Aiden Westfall, et al. (2016) collected data from 16 different international manganese ore and alloy producers that covered almost a fifth of ore production and 8 % of alloy production worldwide. They reported that GWP for 1 ton of average manganese alloy is 6.0 t CO_2 eq. and found that the most significant contributors were coal-based electricity consumption and coke consumption during smelting.

Lithium

LIBs function by transferring lithium ions during charging and discharging (Figure 4). Lithium is found in continental brines and in igneous rocks called pegmatite. Clay minerals and some oil field brines are also potential sources of lithium. Pegmatite is largely mined in Australia, whilst large brine deposits are located in Chile and Argentina. (Wietelmann & Steinbild, 2014). Weimer, et al., (2019) pointed that statements of exact lithium supply are somewhat difficult to give, as only small shares of lithium deposits are reported according to Committee for Mineral Reserves International Reporting Standards (CRIRSCO). Mineral deposit estimates are reported by the member countries of the Committee, which publishes reporting standards for these reports. An approximation is that roughly 80 % of the total lithium reserves in the world (Rongguo, et al., 2016) and little over 50 % of the total lithium supply arise from continental brines (Andrews, et al., 2016).

When the lithium concentration is produced from continental brines, the process is done in two steps. First the salt brine crust is broken or drilled. Secondly, the brine is pumped into evaporation ponds. During the evaporation process, salts like halite are precipitated successively in several stages in alternating ponds. (Choubey, et al., 2016). Finally, the concentrate lithium content is needed to be 6 % so that pure lithium carbonate for LIB cell manufacturing can be processed (Weimer, et al., 2019).

Kelly, et al., (2021) studied GHG emission formation from lithium hydroxide monohydrate (LiOH H_2O) production produced from Australian ore and Chilean brine reserves. They found that emissions of lithium hydroxide produced from ore are higher than brine's equivalent emissions. The result for one ton of LiOH H_2O produced from brine was rougly 7 t CO_2 eq. and from ore 15.7 t CO_2 eq. Finnish producer Keliber (2022) has reported that

their ore-based carbon footprint of lithium hydroxide per produced ton is 10 t CO_2 eq. In the same analysis they pointed that the emission intensity of their lithium hydroxide production chain is the lowest in comparison of seven different lithium chemical producers. The argument is based on an analysis conducted by consulting company Wood Mackenzie. In the comparison, Keliber benefits from energy efficient refining and from the contribution of high share of renewable energy sources in Finnish electricity grid.

2.3. Precursor manufacturing

Globally there are a few different ways to produce cathode active materials. The review of this study is limited to the technical data described in the next two sections (pCAM & CAM manufacturing).

pCAM in this specific case is produced in Hamina production facility, from where the material is transported to and processed in CAM plant. In this study, the operating time of the plant is considered to be continuous, producing 20 000 tons of precursor per year. The production phases are demonstrated in Figure 2. (Korkiakoski, et al., 2021)

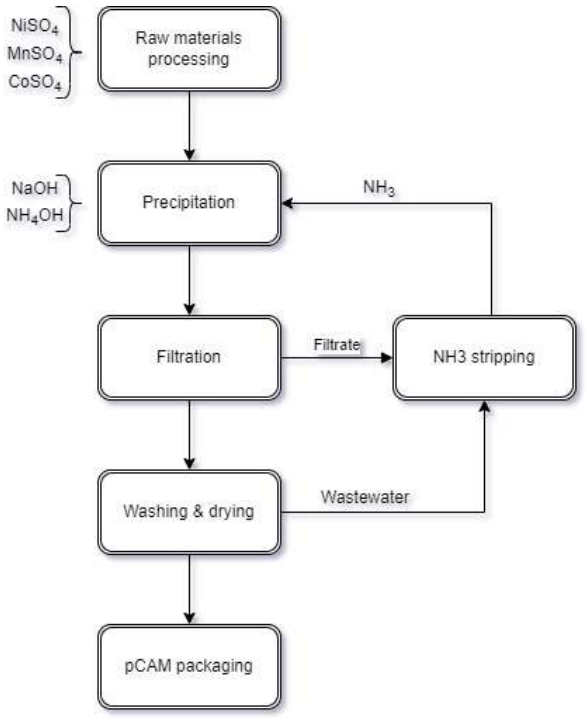

Figure 2 Process diagram of pCAM production (Korkiakoski, et al., 2021; Dai, et al., 2018).

The production starts with raw material processing, where metal sulfates are dissolved in water and mixed together in desired ratio. The feed solution can also be made by dissolving metallic raw materials in sulfuric acid with hydrogen peroxide into sulphate solutions. The metal sulfate alloy is directed to precipitation, in which the metals are precipitated with sodium hydroxide and ammonia water to form a precursor material. The formed solid is separated from the solution by filtration. The filtered powder is dried and, if necessary, packaged for delivery to the CAM plant for further processing. The used ammonia water evaporates to a small extent and leaves the reactors together with nitrogen, which is used as shielding gas. All the exhaust gas is directed to wet scrubber where it is neutralized with dilute sulfuric acid to remove ammonia before being discharged through the exhaust duct into the environment. Dust is generated in raw material and product treatment which is sucked into the bag filters through a vacuum-treated process so that it cannot enter the interior or escape into the environment. (Korkiakoski, et al., 2021)

After filtration, the main solution and the product filtration washings are microfiltered to remove metallic solids and the effluent is treated to remove nitrogen in an ammonia column. Ammonia is condensed back to ammonia water and recycled back to the process. The solutions from wet scrubber and other contaminated aqueous solutions are treated in the same effluent treatment process. Metallic solid can be fed back into process directly or through in-plant acid leaching. (Korkiakoski, et al., 2021).

The operations are designed in a way that a non-compliant product can be recycled within the plant or sent to another plant for treatment, allowing the metals to be recovered for re-use. The used raw materials are nickel, cobalt and manganese sulphate in solid or liquid form. pCAM material can also be produced using different compounds and features according to customer needs. (Korkiakoski, et al., 2021).

2.4. Final product manufacturing

The final purified and calcinated CAM product is produced in Kotka plant. The operations are continuous, and the annual production capacity is also considered to be 20 000 tons per year. The CAM manufacturing process is shown in Figure 3.

Figure 3 CAM manufacturing phases (Korkiakoski, et al., 2021).

The first phase of CAM process is dehydration of lithium hydroxide, in which water is removed from the aqueous lithium hydroxide. The lithium hydroxide is then homogenized with pCAM and the resulting mixture is calcined at high temperature. After calcination, the mixture is then possibly washed to remove soluble compounds and filtrated before grinding and re-homogenization. The final product is then dried and packaged as a raw material for delivery to the cell factory. Generated emissions to air are treated in dry scrubber, in which dusty metal compounds can be separated. The effluents generated in washing phase are treated in effluent treatment process. In the process the dissolved metal-containing compounds are precipitated, after which the solids are separated with microfiltration before leading the purified process effluent to water system. (Korkiakoski, et al., 2021).

The production operations in both plants require commodities such as sodium hydroxide, ammonium water and sulfuric acid that can be manufactured on site either as part of the plants' operations or by external contractors. Besides the main products, the plants utilize process water, compressed air and steam. Demineralized water is used as process water, which is produced at water plants to be built alongside the main plants. Compressed air is produced in the factory area with air compressors and filtration. Steam is produced with boilers where different energy sources can be used. In addition, the CAM plant uses oxygen in calcination. The oxygen is produced in a separate oxygen plant which will also be built alongside the CAM plant. (Korkiakoski, et al., 2021).

3. Lithium-ion Battery

Although this study focus is not on the LIB technologies, it is worthy to present briefly the common LIBs and related cathode materials described in literature to understand the broader

context of cathode materials. The discussion on battery materials also provides background on the current market situation of EVBs.

LIB is rechargeable, energy dense battery and commonly used in EVs (Manu, 2021). Its low maintenance cost and long cycle life have also helped to build up its reputation as dominant technology in many energy sectors such as transportation, aviation and stationary energy storage. EV demand growth create space for LIB market to grow and the combined annual market growth is over 16 %. (Zeng, et al., 2019). Compared to non-rechargeable primary battery which uses metallic lithium as its electrode, secondary LIB uses an intercalated lithium compound (Manu, 2021). Intercalated compound system allows reversible insertion and extraction of Li-ions (Mosa & Aparicio, 2018). In intercalation, Li-ions transfer into an electrode (from anode to cathode during discharge) and in deintercalation, Li-ions transfer out of the electrode (out of the anode during discharge). A reverse process occurs when the battery is being charged. LIBs come as all different shapes, chemistries and sizes. Versatile chemical and structural properties induce different features that often have compromises between efficiency, safety and cost. (Manu, 2021).

LIB consists of cathode, anode, electrolyte and separator, in which cathode is the most critical as its composition and limited specific capacity highly affects to the battery performance (Arshad, et al., 2022). Anode materials have larger Li-ion storage capacity compared to cathode, and thus cathode material is the limiting factor (Liu, et al., 2016). Lithium metal oxides or phosphates ($LiCoO_2$ and $LiFePO_4$) are common cathode materials, while anode materials are graphitic materials. Cathode and anode are separated by separator and they have different chemical potentials. Li-ions move between the electrodes by organic electrolyte during charging and discharging. During discharge, electrons move from anode to cathode, while simultaneously Li-ions penetrate through the electrolyte to sustain charge balance. During charging, a power supply forces electrons and lithium ions to move to opposite direction. (Xu, et al., 2020, pp. 139-164). Figure 4 illustrates the lithium-ion battery functioning.

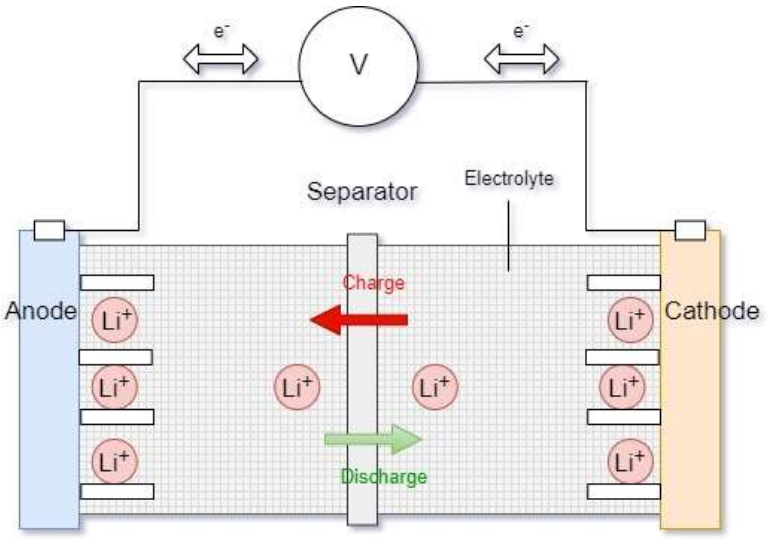

Figure 4 Illustration of Lithium-ion battery working principle (Ghiji, et al., 2020).

Rechargeable LIBs control the battery markets, as they have better energy density in comparison to other battery types. LIBs are utilized in applications that favor high energy and power density, of which EVs and Plug-in Hybrid EVs (PHEVs) are good examples. Plug-in EVs as part of smart home systems are and will be even greater part of smart grids in the future. The LIBs have many advantages such as light weight, high open circuit voltage, high energy density, smaller environmental impacts after disposal and small self—discharge rate. Despite the benefits, the power density and the cycle life still need to be developed for their larger scale use in EVs, large scale energy storages and other applications (Mishra, et al., 2018). One challenge has been unprovoked battery swelling. The battery performance is often measured in energy density, capacity and cell potential. These factors are closely related to material properties that form the electrodes. (Mekonnen, et al., 2016).

In a typical battery design, the price share of electrode materials is approximately 44 % including anode and cathode electrodes, electrolyte, binders, battery jacket and modules. The price of cathode is almost double that of the anode. This may be due to the fact that in the current LIB technology, rate capability, energy density and working voltage of LIB are primarily determined by cathode material thermodynamics and limited theoretical capacity. Therefore, constant cathode material development is critical. (Xu, et al., 2013). Many factors have been studied to enable wider commercialization of LIBs. Xu, et al. (2013) have divided some of these factors into four categories

- Proper electrolyte development with extensive electrochemical window, low volatility and flammability, high anodic stability and good environmental feasibility.
- Development of optimal binders (e.g. alginate and carboxymethylcellulose) to provide a tight bond between electrode materials and current collector in LIBs to improve stability and electrochemical performance during electrochemical cycle.
- Creation of combined experimental and computational procedure for material screening to identify low cost, high capacity and high energy density cathode materials.
- Creation of different LIB prototypes with various promising cathode materials supported by energy density, cost and environmental tradeoff analyses for different applications.

Moreover, today's cathodes contain metal cobalt, which is costly and reported to have many environmentally and socially harmful mining pollution. As demand for LIBs increase, cobalt consumption will fourfold in the next 40 years if improvements in cathode materials will not take place, which further increases environmental and social impacts. As an example, high levels of cobalt have been detected in the blood of Congolese cobalt miners, which increases their cancer risk. Cobalt prices are also globally volatile, which can obstruct LIB development and progress of electric vehicle market. Due to these reasons, research of low cobalt-nickel-rich batteries has become the main direction of many studies in LIB field. (Chen, et al., 2021).

Typical materials used in anode production are synthetic graphite, metallic lithium, graphitic carbon, lithium titanate, hard carbon, silicon-based materials and tin alloys. (Mishra, et al., 2018). Graphite is commercially used as anode material due to its relatively low cost, high conductivity, reversibility, structural stability, high energy efficiency and voltage. However, its voltage rate is low and energy density limited, as it cannot hold more lithium atoms than one against every six carbon atoms (Adi Rachmanto, et al., 2021; Chen, et al., 2021). Silicon is considered one of the most promising anode materials as it has ten times larger capacity than graphite anode. Drawbacks of silicon are, the volume of silicon lattice, which changes remarkably during repeated charge and discharge cycles, and the instability of electrolyte interface film located on the anode surface. The challenges of reversible silicon anodes relate to electrolyte interface crushing and cementation, for which solutions have been found over

the past decade through silicon nanostructure. The repeated charge and discharge cycles result in easy crushing, silicon productivity loss, and low cycle efficiency. Two different approaches have been proposed to solve these issues. The first is to prevent the volume expansion by creating silicon nanoscale structures. The second approach is to blend silicon with other stress-releasing materials like oxygen compounds, carbon materials and metals. (Chen, et al., 2021).

3.1. Cathode materials

LIBs are classified according to the chemistry of their cathodes. Nowadays, six different battery types are commercially available (Figure 5). Typically used cathode materials are lithium nickel manganese cobalt oxide (NMC), alumina doped lithium nickel cobalt oxide (NCA), lithium cobalt oxide (LCO), lithium manganese oxide (LMO) and lithium iron phosphate (LFP). (Li-Battery Safety, 2019). From the cathode materials, LCO ($LiCoO_2$) was the first commercially successful transition metal oxide cathode with layered lithium transition. Its volumetric and theoretical specific capacities are relatively high (1300 mAh cm^{-3} and ~270 mAh g^{-1}). However, today's modern EVs require extremely high power, which limited the LCO's market position and growth, as the LCO's features such as low thermal stability and rapid capacity decay were not sufficient for it to compete in the EV market. LMO ($LiMn_2O_4$) is also old (discovered in 1980s) and commercially long used material but cheaper to manufacture than LCO. It tolerates well high thermal stability, high current discharge and fast charge. Although it seems a good alternative to power EVs, its drawback is limited lifetime, and it is only able to supply two-thirds of LCO's capacity. (Zeng, et al., 2019).

LFP ($LiFePO_4$) is lithium iron phosphate battery and well known for its stable cell chemistry. Its ability to withstand hazard events and harsh conditions is better than others as it does not ignite or explode. Other benefits for its application in a car are long cycle life, enhanced safety and environmental friendliness after disposal. Furthermore, it can provide full power before complete discharge and be recharged quickly within 2,5h (will reach 90% charge in 15 minutes). However, longer distance road trips are limited as its cell has lower operating nominal voltage which reduces the battery energy density. Therefore, it is suggested that its application is more suitable for taxies or other short distance means of transport. (Zeng, et

al., 2019). Shi, et al., (2019) calculated that in the city of Beijing, 45.5 % of the electric powered taxis were able to function with only 200-mile driving range daily, which dropped to 50 miles in case of 40 % of private travel. Thus, the LFP cathode materials with moderate rate performances and good thermal stability are broadly adopted in Asia, to power particularly electric buses and grid applications.

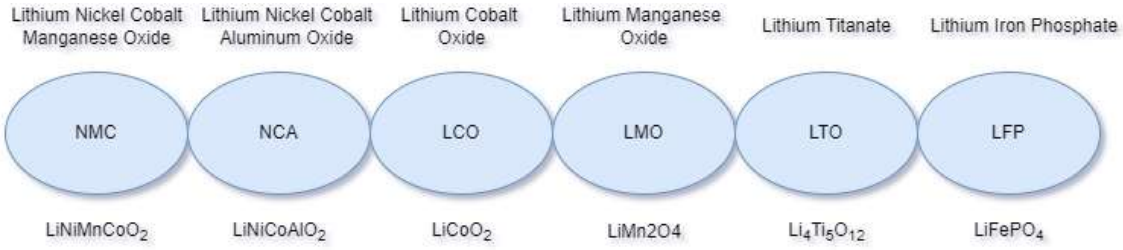

Figure 5 Commercially available LIB types (Boubou, 2019).

NMC ($LiNiMnCoO_2$) and NCA ($LiNiMnAlO_2$) are made of transition metals: nickel, manganese, cobalt (Ni, Mn, Co) and nickel, cobalt, aluminum (Ni, Co, Al). Usage of NMC is becoming more popular due to its great energy density and overall performance. The compound is successful as manganese enables low internal resistance and nickel provides high capacity. Its achievable specific capacity is similar or higher compared to LCO at same operating voltage, and it is not as expensive as LCO due to lower cobalt content in its lattice. Even higher energy densities and capacities are achievable by adding more nickel, but this leads to reduced battery life span and thermal stability. (Zeng, et al., 2019).

In turn, NCA is relatively new cathode containing similar features with NMC, such as long lifetime, high specific energy and energy density. Its material costs are roughly 50 % higher than LFP's, which is cobalt and nickel-free, but NCAs do not need as high portions of active materials that participate in ion exchange. NCAs have also around 30 % higher capacity as well as higher voltage (3,6 V instead of 3,2 V), which compensates the high-cost concern. (Zeng, et al., 2019). Some characteristics of common battery chemistries are presented in Table 1.

Table 1 LIB characteristics of common battery chemistries, where the price per kWh is stated qualitatively in relation to other battery chemistries (Porzio & Scown, 2021).

LIB chemistry	Operating temperature (°C)	Nominal voltage (V)	Cycle life (Cycles)	Price per kWh	Primary use case	Common composition
NMC-Graphite	0–55	3.7	2000+	Med-high	EV, power tools	NMC-111 [1)] NMC-532 [2)] NMC-622 [3)] NMC-811 [4)]
NCA [5)] - Graphite	0–55	3.6	2000+	Med	EV	-
LFP [6)] - Graphite	0–55	3.2	3000+	Low	EV	-
LFP [7)] - LTO	-40–55	2.7	5000+	Very high	Small electronics, some EVs	-
LMO [8)] - Graphite	0–55	3.7	1000–2000	Low	EV, power tools	-

1) $Li_{1.05}(Ni0.33Mn0.33Co_{0.33})_{0.95}O_2$ 2) $Li_{1.05}(Ni_{0.5}Mn_{0.3}Co_{0.2})_{0.95}O_2$ 3) $Li_{1.05}(Ni_{0.6}Mn_{0.2}Co_{0.2})_{0.95}O_2$
4) $Li_{1.05}(Ni0.8Mn0.1Co_{0.1})_{0.95}O_2$ 5) $LiNi_{0.8}Co_{0.15}Al_{0.05}O_2$ 6) $LiFePO_4$ 7) $Li_4Ti_5O_{12}$
8) $LiMn_2O_3$

NCA and NMC are considered as nickel-rich materials and many car manufacturers have selected them as cathode materials for hybrid EVs. For instance, the NCA chemistry is applied in the batteries of car models such as Mercedes-Benz S400 (2010), VW E-Golf and Tesla 3 (2017). Many companies are also actively producing nickel rich NCA and NMC materials to meet the demand in battery market. Longer-term aim is to produce cathodes with higher gravimetric energy density, which requires nickel content of at least 80 %. To achieve this, there are a few challenges that are required to be managed: the residual lithium compound formation, structural damage and gas evolution are needed to be eliminated. Although the cathode electrochemical performance can be enhanced through cathode modification, its commercial feasibility has not been approved under industrial electrode conditions. Many solutions are also under further research for which electrochemical tests are being conducted. (Zeng, et al., 2019).

3.2. Market overview

The EV adoption rate is driven by regulation and supported by customer demand, macroeconomics and technological development allowing more cost-efficient battery production. Light vehicle production is expected to grow globally from ~90 million in 2017 to ~120 million by 2030, where the share of EVs is anticipated to reach 22-30 % with Asia being the market leader. Although the increasing battery demand will result shortages on key raw materials like lithium, cobalt and nickel, the market is expected to adjust to demand in becoming years. Nickel-based LIBs are increasingly winning the market share among other technologies, due to their high performance. Current European EVB production is negligible as China, Japan and Korea dominate the market with over 90 % share. However, there is growing interest to build new local European EVB manufacturing sites. Finland is notable EVB material supplier in Europe by supplying nickel and cobalt and possibly lithium in the future. Only few players in Finland (Keliber, Terrafame, Boliden) provide the materials with limited growth potential. (Finnish Minerals Group, c, 2018).

On European level, the near future production scale is prominent, but small globally. Except for raw material production, EVB value chain is underdeveloped both in Finland and in Europe, as technological barriers among other things are holding back the value chain creation. The value chain in Europe can be expanded in cooperation with Asian partners to overcome technology issues faster, or without partnership, when the construction timeline would be prolonged. (Finnish Minerals Group, c, 2018). China's share of total raw material production required in LIBs is one third and numerous smaller suppliers provide more than half of the raw materials. Australia and Chile are also key suppliers with production shares of 7 and 6 %. (Blagoeva, et al., 2019).

The battery pack price is in the range of 100-200 €/kWh but expected to reach under 100 €/kWh until 2025 due to scale economies, design improvements and chain integration (Finnish Minerals Group, c, 2018; Zubi, et al., 2018). Key technologies towards the end of the ongoing decade are NMC-622, NMC-811 and other lower-cobalt, nickel-based LIBs. (Finnish Minerals Group, c, 2018).

Although LFP battery future role in the transportation industry is uncertain, it is expected to find use at least in power supply systems, where the key criterion is its cycle life in relation to cost, while specific energy and power are given minor relevance. NCA will be presumably

utilized in many fields, but it is unlikely that it will dominate any particular application. It is estimated that until 2030, NMC will have around 35 % market share, NCA and LFP will have 40 % combined share, and LCO, LMO and LTO will have the rest. Furthermore, components of second-hand LIBs can become useful in future markets, as recycled EV batteries can be a source of LIBs for power supply systems. (Zubi, et al., 2018).

4. Carbon Footprint

Carbon footprint is today a commonly used term and it often refers to responsible behaviour and actions against climate change in public debate (Wiedmann & Minx, 2008). Issue of responsibility has become globally important and attention towards the subject has been increasing due to growing climate awareness and concern. Companies understand the growing emissions regulation and have increasingly started to measure their own carbon footprint. Progressive development of corporate responsibility requires the use of appropriate methods and scope to measure the carbon footprint, as without sufficient measures, companies will not be able to pursue the best possible carbon mitigation actions. By ensuring the use of right methods and setting a reasonable scope for their carbon footprint studies, the companies will gather data on the most relevant polluting sources of their production chain. (Matthews, et al., 2008). Emission trading policies that are in place worldwide in different regions also force companies to reduce their GHG emissions. (Tuerk & Zelljadt, 2016).

Earlier a general reflection around carbon footprint has been, what should it measure. Should the calculation include only carbon dioxide (CO_2), or should it consider other greenhouse gases like methane (CH_4) as well? Would it be rational to consider only those substances that have carbon in their molecule, when for example, nitrous oxides (N_2O) would be excluded, and carbon monoxide (CO) included? Other critical point of view has been that should the carbon footprint calculation take into account only direct on-site emissions caused by product/process, or should it include also embodied indirect emissions caused by upstream production. Therefore, a valuable question has been whether the carbon footprint calculation should include all emissions over entire life cycle of a product. As the answer is

positive, the next issue has been, where the boundary should be drawn and how the amount of impacts are calculated. (Wiedmann & Minx, 2008).

Carbon footprint as a term originates from literature of ‘’ecological footprint’’, which indicates the total required land to produce a certain number of commodities. Ecological footprint is calculated in hectares, where the word ‘’footprint’’ also refers to calculation of area-based measurement. (Wiedmann & Minx, 2008). Definition of carbon footprint provides some answers to the previously set questions. The term is defined as an evaluation of total GHGs that are emitted during consumer good production, processing and retailing. (Plassmann & Edwards-Jones, 2010). The GHGs include carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), perfluorocarbons (PFCs), hydrofluorocarbons (HFCs) and sulphur hexafluoride (SF_6) (UNFCCC, 2008).

GHG emissions occur at every stage of a product’s life cycle, and can be either direct (e.g. fuel application, fertilizer use) or indirect (e.g. emissions from raw material extraction) (Chapagain & James, 2013). As each GHG contribute to global warming to a different extent, characterization factors have been determined for every gas to quantify damage to human and ecosystem health per unit of GHG emission (De Schryver, et al., 2009). Intergovernmental Panel of Climate Change (IPCC) has developed a characterization model for climate change, which contains a set of internationally established characterization factors. The factors for carbon footprint are indicated as global warming potential, usually for 100 years time horizon (GWP_{100}) and in kilograms of carbon dioxide emission equivalent (CO_2 eq.)/kg emission. (Chapagain & James, 2013, pp. 217-236). GWP is used as a metric to compare GHGs in terms of their ability to trap heat in the atmosphere. (Durkee, 2006, pp. 43-98). GWP values vary as scientific knowledge improves. The most recent published values are listed in Table 2. The introduced factors (presented in IPCC assessment reports 4 and 5 (AR4&5)) indicate the most commonly used values, as there exists many more. Assessment report 6 (AR6) will be published during the year 2022 (IPCC, a, 2022).

Table 2 Characterization factors of GHGs (Gillenwater, 2015).

Greenhouse gas	GWP 100 years	Report reference
CO_2	1	(IPCC, b, 2013), AR5
	1	(IPCC, c, 2007), AR4
CH_4	28	(IPCC, b, 2013), AR5
	25	(IPCC, c, 2007), AR4
N_2O	265	(IPCC, b, 2013), AR5
	298	(IPCC, c, 2007), AR4
CF_4 (PFC)	6 630	(IPCC, b, 2013), AR5
	7 390	(IPCC, c, 2007), AR4
HFC-23	12 400	(IPCC, b, 2013), AR5
	14 800	(IPCC, c, 2007), AR4
HFC-134a	1 300	(IPCC, b, 2013), AR5
	1 430	(IPCC, c, 2007), AR4
SF_6	23 500	(IPCC, b, 2013), AR5
	22 800	(IPCC, c, 2007), AR4

Furthermore, the carbon footprint calculations are needed for evolving climate policies. As consumers can influence their carbon footprint through daily choices of goods and services, comprehensive carbon footprint estimations are appropriate. Corporations, in turn, can influence to the choice of their suppliers, thus broad estimations will most likely incentivize company policies towards more effective climate policies. However, many businesses can influence their supply chain responsibility only to some extent. Therefore, an appropriate balance is needed and rules must be set within companies to determine the extent of allowable supply chain emissions. (Matthews, et al., 2008).

In carbon footprint calculations an operational boundary needs to be selected, which covers the measurable direct and indirect emissions (Pandey, et al., 2011). Three scopes 1, 2 and 3 are determined especially when conducting organizational carbon footprint study. The system assists in direct and indirect emission limitation, which improves transparency and provides utility for different parties (e.g. organizations, climate policy makers). Scope 1 considers the organization's direct emissions from origins that it owns or controls. These can be, for example, emissions released from factories and transportation. Scope 2 includes GHG emissions from electricity production bought by a company, where the emissions are physically produced in energy production facility. Scope 3 includes other indirect emissions

released from other known sources. The scope 3 is considered as an optional reporting category (The Greenhouse Gas Protocol, 2015). Figure 6 illustrates the carbon footprint measurement entities.

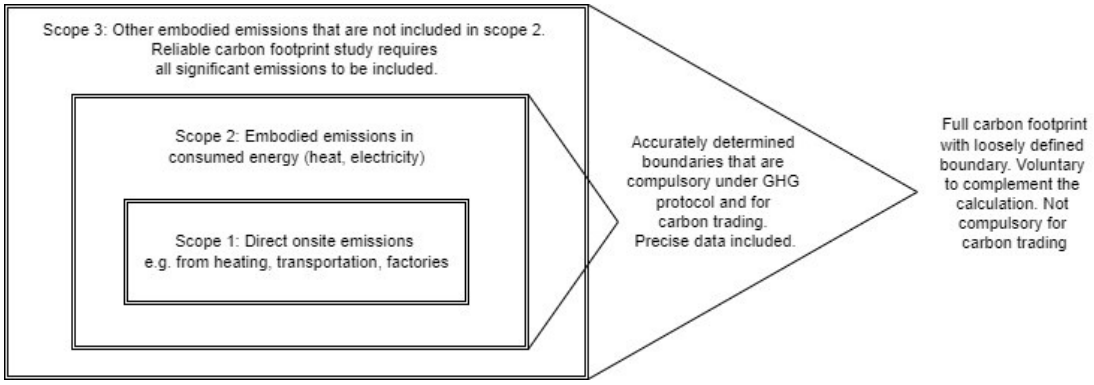

Figure 6. Carbon footprint boundaries for calculation (Greenhouse Gas Protocol, 2011).

Scope 3 includes a wide range of embodied emissions and is not precisely defined. Therefore, many studies set their boundaries to scope 2, as complexity of the estimation increases when the goal is to conduct a reliable carbon footprint study. As organization's responsibilities and control over emissions can be obscure, a relevant issue is to solve to what extent the emission management can be done beyond scope 2. Due to this, most GHG guiding standards, such as GHG protocol or Publicly Available Specification (PAS)-2050, have maintained scope 3 optional. Developing supply chain emission management and tracking advancement will further promote scope 3 reporting. Evident emitters like cement industries, transportation and power plants cover most of the carbon footprint studies, but scope 3 can also contribute significantly to the total emissions in many cases. Hence, the emissions of scope 3 have been encouraged to include relevant emission sources, which can be determined based on size or risk exposure. (Matthews, et al., 2008).

Choice of a proper GHG data collection method depends on desired objective, feasibility, credibility, cost and capacity evaluations. Emissions for events, organizations and products are often calculated using emission factors and models to which data has been gained from fuel consumption, energy use and other emission sources. PAS-2050, IPCC and GHG protocol have, for example, a wide range of emission factors of industrial processes available, but geographical and operational contexts are also needed to be considered. Thus, many countries have developed national inventories of emission factors. Government offices

that keep data of energy and fuel consumption and national GHG inventories can provide reliable data sources. (Pandey, et al., 2011).

4.1. Life Cycle Assessment

Environmental impacts are often determined through life cycle assessments (LCA), which is broadly accepted method for environmental impact assessment of products and processes (Ghattas, et al., 2016). The approach considers arising emissions throughout the whole life cycle of a product or process. Life cycle of a product or system service comprise the following stages: natural resource extraction, manufacturing/construction processes, product use and final disposal. (Dincer & Rosen, 2021, pp. 601-629). The LCA studies can help engineers, designers and decision makers by providing valuable information about environmental impacts of produced goods and services. Without LCA studies, many decisions would likely be made based on initial costs, where great emphasis would not be given for environmental aspects. Methods for conducting LCA studies are based on International Organization for Standardization (ISO) 14040 -standard series, which suit for different scopes, objectives and limitations. (Rashid & Yusoff, 2015, pp. 244-248). Besides the ISO standards, a British standards institution has published the above mentioned PAS-2050, which further specifies requirements for life cycle GHG emission assessment based on key LCA techniques and principles (PAS 2050, 2011).

LCA studies examine the emissions systematically using different procedures to compile required inputs and outputs of materials and energy (Dincer & Rosen, 2021). Complete life cycle involves material procurement, processing, transportation, as well as production, distribution, usage, recycling and disposal of a product (Ympäristöhallinto, 2022). The implementation of LCA studies have four major phases: goal and scope definition, inventory analysis, impact assessment and result interpretation (Figure 7).

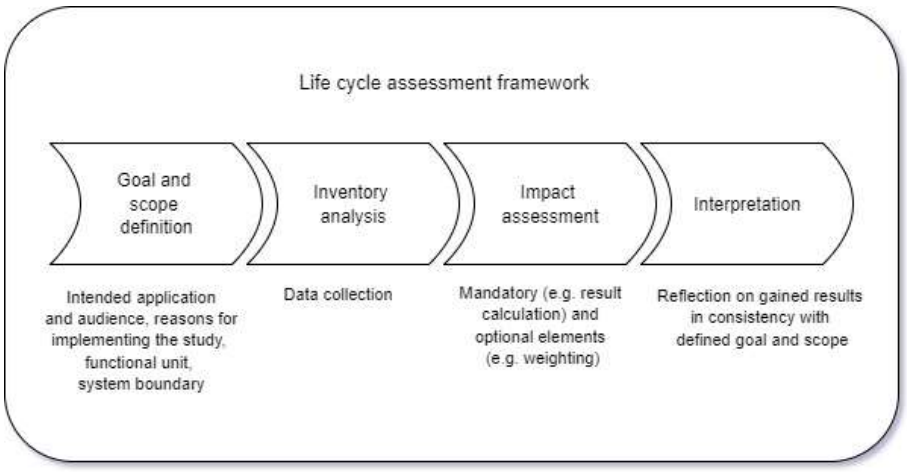

Figure 7 Phases of LCA (ISO 14040, 2006).

Goal and scope defines objectives, functional unit and system boundaries for the study, where the system boundary limits the processes that are included or excluded in the study. Identified functions of a studied product are quantified with functional unit in numerical sense. The definition of functional unit is important to allow uniform comparability of LCA results. All data for inputs, outputs and processes is collected in second (inventory analysis) phase and calculation procedures are made to quantify important inputs and outputs included in the scope. Life cycle impact assessment (LCIA) quantifies environmental impacts and input resources regarding conducted inventory analysis. In this phase the LCI results are used to assess the extent of potential environmental impacts. The LCIA includes also compulsory and optional elements that are presented in Table 3. The final phase is result interpretation, which in addition to the result analysis, includes recommendations for improvements. This phase should consider observations together from the inventory analysis and the impact assessment and deliver results coherent with goal and scope. Finally, conclusions, limitations and recommendations are provided. (Chau, et al., 2015, pp. 395-413; ISO 14040, 2006).

Table 3 Mandatory and optional elements of LCIA (ISO 14040, 2006).

Compulsory elements	**Optional elements**
Impact category selection, determining category indicators and characterization models	Calculation of the extent of category results according to reference information
Determining LCI results	Grouping
Category indicator result calculation	Weighting

Building

In general, total share of buildings' energy consumption is remarkable, as buildings and construction account for almost a third of global energy consumption. If the emissions from power generation to cover building energy needs are taken into account, the share of global energy-related carbon emissions are almost 40 %. Many LCA studies have conducted studies for residential and office buildings, but industrial buildings have received less attention. (Rodrigues, et al., 2018). Buildings can achieve significant energy savings through reasonable designing. Thus, the work towards energy conservation and carbon emission mitigation has longer-term significance in the progress of low-carbon economy. In contrast to traditional buildings, some characterizing features of industrial buildings are short construction time, efficient construction process and fairly simple maintenance. (Chen, et al., 2021).

The building life cycle carbon footprint assessment includes emissions from product, construction, use, and end of life phases (Figure 8). Considering the energy consumption and carbon emissions, the key life cycle phases are product and use stages. The allocation into different life cycle stages helps to identify which stages causes the most emissions when the focus can be targeted to reduce emissions from those stages. (Ministry of the Environment, 2016).

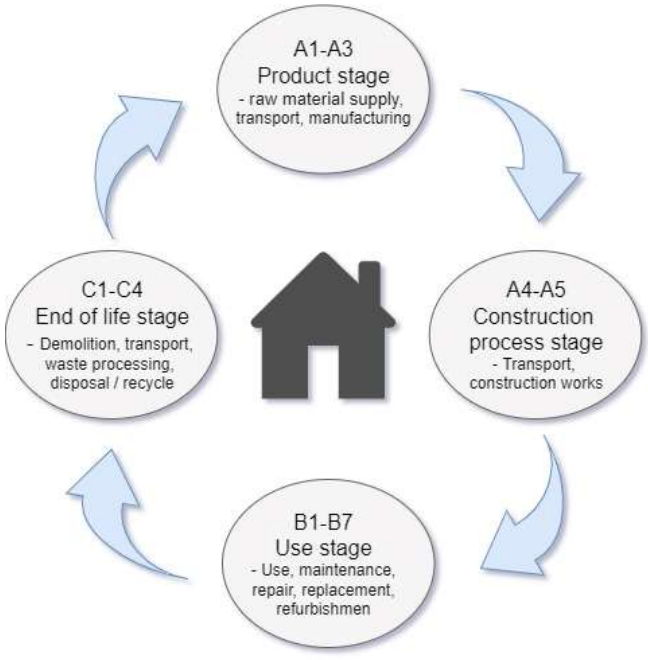

Figure 8 Building life cycle stages.

Life cycle assessments are used to make knowledge-based optimizations and to evaluate individual processes in relation to the entire life cycle of a building. LCA is done for a period for which building maintenance and repair can be assessed with reasonable accuracy. In principle, it is recommended to select the service life required for the building as the reference period. Target life of buildings is most often 50-100 years. (Ministry of the Environment, 2016).

Battery materials

Novel LCA studies of battery manufacturing processes help to enhance the process' environmental efficiency and to replace lead acid batteries by employing discarded electric vehicle LIBs. GHG emissions in battery value chain are arising from production, transportation, use and disposal phases. In the raw material production, majority of raw elements used in LIBs are extracted from their respective ores. As described earlier, lithium, nickel, cobalt, and manganese are the most common raw materials used in LIB cathode manufacturing, whereas the key processes to convert metals to the precise material form used in batteries are mining, processing, smelting, leaching and refining. Battery use phase causes indirect emissions from various activities, such as energy consumption from battery weight carrying, energy conversion losses (determined based on battery's energy efficiency), and conventional energy production. Due to health risks and environmental issues associated with improper landfilling or incineration of LIBs, many industrial scale recycling techniques are being developed (e.g. hydro- & pyrometallurgy) to utilize valuable components incorporated in LIBs. Better resource use efficiency and other environmental benefits are achieved through improved recycling techniques. (Arshad, et al., 2022).

Battery value chain is broad and complex meaning that there are often many uncertainties also in LCA studies. Challenges of applying LCA studies to batteries are related to methodological choices and battery manufacturing primary data scarcity. Common consensus on how LCA studies should analyze and report battery environmental impacts has not been made. This makes mutual comparison of different technologies challenging, which can also limit a common ability to detect and correct literature errors. However, LCAs can be applied in many ways, which can produce useful information for different decision-making situations. Life cycle inventory results also often differ by one or more orders of magnitude in the literature, and many analyses are unable to explain the root cause of the differences. (Porzio & Scown, 2021).

Besides the ISO 14040-14044:2006 – standards that guide the LCA process, the Product Environmental Footprint Category Rules (PEFCR) by The Advanced Rechargeable & Lithium Batteries Association (2018) provides comprehensive guidance on how to conduct a PEF study for batteries. The PEF methodology does not discuss cathode materials in more detail, but the guidelines can be utilized in cathode material carbon footprint calculation to support the information of other standards. Besides GWP, other relevant environmental impact categories mentioned in the PEFCR are acidification, eutrophication, land use, ozone depletion, resource use and water scarcity.

4.2. Regulation of Carbon Footprint Calculation

Regulation of carbon dioxide emissions from building materials in Europe consists of obligatory regulation in the form of emissions trading, and requirements that enable regulation e.g. in the Construction products decree. However, the majority of European guidance is standard and information-based guidance. At the EU level, emissions trading is the only obligatory control system for emissions of building materials, which applies to production plants with capacity above a certain minimum size in certain sectors. Emissions trading obliges production plants (e.g. iron, steel, gypsum, lime glass, cement, ceramics, mineral wool, wood, aluminum production) in accordance with section 2 of the Emissions Trading Act (311/2011), to limit its emissions to its quota, or to acquire allowances on the market. (Bionova, 2017).

Carbon dioxide emissions data is available in variety of sources. These are mainly product environmental statements and emission calculation softwares that include separate emission databases. Material emissions also differ within the same group of materials and the emissions of construction products can also be calculated differently. The calculations may apply to technically different products and describe the carbon footprint of the products, for example in different countries of manufacture, with different manufacturing techniques or characteristics. It is essential for the practical emissions calculation that the user has reliably representative emission data for the materials used in Finnish conditions, the data is consistent and have been produced in compliance with the requirements of EN 15804. Data produced using critically different methods should not be used in the calculation, as calculation made with using irregular data may not take into account all required life cycle

emissions and limits. LCA in all sectors generally relies on ISO 14040 and ISO 14044 standards. (Bionova, 2017).

Green Building Council Finland (FIGBC) has developed project phase and use phase life cycle indicators, to help to produce environmentally better buildings that are also healthy for users and profitable investments for owners. The indicators are suitable for Finnish climate and legislation. Carbon footprint is one of the indicators, which enables the design, evaluation and comparison of low carbon solutions to manage life cycle carbon emissions. Other indicators are, for example, life cycle cost and indoor air class.

The life cycle indicators are based on European CEN/TC 350 – Sustainability of Construction Works -standard set, which promotes sustainable construction and enables measurement of international building materials and building related emissions with co-dimensional method. The standard set have been created to provide a framework for evaluating the sustainability of buildings and to enable comparability of the assessment results. It is divided into three different levels: framework, building, and product levels, in which the most important ones regarding carbon footprint are the following:

- EN 15643 Framework of Environmental Performance
- EN 15978 Sustainability of construction works - Assessment of environmental performance of buildings – Calculation method
- EN 15804 Environmental product declarations – Core rules for the product category of construction. (FIGBC, 2013).

EN 15643 provides a framework level principles, guidelines and requirements to evaluate building environmental performance based on life cycle approach. EN 15978 provides calculation rules for environmental performance assessment of new and existing buildings. EN 15804 presents product category rules for construction products and services. Its structure ensures harmonized derivation and verification of all Environmental Product Declarations (EPD) of construction products and construction services and processes. (EN 15643, 2021; EN 15978, 2012; EN 15804, 2012). Companies manufacturing building materials have increasingly started to produce EPDs that indicate manufacturer's commitment to assess and reduce its product environmental impacts and report those impacts transparently. (The International EPD System).

GWP is calculated separately for each life cycle stage. The EN 15978, (2012) -standard presents the calculation of environmental impacts including all impact categories. The calculation includes multiplying each product and service with its respective environmental indicator value (Equation 1)

$$EP_i = \overrightarrow{a_j} \times M \quad (1)$$

where

EP_i is the building indicator value of the module *i*;

$\overrightarrow{a_j}$ is the vector including all the amounts of products and services used in the module j of the building;

M is a matrix that contains in its columns the environmental indicator values per unit of all products and services used in building module *i*.

The above equation is exemplified in the same standard with Equation 2

$$GWP_i = a_{1,i} \times GWP_{a_1,i} + a_{2,i} \times GWP_{a_2,i} + a_{3,i} \times GWP_{a_3,i} + \ldots + a_{N,i} \times GWP_{a_N,i} \quad (2)$$

where

GWP_i is the global warming potential quantified for the module *i* of the building;

$a_{n,i}$ is the amount of product or service *n* used in the module *i* of the building;

$GWP_{a_n,i}$ is the global warming potential of product or service *n* used in the module *i* of the building (n = 1, 2, 3, …, N)

5. Carbon Footprint Calculation

This chapter describes materials and methods applied to the empirical study. The study follows the LCA structure according to ISO 14040 -standard series. At first the goal and scope are defined, followed by an inventory analysis. The main method was internet-based calculation tool Oneclick LCA, which is a broadly used tool for conducting building LCAs. Use of the tool and GWP calculation are part of LCA, in which the aim is to identify items that are producing high amounts of emissions that have room for improvement, and to define already sustainable materials. The inventory analysis helps to outline material flows with consistent allocation and to identify contribution of each process or material to the total emissions. In addition, a brief expert interview was conducted to support the findings in previous chapters. In the interview some fundamental questions of pCAM and CAM manufacturing were asked from a Chief executive officer of a company that will run Hamina pCAM plant to better understand the plant functions, which will have impact on the emissions formation. The questions are shown in Appendix 3 and the answers are summarized in the two paragraphs below.

The interview revealed that the pyrometallurgical calcination during CAM production is the most energy intensive process, in which lithium hydroxide and pCAM mixture are heated to high temperatures to reach desirable level of material porosity. NMC chemistries are currently preferred in the Finnish production due to good energy density, however LFP was considered to have potential in the future, as it is cost-effective, requires less raw material mining and is cheaper to produce than NMC. In NMC cathodes, cobalt content is desired to reduce as its price is volatile and its production is subject to environmental, social and governance (ESG) concerns. In contrast, nickel and manganese share is wanted to increase in the mix.

Although there is a lot of discussion on sustainable battery production, it is good to remember in wider perspective that the ultimate goal behind the whole industry is to promote more sustainable and comfortable life. If some materials become too expensive for certain reasons, alternative solutions are made and other materials are brought to use. Battery recycling will have even higher importance in the future for the reuse of raw materials due to limited natural resources. Environmentally, the main concern in pCAM plant is the sodium sulfate effluent

treatment and its release into waters, whilst the corresponding challenge of CAM plant is high electricity consumption, where energy production causes emissions to air unless renewable sources are fully used. During disruption or accident there are also risks with toxins control, where gaseous and liquid leakages are possible.

5.1. Goal & Scope

The goal of the study was to define a carbon footprint of planned CAM production and industrial building plants. The results can be compared and may be used to demonstrate the low carbon content of a Finnish CAM, which can increase buyers' attractiveness towards the product. The resulting emissions are considered together as a whole, but also as separate entities to identify the most significant factors from CAM production and building materials.

In the literature it has been found in many battery LCA studies that raw material production has the highest impact on GWP during the battery life cycle. Carbon footprint of Finnish pCAM raw materials production ($NiSO_4$, $CoSO_4$, $MnSO_4$) were calculated based on values given by manufacturers and literature. There are also other commodities such as ammonium water, sulfuric acid, sodium hydroxide and lithium hydroxide that are needed in pCAM and CAM production, which are produced by external manufacturers and transported to the Hamina and Kotka sites.

This study examined GHG emissions from CAM product manufacturing processes from cradle-to-gate, which also included emissions from building infrastructure life cycles of two CAM manufacturing plants. Cradle-to-gate refers to LCA process where product emissions are evaluated from resource extraction to product manufacturing (Figure 9). Such research covers all stages of production from raw materials to a finished product.

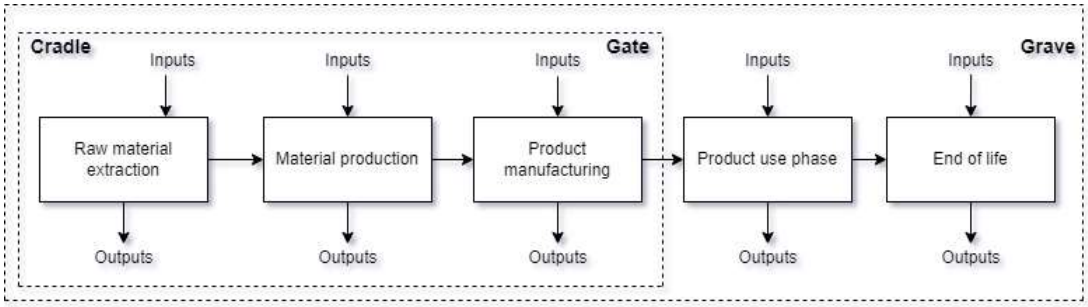

Figure 9 Cradle-to-gate and cradle-to-grave views of LCA.

Since it has been discussed that raw materials ($NiSO_4$, $CoSO_4$, $MnSO_4$) production has remarkable impact on the final results, and in raw material emissions calculation it was decided to rely on the values provided by their manufacturers, it was decided to calculate the emissions of other commodities (NaOH, H_2SO_4, LiOH) also based on values provided by their manufacturers. For ammonium (NH_4OH) the emissions are calculated based on literature value. Thus, emissions of production itself per specific production capacity of raw materials and commodities were not calculated separately in this study, but the collected data from these materials were seen reliable and optimal for the respect of the work. According to Figure 10, CAM is considered as component material within the battery manufacturing material stages. Thus, the study's scope was limited from raw material stage to product material stage and did not include final disposal or the final phase of CAM processing (cell and pack manufacturing). As the study was conducted on this extent and the CAM manufacturing process was considered as an independent process from the rest of the battery value chain, ''cradle-to-gate'' was used as a concept to describe the system boundary.

The scope neither included other component manufacturing (anode, electrolyte, separator) or downstream products, such as EVs or consumer electronics (Figure 10). Since the study was conducted to a private company, the next stage usage of the product after manufacturing process from the company's point of view is yet unknown or confidential information. These stages were limited out mainly for these reasons.

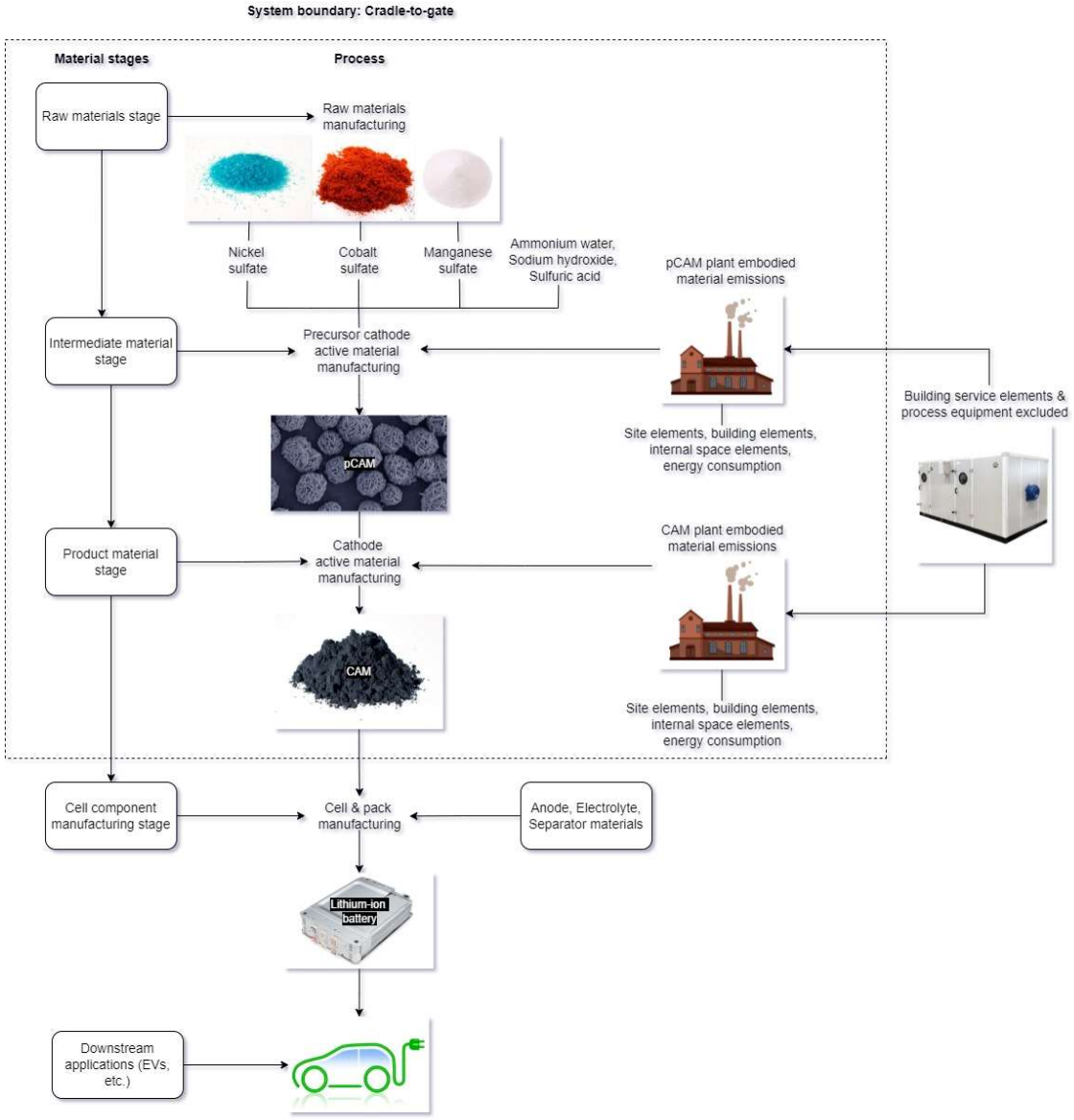

Figure 10 System boundary of the LCA.

Images: Nickel sulfate Sumitomo Metal Mining, a (2022); Cobalt sulfate Minerals Feed (2016); Manganese sulfate Pestell Nutrition (2015); pCAM Sumitomo Metal Mining, b (2022); CAM Sumitomo Metal Mining, c (2022); Lithium-ion battery Nissan (2022); Factory building Vector Stock (2022); Air handling unit Gobiz Korea; Electric vehicle EV Charge + (2022).

Although LCA studies often quantify several impact categories, such as GWP, ozone depletion potential, acidification potential, eutrophication potential, land use, resource use and water scarcity, this study focused determining GWP. Moreover, according to PEFCR by The Advanced Rechargeable & Lithium Batteries Association (2018), GWP and resource use are one of the most relevant environmental impact categories of battery manufacturing, in which the most important life cycle phase is raw material acquisition. This observation

and the fact that the GWP is a commonly used measure of environmental impacts supported the choice of GWP as the studied impact category.

Since estimation of annual production capacity of CAM in Kotka factory is 20 000 tons/a and main focus of this study alongside building materials was on the process of pCAM and CAM production, the annual CAM production capacity was used as functional unit: t CO_2 eq./20 000 t CAM, a. Geographically the scope was limited to examine Finnish CAM manufacturing process.

Regarding building materials emissions calculation, the materials were added to the calculation tool according to Construction 2000 classification, which is a Finnish classification system of construction products established in co-operation within construction sector. In the construction sector it is a basis for information exchange for the use of all parties (Rakennustieto, 2022). Initial data used for the calculation of pCAM plant were primarily a 3D-model, structure types and floor plans that were created for the project by designers. In pCAM plant many of the materials were also measured from the plant 3D-model. In CAM plant, bill of quantities was the main source of materials in the calculation. Energy consumption estimates of the pCAM and CAM plants is based on preliminary energy simulations, created for the main process building by experts in the projects. As the design process was still in progress at the time of calculation, some discretion was needed to use to evaluate all the necessary materials. It had to be noted that the designs may still change as the projects progress, which could have some impact on the final results.

Besides core process building, the pCAM plant consisted of six other buildings: storage building, steam plant, electric rooms, chemical wastewater treatment plant, demineralized water plant and chemical storage plant. The CAM plant included nine separate buildings: 2 process buildings, office building, office warehouse, automation storage, utility building, cooling water building, oxygen plant and process plant. All the buildings in both factories were included in the calculation.

Oneclick LCA calculation software was used as method to calculate the carbon footprint of the plants. The automated software has been developed to facilitate LCAs in construction industry and it enables organized calculation of carbon footprint for different building types. Building low-carbon assessment method by the Finnish Ministry of the Environment was used as calculation tool in the software, which is based on European Commission's Level(s)

-method and EN-15643, 15978, 15804 -standards (Ministry of the Environment, 2019). The low-carbon assessment method provides a procedure for calculating the carbon footprint, in which emissions from materials and energy consumption are based on individually calculated emission factors. The emission factors are obtained from Finnish construction emissions database, which provides impartial data on the climate impact of construction products used in Finland, such as carbon footprint and carbon handprint. The data is based on EPDs provided by material suppliers. The Finnish Environment Institute (SYKE) responses from maintenance and development of the database on behalf of the Ministry of Environment. Besides materials, the database also contains emission data for energy production, construction and demolition processes and transportation.

The emissions are calculated by multiplying the used material or quantity of energy by its emission factor. Material transportation, replacement, refurbishment and disposal are also included in the building emissions calculation, of which for transportation, refurbishment and final disposal have been given default values by the Ministry of Environment that are used for all materials. The necessary material replacements are calculated based on material technical life and the building assessment period. (Oneclick LCA, 2022). Calculation period, which also indicates the building service life, was needed to calculate emissions for product replacement, maintenance and energy consumption. As the exact service life of the buildings was unknown at the time of calculation and in order to calculate the emissions from the CAM manufacturing process over a reasonable period of time, calculation period was set to ten years for both plants. Due to this choice, emissions from material replacements were not included in the calculation.

5.2. Inventory Analysis

5.2.1. Cathode active material production process

The inventory data is mainly based on environmental impact assessment of Hamina and Kotka plants by Korkiakoski, et al., (2021), which is a Finnish procedure to mitigate or prevent harmful environmental impacts of different projects. Finnish law defines the projects for which the environmental impact assessment is required. As the design processes of

Hamina and Kotka factories was still incomplete this was the most optimal source for assessing material flows. Since there were still uncertainties related to the raw materials and commodity production of pCAM and CAM, it was not possible to precisely determine all required material quantities. Many of the commodity chemicals used in the manufacturing processes are produced elsewhere and will be imported to the factories.

As the emissions were evaluated from cradle-to-gate, all relevant unit processes from different material stages were identified. Range of production volumes fluctuate highly in many processes as there are many variables related to production of different raw materials. As an example, larger perspective need for raw materials and CAM is eventually dependent on EV demand. The products can also be made with different compositions or with special features according to customer needs. Raw materials are also produced in various locations in different forms, which affects the production rates among producers. Additionally, the quantities are affected by which battery chemistries are produced at the highest volume, as for example nickel is needed more in NMC-811 cathode than in NMC-532 cathode.

According to the reported functional unit, roughly 20 000 tons of pCAM is needed to produce 20 000 tons of CAM. Material flow quantities have been calculated based on this evaluation and the production values reported by Korkiakoski, et al. (2021). Preliminary evaluations of the unit process quantities in CAM manufacturing are presented in Figure 11. The figure includes production volumes in tons for substances, that contribute to carbon footprint and are manufactured off-site. Emissions of other manufactured substances consist of energy consumption of the plants and are produced mainly on-site.

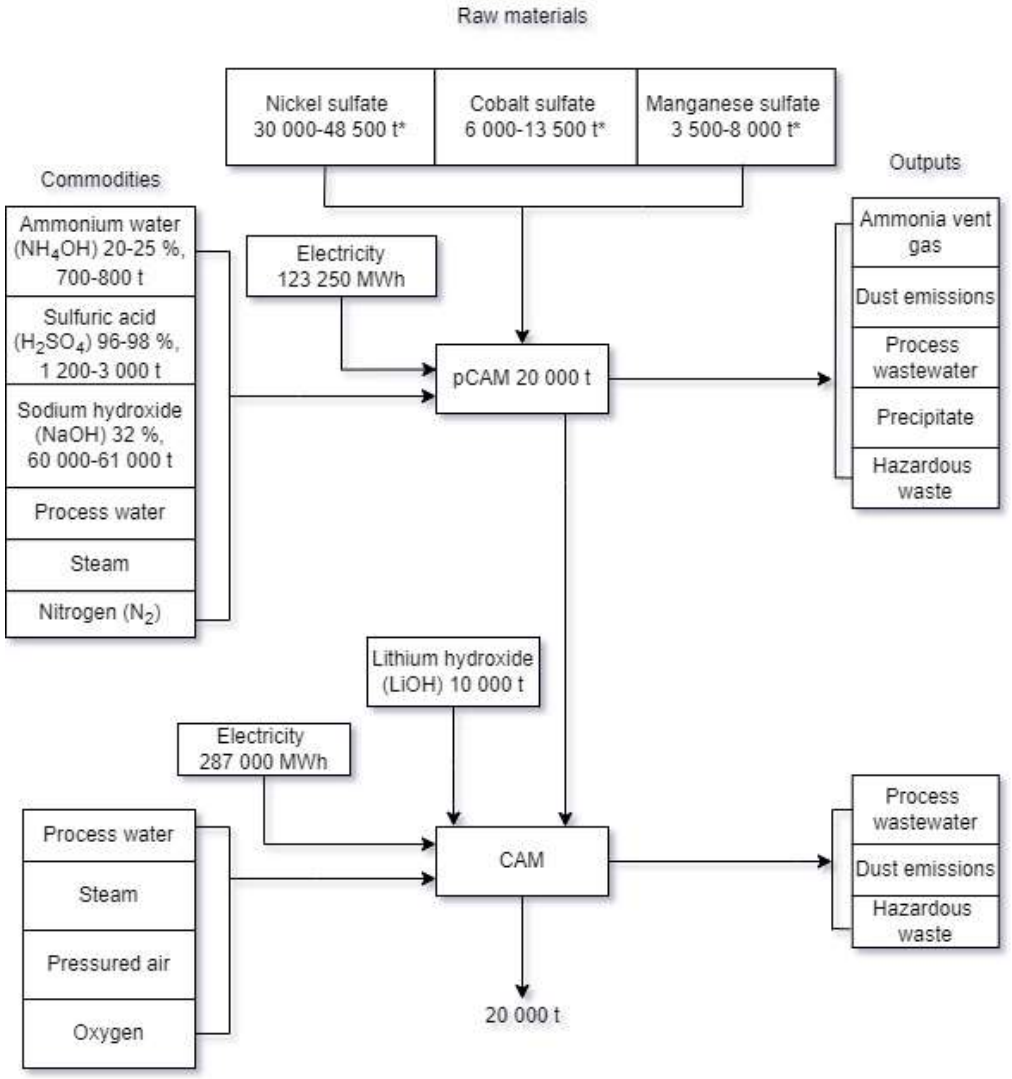

Figure 11 Inventory of CAM production, when annual production capacity is 20 000 t (Korkiakoski, et al., 2021).

* Input either as metallic sulfate or metal (presented as metallic sulfate). Weights as metal would be lower.

It was assumed that both plants use electricity from Finnish grid mix, which today is produced mainly from renewable energy sources. In 2021, the share of carbon dioxide-free electricity in the grid mix was 87 %, with nuclear power accounting for 32,9 %, hydropower 22,5 %, biomass 19,5 % and wind power 11,7 % (Energiateollisuus, 2022). Oneclick LCA tool uses benefit allocation method to calculate the emissions for energy consumption, which allocates the emissions of electricity and heat cogeneration to each energy commodity. In the method, the emissions are allocated and stressed according to the produced energy and efficiency. The method distributes emissions based on the assumption of how energy would

be produced without cogeneration. The efficiency ratios that best suit in the situation can be used. (Pasanen, et al., 2013). According to Pasanen, et al. (2013), if it is not necessary to use other values, the efficiency of electricity production is usually assumed to be 39 % (condensate production) and the efficiency of heat production to be 90 % (water boiler). For this, they have given an example, that if a power plant produces the same amount of both electricity and heat, the emissions are divided in ratios 1/0.39 : 1/0.9.

5.2.2. Building materials

In building materials, the calculation covered all the main structures in both plants, including foundations, basements, retaining walls, external walls and façade, columns and beams, internal walls, floor slabs, ceilings and roofs. From other structures, pavements of outdoor areas were included, but building service elements and site equipment were excluded. The calculation tool takes materials service life automatically into account, which affects the emissions caused by material renewals. It is not necessary to renew building materials during 10-year reference period, thus those were not needed to consider in the calculation. Apart from the main structures, other materials such as internal dividers and space surfaces were added to the calculation depending on the available input data. Breakdown of the included materials is given in Table 4.

Table 4 Building materials included in the calculation in Hamina pCAM and Kotka CAM sites.

Element	**Structure**	**Hamina (pCAM)**	**Kotka (CAM)**
Site elements	Ground elements	x	x
	Soil stabilization & reinforcement elements	x	x
	Pavements	x	x
	Site constructions	x	x
	Site equipment		
Building elements	Foundations	x	x
	Ground floors	x	x
	Structural frame	x	x
	Facades	x	x
	Roofs	x	x
	External decks		

Internal space elements	Internal dividers	x	x
	Space surfaces	x	x
	Internal fixtures		
	Other internal space elements		
Building service elements	Air conditioning elements, plumbing, electrical, data transfer, mechanical elements		

Materials such as site equipment, internal fixtures, other internal space elements, process equipment and building service elements were excluded from the calculation, as data of many of these materials were not available and difficult to estimate due to lack of reference cases. Some of the excluded materials can also be expected to have low impact on the final results. However, in case of building service elements, the embodied emissions can have somewhat remarkable impact on total building material emissions. Nonetheless, in industrial building, the ventilation volumes are larger than in conventional building and the emissions of building service energy consumption are presumably higher than its embodied material emissions. For process equipment, the evaluation of material quantities at the early state of the projects' design processes was yet challenging.

In some materials Oneclick LCA tool considers automatically multiple materials under a single item. A steel structured sandwich panel is an example of one of these structures, where one item includes external steel shells and mineral wool in between. Some materials, such as reinforcement in concrete needed to be added separately in the calculation if they were not automatically included in these items. When quantities for concrete structure reinforcements were not available, typical average values by Janicki (2021) were used to evaluate the amounts. The calculation tool included also standard values for material transportation to construction site, thus estimated values from material transportation were also included in the calculation.

6. Results and analysis

Results for the carbon footprint calculation are presented in this chapter. The results are presented separately for the CAM production and building materials of both plants. Additionally, a brief comparison of emissions between Finnish and Chinese CAM production is presented. Summary of the total results is presented in this paragraph. In building materials, emissions of different life cycle stages are reviewed.

Summary of the emissions for 10-year period is presented in Figure 12. Total calculated carbon footprint for all materials and energy for 20 000 ton annual production in 10-year period is 3 046 005 t CO_2 eq. The figure shows the shares of different materials and energy consumption in total emissions. The largest emissions are caused by the nickel and cobalt sulfate and lithium hydroxide production, which together account for 87 % of total emissions. The building material emissions of the pCAM and CAM factories are minor with the share of only 1.6 %. However, this value is slightly higher in reality as HVAC and process equipment were excluded from the scope. Manganese sulfate, ammonium, sulfuric acid and sodium hydroxide production have also minor impact to the total emissions with 5.4 % combined share. The share of energy used in manufacturing processes is 5.9 %.

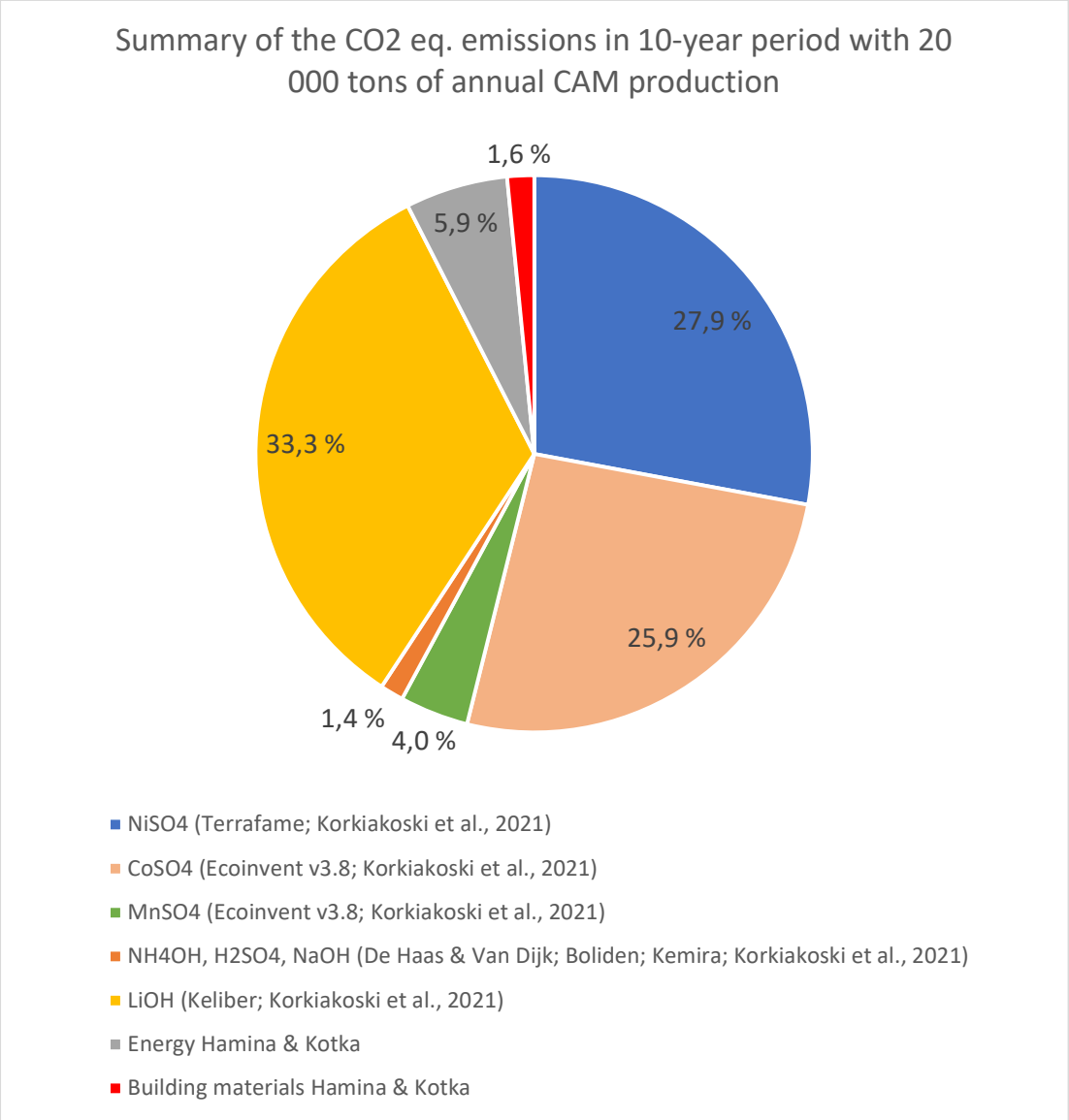

Figure 12 Total shares of carbon footprint for Kotka and Hamina 20 000 t plant production.

6.1. Cathode active material production

In the particular plants, the materials can be purchased from different manufacturers, meaning that the results can vary depending on the manufacturers' production methods. Although it is uncertain where the substances are acquired to the factories, it is probable that most of the amounts will be procured from Finnish manufacturers. Therefore, data was aimed to gain from Finnish operators for most of the materials.

GWPs of raw materials needed for pCAM production are compiled into the following table (Table 5). Emissions are presented per one ton of material production. Nickel sulfate's value is reported by Terrafame and the emission for cobalt and manganese sulfates are provided in Ecoinvent database v3.8. The values for sodium and lithium hydroxide and sulfuric acid are publicly announced by Finnish chemical producers Kemira, Keliber and Boliden, whereas the emission for ammonium was gained from literature. Reference values have also been collected from the literature to compare the values used in this study. By comparing these values, it can be seen that the used values are lower for each substance, which is mainly due to lower emissions of Finnish production.

Table 5 Emission results for pCAM raw materials per ton of production.

Raw material / Commodity	**t CO_2 eq./t of production**	**Source**	**Reference values t CO2 eq./t of production**	**Source**
Nickel sulfate ($NiSO_4$)	1.75	Terrafame, b (2020), Finnish production	5.4	Nickel Institute, (2020), industry average
Cobalt sulfate ($CoSO_4$)	Supplier specific	Ecoinvent database v3.8, (LCA consulting database values)	38	Cobalt Institute, (2015), Cobalt metal
	-	-	1.58	First Cobalt, (2020), Canadian production
Manganese sulfate ($MnSO_4$)	Supplier specific	Ecoinvent database v3.8, (LCA consulting database values)	6.0	Aiden Westfall, et al. (2016)
Lithium hydroxide (LiOH)	10 (from ore)	Keliber (2022), Finnish production	7.0 (from Chilean brine), 15.7 (from Australian ore)	Kelly, et al., (2021)
Ammonium water (NH_4OH)	1.95	De Haas & van Dijk (2010), Europe average	2.18	Yueling, et al., (2022), Chinese production
Sulfuric acid (H_2SO_4)	0.033	Boliden (2022), Finnish production	-	-
Sodium hydroxide (NaOH)	0.187	Kemira (2021), Finnish production	0.633	Thannimalay, et al. (2013), Malaysian production

Maximum values for the announced material ranges were used based on material flows presented in Figure 11. The results consider also the percentages of substances (included in Figure 11) in ammonium water, sulfuric acid and sodium hydroxide to produce the required amounts of pCAM. Thus, the GWP for ammonium water, sulfuric acid and sodium hydroxide was calculated as shown in Equation 3

$$GWP = Feedstock * Substance_{percentage} * Emission * 10\ years \quad (3)$$

where

GWP	is the quantified global warming potential for the substance
Feedstock	is maximum input of the feedstock (Korkiakoski, et al., 2021)
$Substance_{percentage}$	is substance percentage in the solution (Korkiakoski, et al., 2021)
Emission	is emission based on reported value (Table 5)
10	is 10-year calculation period

The result for example for sodium hydroxide is then

$$61\,000\ t * 0{,}32 * 0{,}187\ t\ CO_2eq./t * 10\ years = 36\,502\ t\ CO_2eq.$$

All the results are presented in Figure 13.

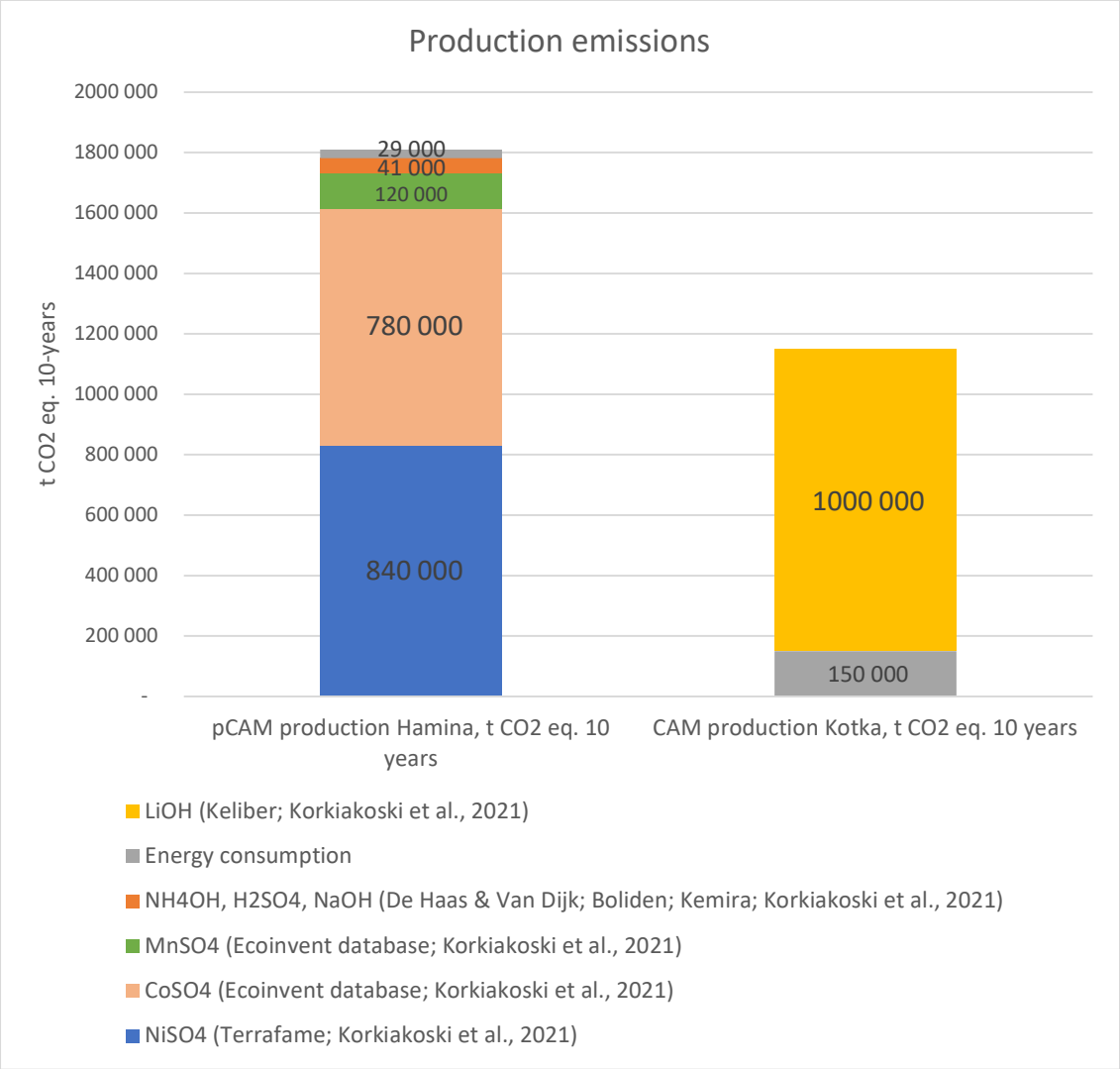

Figure 13 Carbon footprint of pCAM and CAM production.

In pCAM production, nickel sulfate causes the highest emissions of the raw materials due to its highest material demand towards 20 000 tons of pCAM. Cobalt sulfate produces the most emissions among the metal sulfates per ton of material production, but it is needed less than nickel sulfate based on the material flows. In turn, lithium hydroxide causes high carbon footprint in CAM production. Keliber has announced that most of its lithium hydroxide emissions (78 %) are originated from lithium chemical plant's refining stage.

In all materials, energy consumption is an important single factor causing a large share of the emissions. In this study the electricity consumption emissions from pCAM and CAM production were calculated according to the Finnish national grid average. The difference in energy consumption between the factories is mainly due to the calcination process in CAM

production. It is probable that the share of renewable energy sources is higher in reality and thus the emissions from electricity consumption might be lower. However, the used energy consumption values can also still change during the design process.

To evaluate the magnitude of the emissions and to point out a bigger perspective, the results were compared to Chinese reference CAM production (Figure 14), which is a rough cradle-to-gate estimate. The reference CAM calculation was implemented by a Finnish company called LCA consulting and initial values used in the calculation are based on study conducted by Dai, et al. (2018). From these studies the emissions were calculated for 10-year period, from which emission savings were determined. In the middle column, the emission of pCAM is calculated for 100 % material produced in Hamina plant. However, in reality part of the pCAM needed at the Kotka CAM plant is purchased from foreign producers with a likely higher carbon footprint. Therefore, the result of the project plant's pCAM share is higher in reality, which lowers also the savings. If pCAM was produced entirely in Finland, the 10-year emission reduction potential would be, according to this calculation as much as described in the right-side column of the figure.

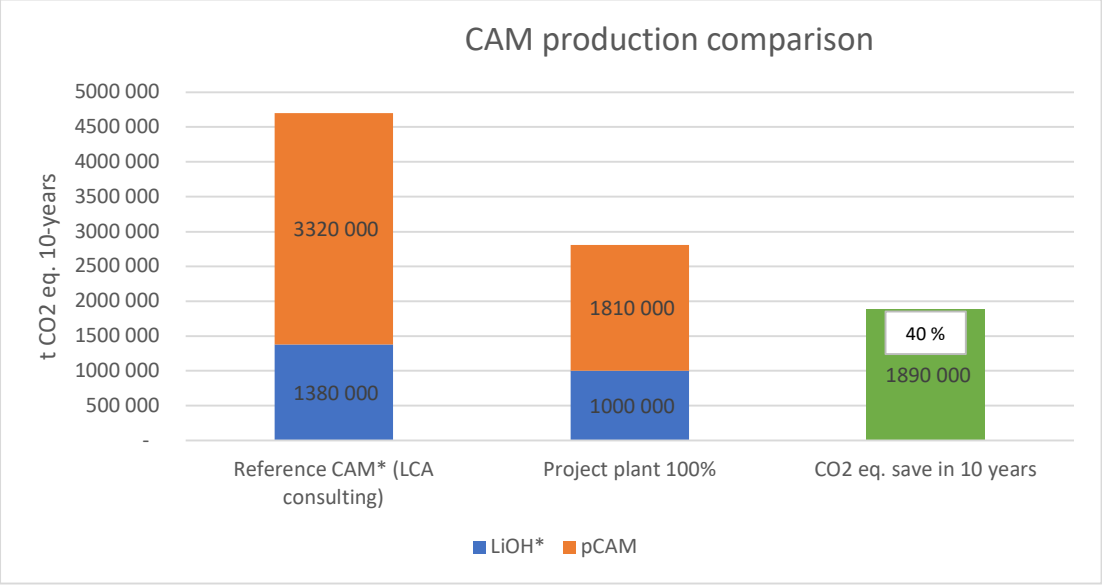

Figure 14 Comparison of CAM production emissions.

*Lithium hydroxide used for CAM production, which accounts for most of the emissions in CAM production.

Electricity consumption of the processes has not been taken into account in the comparison for few reasons. Chinese pCAM manufacturing processes are most likely simpler and thus less energy intensive than Finnish. Even if data on the electricity consumption of a Chinese

plant was available, it is not comparable to Finnish equivalent, as Chinese production volumes in relation to electricity consumption are not known. However, carbon footprint of the Chinese process is likely to be higher even if the electricity consumption towards an amount of a product was lower due to notably higher carbon intensity of Chinese electricity grid. According to International Energy Agency (2021), carbon intensity of electricity generation in China was 611 g CO_2/kWh in 2020. The corresponding value reported by Finnish Ministry of the Environment (2019) in the same year was 121 g CO_2/kWh.

6.2. Building materials of the plants

The emissions for building materials are presented for each life cycle phase in Figure 15. The life cycle phases include emissions before use (A1-A5), use phase (B1-B6) and end of life impacts (C1-C4). The results are given in t CO_2 eq./10 years. The biggest difference in emissions between the two plants is caused by use phase energy consumption, which in both plants is calculated for electricity use of HVAC, lighting and district heating. The presented default values of end-of-life phase are based on typical emissions reported by Finnish Ministry of the Environment (2019). From the default values (see Tables 9 and 10), the emissions for A4 and C2 transportations are calculated values for average transportation distance in Finland. A5 construction site - material wastage and C1 deconstruction emissions consist of site energy and fuel consumption.

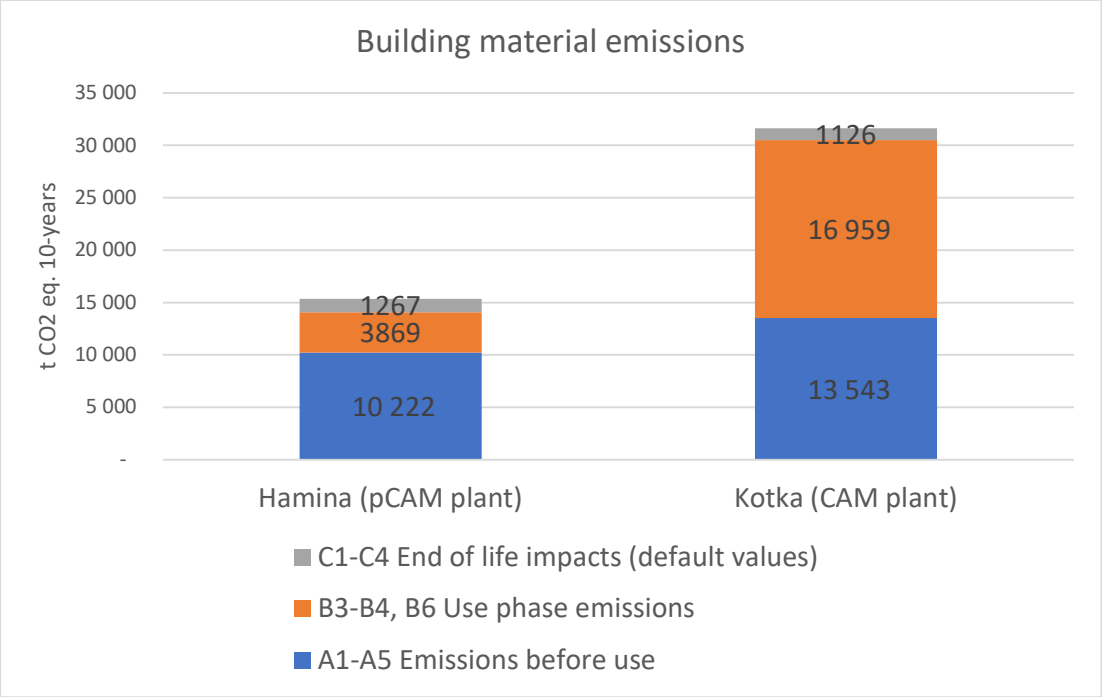

Figure 15 Carbon footprint of building materials of Hamina and Kotka plants.

The results are presented more detailed in Table 6. In addition, appendices 1 and 2 show the emissions divided into building component headings. In Hamina plant, the material embodied emissions have the highest impact on total emissions with over 66 % share. Use phase energy consumption, which includes energy consumption of HVAC equipment and lighting, as well as district heating contributes 25 %. From that percentage district heat's share is 5 % and electricity's 20 %. Share of end-of-life impacts is 8 %.

Table 6 Hamina pCAM plant emissions from buildings for 37705 m2 and 20 000-ton annual production capacity.

Life cycle phase	Result category	Global warming potential t CO2 eq. 10-years	Share
A1-A5 total	**Emissions before use**	**10 222**	**66.6 %**
A1-A3	Manufacturing of materials	8408	54.8 %
A4	Transportation, default value (Ministry of the Environment, 2019)	385	2.5 %
A5	Construction site - material wastage	385	2.5 %
A5	New construction site operations, default value (Ministry of the Environment, 2019)	1044	6.8 %
B1-B6 total	**Use phase emissions**	**3869**	**25.2 %**
B1-B2	Use and maintenance	-	-
B3	Repairs energy consumption, default value (Ministry of the Environment, 2019)	83	0.5 %
B4	Material replacement	-	-
B5	Refurbishment	-	-
B6	Energy use	3789	24.7 %
C1-C4 total	**End of life impacts**	**1267**	**8.2 %**
C1	Deconstruction default value, (Ministry of the Environment, 2019)	294	1.9 %
C2	Waste transportation, default value (Ministry of the Environment, 2019)	385	2.5 %
C3-C4	Waste treatment and disposal, default value (Ministry of the Environment, 2019)	588	3.8 %

A-C total	**Carbon footprint of all phases**	**15 357**	
A-C	Carbon handprint (Benefits of reuse and recycling)	-3412	-22 %

In Kotka CAM plant the product phase (A1-A5) contributes less to the total emissions with only 43 % share, while use phase energy consumption has higher share, 52 %. This is caused by significantly higher electricity consumption. Major energy consuming components from the HVAC equipment at the factory are ventilation and air drying. The value of use phase emissions consists completely of electricity, as the factory will probably use waste heat from the kilns for heating. Share of end-of-life impacts is almost 4 %.

Table 7 Kotka CAM plant emissions from buildings for 33522 m2 and 20 000 ton annual production capacity.

Life cycle phase	**Result category**	**Global warming potential t CO2 eq. 10-years**	**Share**
A1-A5 total	**Emissions before use**	**13 542**	**42.8 %**
A1-A3	Manufacturing of materials	11 642	36.8 %
A4	Transportation, default value (Ministry of the Environment, 2019)	342	1.1 %
A5	Construction site - material wastage	630	2.0 %
A5	New construction site operations, default value (Ministry of the Environment, 2019)	929	2.9 %
B1-B6 total	**Use phase emissions**	**15 916**	**52.0 %**
B1-B2	Use and maintenance	-	-
B3	Repairs energy consumption, default value (Ministry of the Environment, 2019)	74	0.2 %
B4	Material replacement	-	-
B5	Refurbishment	-	-

B6	Energy use	15 842	51.8 %
C1-C4 total	**End of life impacts**	**1 126**	**3.7 %**
C1	Deconstruction, default value (Ministry of the Environment, 2019)	261	0.9 %
C2	Waste transportation, default value (Ministry of the Environment, 2019)	342	1.1 %
C3-C4	Waste treatment and disposal, default value (Ministry of the Environment, 2019)	523	1.7 %
A-C total	**Carbon footprint of all phases**	**30 585**	
A-C	Carbon handprint	-4918	-16 %

According to Appendix 1, midsole structures and exterior walls are single structural groups having the highest impact on the material emissions in Hamina plant. The midsole structures are mainly located in the core building, which consists of several floors. These structures contain a lot of concrete as well as steel structures with a relatively high carbon footprint. Exterior walls consist of steel and concrete sandwich elements, of which steel sandwich is less carbon intensive. The concrete sandwich structure requires steel reinforcement in addition to two concrete shells and insulation, while steel sandwich consists of steel outer and inner shells with wool insulation in between. Steel sandwich is a typical structural exterior wall solution of a factory hall.

In Kotka plant (Appendix 2) the foundation footings and ground floors form the largest emissions among the structures, which require large amounts of concrete and reinforcement. Upper soles are the third largest source of emissions, in which hollow core slabs are used in high volumes. Hollow core slab is common load-bearing structure of upper and midsoles. The slab does not contain as much concrete or reinforcement compared for example to a solid concrete structure and is therefore less carbon intensive. The benefits of carbon handprint are gained from material reuse and recycling.

All in all, both plants use rather similar structural solutions due to characteristics of factory construction. Concrete is the most emissive material group in both plants, as it is in use in

almost all building structures either as ready-mixed or in-situ casted. The second largest material group is steel sandwich panels in Kotka and concrete reinforcement in Hamina plant. The hollow core slab is the third most emissive material group in both plants.

Considering energy consumption, the basic principle of the design process is to fulfil regulations related to cleanliness and temperature levels. Arrangement of periodical ventilation might be challenging due to continuous operations of the plants. This implies that HVAC systems must be running almost constantly, and there are limitations for electricity use regulation. For heating, the process equipment releases heat to some extent, which affects the need for district heat of the buildings. However, energy efficiency and thus the carbon footprint can be influenced by taking into account general energy planning issues such as lighting, ventilation heat recovery, utilization of heat loads, building structural tightness, functioning of loading openings and monitoring of energy use.

6.3. Consistency check

The main results of the study rely on primary data provided by raw material manufacturers and data given in literature. Consistency check can be conducted for different studies to evaluate a study's data consistency from different viewpoints. In this study, the consistency check was done in separate tables for pCAM and CAM production (Table 8) and for building materials (Table 9). The consistency check is based on ISO 14044 (2006) -standard table B.13.

Table 8 Consistency check of pCAM and CAM production.

Check	Hamina pCAM		Kotka CAM		Comparison	Action
Data source	Primary & literature	OK	Primary & literature	OK	Consistent	No action
Data accuracy	Sufficient	OK	Sufficient	OK	Consistent	No action
Data age	Recent	OK	Recent	OK	Consistent	No action
Technology coverage	Existing technology	OK	Existing technology	OK	Consistent	No action

Time-related coverage	Old	OK	Old	OK	Consistent	No action
Geographical coverage	Finland, Europe	OK	Finland	OK	Consistent	No action

From the Table 8 it can be stated that the data is consistent and further action to revisit the study did not occur. The data accuracy is considered sufficient in both, but it is not fully precise and will update as implementation of the projects proceed. Otherwise, the data is recent, geographically coherent and based on similar sources. Sources have been reported to be both primary and literature based. Here the data reported by the manufacturers is considered primary and the data from scientific publications is literature based. The ‘’OK’’ entry in the table columns indicates that there are no inconsistencies in the subjects and the ‘’action’’ column specifies any actions required to correct the inconsistencies.

Table 9 Consistency check of Hamina and Kotka building material data.

Check	Hamina site		Kotka site		Comparison	Action
Data source	Primary & literature	OK	Primary	OK	Consistent	No action
Data accuracy	Moderate	OK	Good	OK	Not consistent	Revisit pCAM plant data
Data age	Less than 1 year	OK	Less than 1 year	OK	Consistent	No action
Technology coverage	Existing technology	OK	Existing technology	OK	Consistent	No action
Time-related coverage	Old	OK	Old	OK	Consistent	No action
Geographical coverage	Finland	OK	Finland	OK	Consistent	No action

Table 9 indicates that the building material data accuracy was not fully consistent. The data was mostly considered primary as the material information was collected from the building plans. However, it was not possible to base the data on similar plans, as different type of

qualitative and quantitative data was available for both. As an example, some concrete reinforcement amounts were estimated based on values given in literature, which generated little uncertainty for the calculation. The concrete reinforcement has somewhat remarkable impact on the building material emission results and may need re-checking when more advanced data is available.

The Oneclick LCA tool was assumed to be reliable and its material database to represent credible material-bound emission factors for the used products. For each material, the best possible product corresponding the material description were chosen and used in the tool. If a desired product was not found in the tool, it was replaced with similar product. Primary and literature data used in the study were also considered reliable.

7. Conclusions

This study determined carbon footprint of planned CAM production and industrial buildings. The results indicated that the CAM production phase causes significantly higher carbon footprint than the plant building materials. Although emissions over a ten-year period appeared to be high, the production of many battery raw materials in Finland result relatively low in emissions in relation to similar processes used globally. In general, the study raised awareness of CAM significancy as part of LIB and the impact of its GHG emissions in battery production. Raising the awareness can influence the public's attitudes on how production of the factories and CAM are reacted after preconceived notions. Increasing knowledge and identification of high emissive sources help to reduce the emissions.

Due to Paris Climate Agreement and raise of general environmental awareness, carbon neutrality has become a relevant part of corporate responsibility in companies during the past years and a goal to pursue in the future. Carbon footprint is also recognized as an environmentally important indicator in the industry. Multiple production stages of battery value chain require input of many different companies. Thus, there are many variables involved in the carbon footprint formation and its determination in battery LCA studies. These relate for example to different production methods, produced chemistries, customer preferences and measurement methods. Globally the energy production for raw materials

manufacturing is often based on coal combustion, which has a major impact on carbon emissions formation. Battery technologies are also evolving, meaning that the required material compositions used in battery cells are developing according mainly to the needs of EV production. An example of this is growing utilization of LFP batteries, as for instance Tesla has announced to use LFP batteries even in half of its new cars to reduce nickel and cobalt supply issues (Lambert, 2022). Properties of LFP battery are sufficient to certain usage needs, which is why it is not always reasonable to use NMC batteries.

By carbon footprint calculations, life cycle emissions of a building can be affected at an early stage of design process for example through material choices. However, in industrial buildings alternative material and structural solutions are more limited compared to conventional buildings, in which the alternative solutions (e.g. wooden structures and low carbon façade materials) can be more diversely used. Thus, in case of industrial buildings' emissions reduction, emphasis need to be often put on energy savings. Generally, conditions of the area to be built, such as soil quality and even weather conditions may sometimes influence to mandatory material choices, as if for example soil is not load-bearing, installation of either steel or concrete piles is required. One questionable point is the site asphalting, which could be partly replaced by green areas. This could also reduce heat loading of the buildings, although the cooling share is small in the total energy demand.

In addition to what has been discussed about the effects of the upstream functions to the carbon footprint in the study, the rest of the battery components, cell and pack manufacturing and downstream applications of the LIB need to be taken into account in comprehensive LIB LCAs. These studies are most often limited to assess battery life cycle emissions and do not similarly consider factory building materials. According to the results of this study, a major question was how remarkable the CAM emissions are in bigger picture, when the Finnish CAM product is included in the entire battery production? Therefore, the life cycle emissions of a European EV were compared to another European EV as follows, where the cathode of the battery and use phase electricity are produced in Finland. The emission values for EV were found from literature, whereas emissions of CAM were calculated per kilogram based on the results of this study.

To determine the life cycle emissions of the EV, it was first needed to calculate the emissions from battery production. A study conducted by Kawamoto, et al. (2019) were used as reference for the calculation, where they determined the life cycle emissions for Volkswagen

e-Golf (2018) for 100 000 kilometers with 35.8 kWh NMC battery. In order to find out emission factor of the battery produced from Finnish CAM, information was needed on how much CAM is needed in 35.8 kWh battery. Porzio & Scown (2021) reported that a 10 kWh NMC LIB requires approximately 1.3 kg of CAM and 0.84 kg of graphite in anode. According to these findings, the following material requirements and emissions (shown in Table 10) were calculated for the 35.8 kWh NMC battery. Furthermore, Han, et al. (2017) reported that 28 kWh NMC battery cell production and assembly produces 4.1 kg CO_2 /kWh, from which it was calculated that the cell production and assembly GWP for the 35.8 kWh battery is 188 kg CO_2.

Table 10 Material requirement and emissions of CAM and graphite for 35.8 kWh LIB.

Battery	**Requirement (kg/kWh)**	**Total requirement (kg)**	**GWP (kg CO_2/kg product)**	**GWP (kgCO_2)**	**GWP (kgCO_2/kWh)**
Cathode active material					
NMC, 10 kWh	1.3 (Porzio & Scown, 2021)	12.6	14.0 (CAM production in Finland)	175.5	17.6
NMC, 35.8 kWh	4.5 (calculated based on Porzio & Scown, 2021)	161.1	14.0	2249.6	62.8
Graphite in anode					
NMC, 10 kWh	0.8 (Porzio & Scown, 2021)	8.4	4.7 (Dai, et al., 2019)	39.5	4.0
NMC, 35.8 kWh	3.0	107.8	4.7	1505.1	42.0
Total for NMC battery with 35.8 kWh capacity				3942	

In use phase, emissions from energy consumption for battery charging and EV maintenance were considered. Kawamoto, et al. (2019) assumed that the battery needs to be replaced after driving 160 000 km and thus the replacement was not considered either in this comparison.

It is likely that in the future the lifespan of batteries will be extended as recycling processes improve. By knowing European average and Finnish electricity efficiency, as well as electricity emission factors, it was possible to calculate the emissions from electric power generation for both regions. These are shown in Table 11. The use phase emissions were calculated from equation

$$CF_{electric\ power}/E_{BEV} * D \quad (4)$$

where

$CF_{electric\ power}$ is electric power emission factor (kg CO_2)

E_{BEV} is EV electric efficiency (km/kWh)

D is driving distance (km)

Table 11 Electricity efficiency and emission factors of Europe and Finland.

	Europe	Finland	Gap
Electricity efficiency (km/kWh)	7.87 (Kawamoto, et al., 2019)	7.87 (assumed to be same as Europe average)	-
Electricity emission factor ($kgCO_2$/kWh)	0.52 (Kawamoto, et al., 2019)	0.11 (Ministry of the Environment, 2019)	79 %
Use phase emissions ($kgCO_2$)	6620	1390	79 %

Lastly the emissions from all life cycle phases were compiled into Table 12. Besides battery, the car manufacturing phase included inverter (641 $kgCO_2$), motor (1070 $kgCO_2$) and chassis parts (body, tires, interior: 4219 $kgCO_2$). European average value for the battery was calculated based on average emission factor (164 kg CO_2/kWh) reported by Kawamoto, et al. (2019). Regarding maintenance, Kawamoto, et al. (2019) estimated that the tire replacement interval would be 40 000 km and the lead acid battery 50 000 km. Hence both were estimated to be replaced twice during 100 000 km driving distance. End of life phase

comprised four stages (disassembly, shredding & sorting, transport, landfilling) of which ‘’disassembly’’ is not shown in table as Kawamoto, et al., (2019) saw its energy consumption contribution to emissions to be negligible.dd

Table 12 Life cycle emission comparison of European and Finnish EV (Kawamoto, et al., 2019).

EV (Volkswagen e-golf 2018), European average		**EV (Volkswagen e-golf 2018) with Finnish CAM and electricity production**
Manufacturing, kg CO_2		
Battery (NMC)	5871	3942
Car	5930	5930
Use phase, kg CO_2,100 tkm		
Electric power generation	6620	1390
Maintenance, kg CO2		
Tires	108	108
Lead acid battery	19,5	19,5
End of life, kg CO_2		
Shredding & sorting	24	24
Transport	4	4
Landfilling	38	38
Total	18 615	11 455

The results show that emission savings can be achieved when both CAM and vehicle use phase electricity are produced in Finland. The biggest difference in emissions is in the use phase energy consumption, where Finland’s electricity grid emission factor is clearly lower than those of European grid mix average. Finnish CAM manufacturing also achieves emission savings within battery production chain, in which cell and pack production emission values were assumed same as the European equivalents. To further estimate the EV sustainability, it would have been valuable to similarly include life cycle emissions of internal combustion vehicle (ICV) to the comparison. However, this would have required more extensive research on ICVs, as their emission evaluation comes with many variables.

In ICV, fuel consumption is for example more affected by things such as car type, speed, weight, terrain and season, as well as whether the car is driven on a highway or in a city. For these reasons gasoline emission factors vary, and ICV lifetime emissions were not included in this comparison.

Since in EV production the LIB has been considered to be the single component that clearly produces the most emissions, work on the development of battery chemistries must be continued in order to reduce production of such materials that have high environmental and social impacts. The development is needed without much compromising the battery performance. A product attractiveness is now and in the future being looked through the carbon footprint and other environmental impacts, as well as material traceability, which in fact is one important subject of further research. Traceability is strongly linked to environmental assessment as an indicator of sustainable material production. Further research is also needed to study other environmental impacts, as carbon footprint is only one of many impact categories. In addition to these, according to the European Commission's Green Deal, a sustainable battery includes, among other things, the limited use of hazardous substances, recyclability goals and durability. All of these should be taken into account in broader contexts when dealing with the subject of sustainability.

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Appendix 1. Hamina plant emissions of construction materials divided into building component headings.

Table 13 Hamina pCAM plant emissions from buildings.

Structure	**Global warming potential t CO2 eq. 10-years**	**Share %**
Site coverings	189	1.2
Foundations: footings	483	3.1
Foundations: retaining walls	788	5.1
Ground floor	1093	7.1
Frame: columns	679	4.4
Frame: beams	863	5.6
Frame: midsole	1610	10.5
Frame: upper sole	671	4.4
Façade: exterior walls	1561	10.2
Partition walls	385	2.5
District heat use	765	5.0
Electricity use	3024	19.7
Construction site operations	1044	6.8
End of life: deconstruction, waste transportation, waste treatment & disposal	1267	8.2
Others	928	6.0

Appendix 2. Kotka plant emissions of construction materials divided into building component headings.

Table 14 Kotka CAM plant emissions from buildings.

Structure	**Global warming potential t CO2 eq. 10-years**	**Share %**
Site coverings	335	1.1
Foundations: footings	2075	6.8
Ground floor	2025	6.6
Frame: columns	560	1.8
Frame: beams	801	2.6
Frame: midsole	1294	4.2
Frame: upper sole	1911	6.2
Façade: external walls	1100	3.6
Partition walls	841	2.8
Floor surfaces	724	2.4
Electricity use	15842	51.8
Construction site operations	929	3.0
End of life: deconstruction, waste transportation, waste treatment & disposal	1126	3.7
Others	972	3.2

Appendix 3. Interview questions

Which processes consume the most energy in pCAM and CAM production and why?

Why specifically NMC cathode active materials are wanted to produce and not for example LFP?

What do you believe will be the biggest differences between Finnish and Chinese pCAM production when considering the processes and energy consumption?

Why is nickel share wanted to increase in the materials?

What are the key factors for sustainable material production?

What are the main factors that affect to the annual production capacities?

What are the main environmental concerns of the factories?

What are the future market prospects for different cathode material?